

NJORD

Annual report 2020



UiO : **University of Oslo**



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

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01

About
Njord



The Mulafoosur waterfall in front of the village Gásadalur at the Faroe Islands. Árnafjall (722 m a.s.l.) in the back is the highest mountain on the island of Vágar and composed of basalt flows. These volcanic rocks are a potential storage site for large volumes of CO₂.



“It's not what you look at that matters, it's what you see”

– Henry David Thoreau

The cross-disciplinary geoscience-physics centre Njord was officially established on January 1st 2018. Njord is a merger of the 1st generation Norwegian Centre of Excellence (CoE) PGP (Physics of Geological Processes, running in the period 2003–2013), and the Oslo node of the 4th generation CoE PoreLab (Porous Media Laboratory, started in August 2017). Through curiosity-driven research at the interface between physics and geoscience, our ambition is to advance the frontier of knowledge about the behavior of Earth-like systems at conditions far from equilibrium. To achieve these aims, we build on our diversity in an open environment with a high level of technical skill.

During our third year in operation, the infamous Covid-19 year, Njord staff produced 82 papers in international journals, keeping the pace from the very productive 2019. Papers include 2 in *Nature Communications*, 1 in *Scientific Reports*, 1 in *Astrophysical Journal Letters*, 4 in *Earth and Planetary Science Letters*, 2 in *Geophysical Research Letters*, 2 in *Geology*, and 1 in *Physical Review Fluids*. In addition, 41 papers are under review

or accepted. For a research centre with 10 senior staff members and the Covid-19 virus limiting our degrees of freedom, this production is remarkable.

In contrast to the anomalous 2019, where 13 PhD students graduated from Njord, only Claire Aupart graduated in 2020. From 2021 onwards, 7 new PhD students will join Njord funded by a large ‘Cofund’ project (CompSci) led by Anders Malthé-Sørenssen, Director of the Center for Computing in Science Education (CCSE). The CompSci program will train a new generation of natural science researchers with disciplinary, interdisciplinary and transferable skills and a foundation in computational methods – providing them with the knowledge, skills and vision to digitally transform the European education, research, government and industry sectors.

Njord outreach in 2020 includes two new books by Anja Røyne (‘Varm klode, kaldt hode. Løsninger på klimakrisen’, published by Kagge, and ‘Fysikk – enkelt forklart’, published by Universitetsforlaget). Her 2018 book ‘Menneskets grunnstoffer’ has so far been published in 11 countries, including the UK, USA, Italy, Poland and Holland. Anja had an extremely busy outreach year in 2020 with numerous popular talks, podcasts, and appearances in radio, notably NRK P2’s ‘Ekko’ program. Other

Njord outreach contributions include radio interviews and newspapers articles in *Aftenposten* about volcanism on Iceland by Olivier Galland, and the Porous Media Tea Time Talks by Marcel Moura.

During 2021, Njord will keep working to increase synergy and interactions between its main components (PoreLab and PGP) through joint projects and new research initiatives in an open and friendly, but yet quality-minded, atmosphere under the Njord umbrella.

2020 was my last year as Njord Director and I wish François Renard the best of luck as he takes over the responsibilities involved in leading this very exiting physics-geology collaboration into the future.



Bjørn Jamtveit

Bjørn Jamtveit
Director of the Njord
Centre

"For to er ingen klev for bratt
(A hill is never too steep when
you are two)"

– Henrik Ibsen

For to er ingen klev for bratt (A hill is never too steep when you are two), wrote Henrik Ibsen more than 100 years ago. At Njord, we continue this tradition to acknowledge that greater outcomes are reached together rather than alone. Njord is an open, cross-disciplinary and curiosity-driven research environment. Our main strength is the ability to raise and solve original scientific questions. We can solve such problems because we recognize that the diversity in competence we have developed over the past twenty years is an asset that allows us to tackle difficult problems by simplifying them to basic processes. The cross-disciplinary research developed in Njord, at the interfaces between physics, geosciences and, more recently, biology and data science, continuously renews our scientific questions and ensures they are at the forefront of knowledge and relevant to society.

In 2020, researchers and engineers have developed and upgraded Njord's laboratory facilities. A fully renovated and equipped room in the Department of Physics is now hosting the Oslo Analogue Laboratory. The Kore rig, a new rock deformation apparatus built by Njord's researchers, is now installed at the European Synchrotron Radiation Facility. PoreLab researchers have developed a new four-dimensional optical imaging technique in their fully renovated laboratories, from which exciting and original new data are now produced. The University of Oslo has decided to fund a nano-indenter apparatus to study deformation processes in natural rocks and fabricated materials. Njord members have obtained funding for the first stage

of the Goldschmidt laboratory, dedicated to geochemical analysis, and written an application for the second stage of this national facility, dedicated to imaging and microstructural studies. Njord, in collaboration with the departments of Geosciences, Physics, and Odontology, will participate in the EXCITE EU infrastructure that helps build state-of-the-art analytical facilities all over Europe. Finally, Njord researchers have submitted successful applications to get access to large international facilities (neutron and synchrotron sources), and high-performance computing and data storage national facilities (Notur, Norstore). With these fully equipped, state-of-the-art facilities at the highest international level, 2021 will be the year to submit new proposals and start innovative projects.

The national and international visibility that Njord has acquired in the past three years relies on the senior academic staff and early career researchers who are continuously pushing the frontiers of knowledge, training students, communicating science to stakeholders and the public, and importantly, encouraging new ideas, particularly if some are outside our comfort zone. This freedom is possible because the Department of Geosciences and the Department of Physics, together with the Mathematics and Natural Sciences faculty, recognize that the Centre represents a unique opportunity to develop cross-disciplinary and high-level science at the University of Oslo.

I will start as Njord's director in 2021 after Bjørn established this research environment in 2018. I share his vision of curiosity and freedom in academic research. Bjørn is now Vice-Dean of the Faculty of Mathematics and Natural Sciences. UiO will surely benefit if Bjørn can spur the faculty to push the frontiers of knowledge towards the highest international level to the same degree he did at Njord and PGP.



Looking at outcrops of fossil earthquakes, Nusfjord, Lofoten Archipelago, May 2020.



F. Renard

François Renard
Director of the Njord
Centre from 1.1.2021

About Njord

Njord is a cross-disciplinary geoscience-physics centre at the Faculty of Mathematics and Natural Sciences at the University of Oslo. Our research focuses on the fundamental physics of geologically relevant processes, such as transport and reactions in deformable porous media, fracturing and fragmentation, interface dynamics during geophysical flows, and intermittency and pattern formation in geological systems far from equilibrium.



At Njord we conduct research on systems that range in scales from atoms to continents, and apply methods where fieldwork, numerical modelling, experiments and theory act in concert. The prime products of our centre are high quality fundamental research and education. We also focus considerable efforts on outreach and innovation through collaboration with media, renowned artists and industry partners.

Our research is directly relevant to a wide range of applications, including the transport of water, pollutants and hydrocarbons in porous and fractured rocks, carbon sequestration and storage, avalanche dynamics, earthquakes, volcanoes and other geohazards.

Who are we?

The Njord centre involves researchers from the former Centre of Excellence (CoE) 'Physics of Geological Processes' and the University of Oslo's node of the new CoE 'NTNU-UiO Porous Media Laboratory'. Physics of Geological Processes (PGP) was a first generation Norwegian CoE running in the period 2003–

2013. At the end of the CoE period, PGP was 'phased-into' the host departments as one section in the Department of Geosciences (PGP), and one section in the Department of Physics (Condensed Matter).

Porous Media Laboratory (PoreLab) is a fourth generation CoE and is running in the period 2017–2027. The centre is directed by Professor Alex Hansen at NTNU, and a major component of PoreLab's staff and activities is located at UiO coordinated by professors Knut Jørgen Måløy and Eirik Grude Flekkøy. The goal of PoreLab is the development of theories, principles, tools and methods to reduce the trial and error approach to porous media with relevance in biology, chemistry, geology and geophysics based on fluid mechanics, non-equilibrium thermodynamics and statistical mechanics. The goals and methods of PoreLab is highly cross-disciplinary and overlaps with ongoing PGP activities.

By merging the geology and physics activities into the Njord Centre, we gain an obvious and considerable potential for increased

synergies between the departments of Physics and Geoscience at the University of Oslo. Our cross-disciplinary research allows us to make progress in answering scientific questions that individuals could not solve alone, as demonstrated by our main findings in 2020 presented in this report.

We aim to:

- Maintain and develop a world leading cross-disciplinary research centre in physical sciences at UiO with focus on a fundamental understanding of the dynamics of fluid-solid systems with Earth-like complexity.
- 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, avalanches, landslides, and other geohazards.
- Generate an outstanding environment for research-based education at the Masters and PhD levels.
- Make the complex Earth System visible in the public sphere.

Our research strategy is to:

- Create an interactive co-localized organization of geoscientist and physicists conducting field geology, theory, numerical modeling and experiments in concert.
- Be an active, and often leading, partner in international collaborations.
- Participate in international projects (IODP, ICDP, Inter-Reg MAXIVESSFUN, Excite) and be a user of large-scale national and international facilities where Norway is a partner (ESRF, ESS, IFE, IOR, Goldschmidt laboratory).

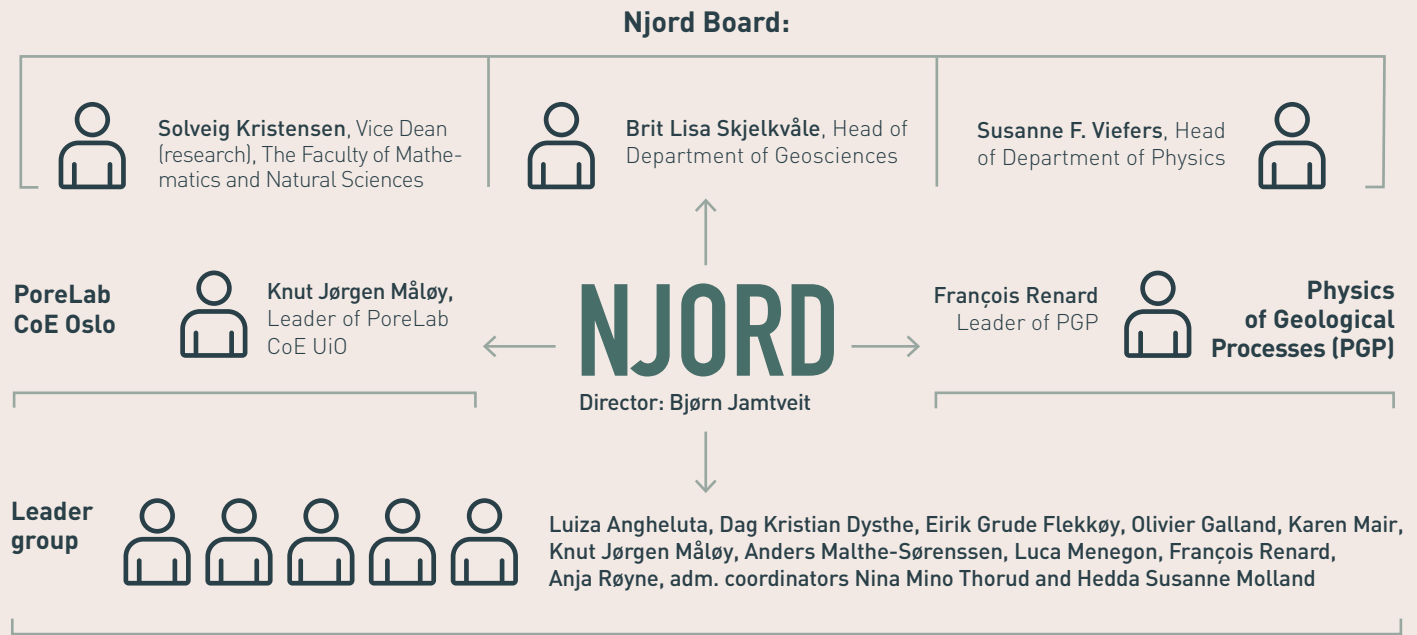
Our philosophy, in line with UiO strategy, is that our research is leading our educational activities where we valorize the approach 'Learning by doing'. We are doing this in close collaboration with the Centre for Computing in Science Education (CCSE), a CoE in education directed by Njord's Anders Malthe-Sørenssen.

Organization

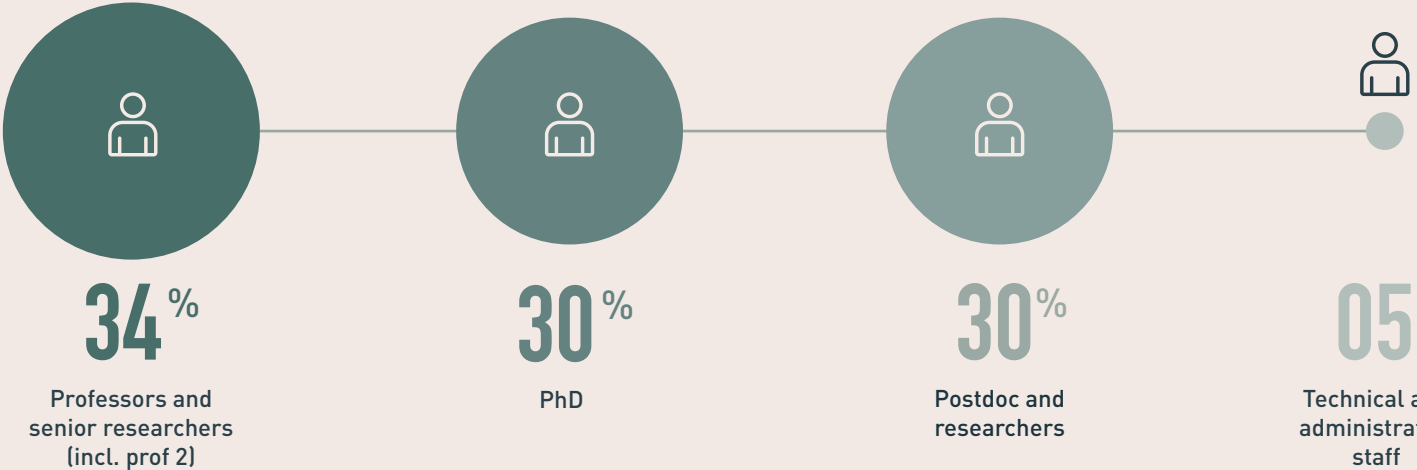
Njord is a cross-disciplinary geoscience-physics centre at the Faculty of Mathematics and Natural Sciences at the University of Oslo (UiO). We consider ourselves as one of the main UiO cross-disciplinary 'drivers' for the future development of Physical Sciences in general, and Earth and Space related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

In the first years of the centre (2018–2020), Njord was directed by Professor Bjørn Jamtveit. As Bjørn Jamtveit becomes vice dean of the Faculty for Mathematics and Natural Sciences at UiO from January 1st 2021, Professor François Renard will become the 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

Centre includes the Oslo node of the Centre of Excellence PoreLab, led by Professor Knut Jørgen Måløy, and the Physics of Geological Processes (PGP) at the the section for Physics, led by Professor François Renard. Professor Luca Menegon will be leading PGP from 2021. The Njord leader group includes ten senior scientists. In total, Njord comprises about 56 members, 25 % of which are women. There are members from both the Department of Physics, the Department of Geosciences and from Njord.



Staff

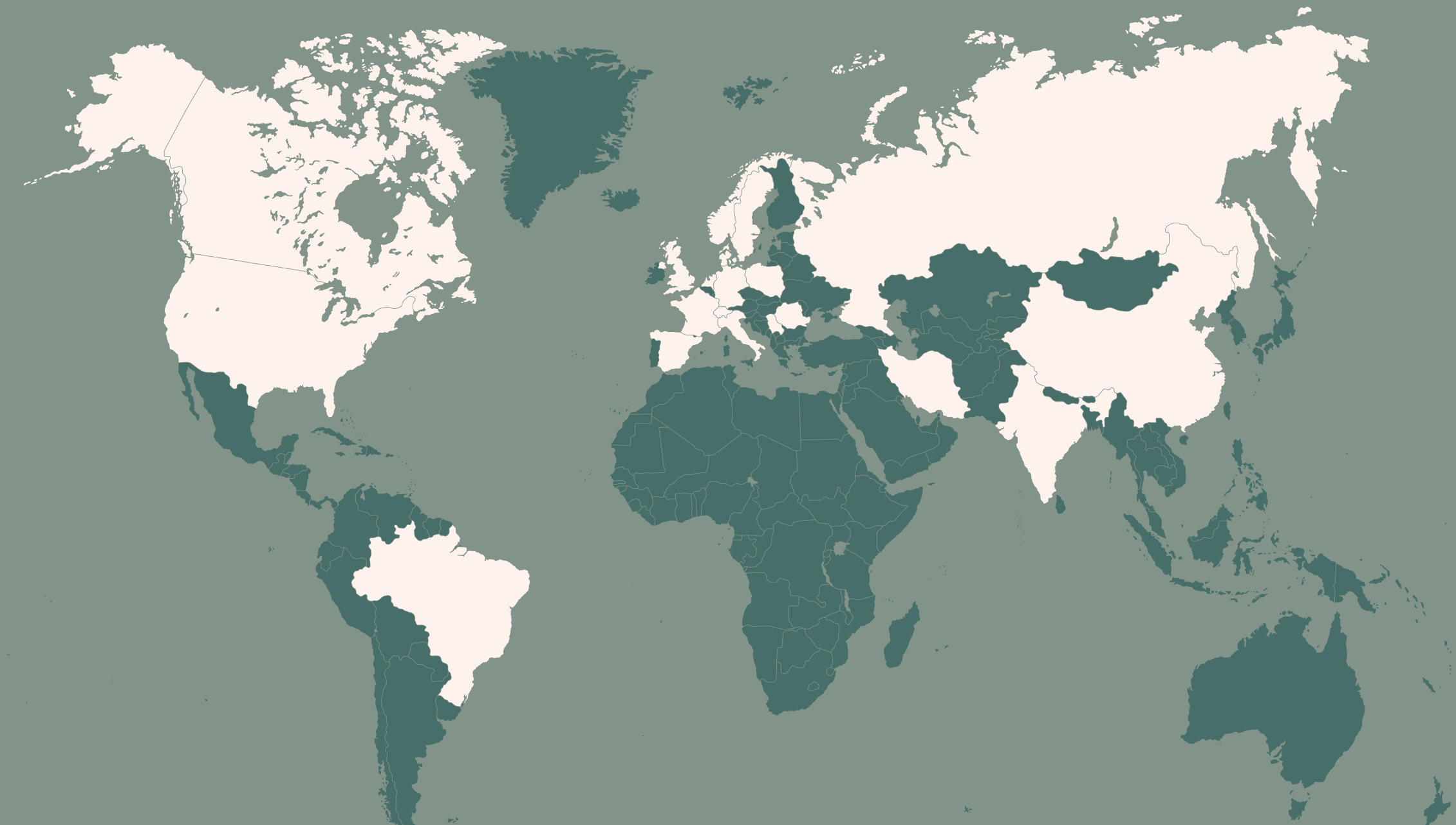


Geographical origins of Njord employees

Norway

39%

Geographical
origin by
percentage



18%	05%	04%	04%	04%	04%
France	Italy	Canada	China	Germany	Iran

02%	02%	02%	02%	02%	02%
Brazil	Denmark	Greece	India	Poland	Romania

04%	02%	02%	02%	02%	02%
Switzerland	Russia	Serbia	Sweden	UK	USA

Finances

and

Funding

45 MNOK

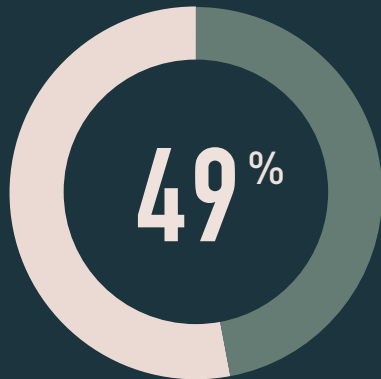
Funding in total in 2020

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.

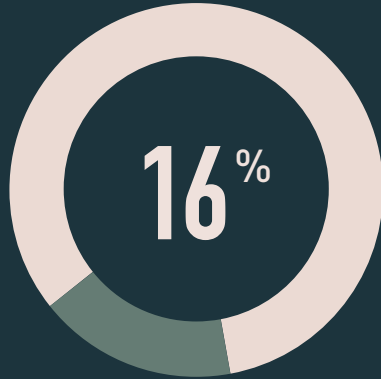
The staff at Njord is employed by either one of the departments or by projects at Njord. The centre did in the first two years of running receive contributions from both departments to cover running costs. The ambition has been that the contributions

from the Research Council of Norway, the European Research Council and other sources will replace funding from the departments to cover running costs. In 2020 the centre had secured enough funding for the running costs, and became 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.

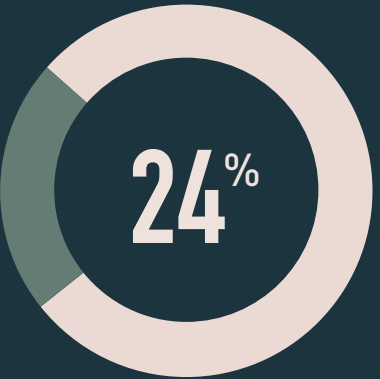
Distribution of funding



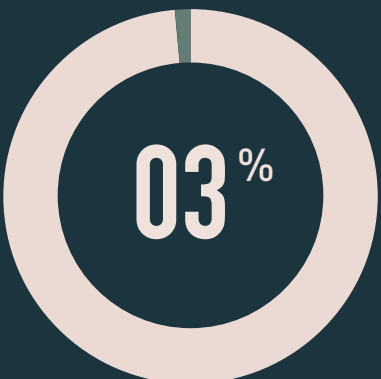
University of Oslo



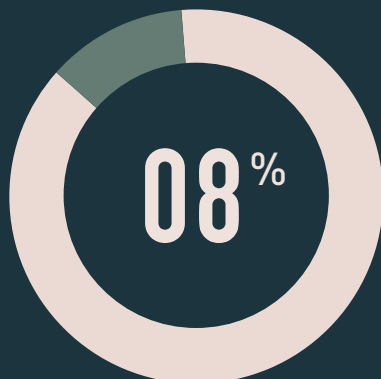
CoE from NRC



Other NRC-grants



EU/ERC



Industry and others



Funding in total



02

Activity
at Njord

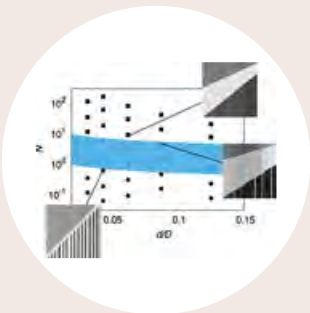


Highlights of 2020



January

The PoreLab Seminar is held in Courmayeur, Italy



March

Guillame Dumazer, Bjørnar Sandnes, Knut Jørgen Måløy & Eirik Grude Flekkøy publish “Capillary bulldozing of sedimented granular material confined in a millifluidic tube” in *Physical Review Fluids*



June

EarthFlows holds its 6th annual seminar. This year as a hybrid event, partly on Zoom



September

PoreLab UiO opens a virtual gallery “The Art of Porous Media”



October

Anja Røyne launches her second book in 2020: «Hot planet, cool minds”



November

Jane Luu, Eirik Flekkøy and Renaud Toussaint’s article “Oumuamua as a cometary fractal aggregate: The “Dust Bunny” model” in *Astrophysical Journal Letters*, reaches more than 100 popular science postings all around the world

January

Lucy Campbell, Luca Menegon, Åke Fagereng & Giorgio Pennacchioni publish “Earthquake nucleation in the lower crust by local stress amplification” in *Nature Communications*



May

Njord contributes to UiOs high ranking on Nature Index



August

Luiza Angheluta is promoted full professor



September

The Department of Geosciences is granted funding for the Goldschmidt I-laboratory by the Research Council of Norway, with Njord in a leadership role for the project



October

Kristina Dunkel is awarded “Teacher of the year” by the students at the Department of Geosciences



November

Marthe Guren Grønlie, Henrik Sveinsson, Anders Hafreager, Bjørn Jamtveit, Anders Malthe-Sørenssen, François Renard publish “Molecular dynamics simulations of confined water in the periclase-brucite system under conditions for reaction-induced fracturing” in *Geochimica et Cosmochimica Acta*



December

Njord gets INTPART grant from the Research Council Norway for the project COLOSSAL, a collaboration project on flow across scales with 8 universities from Norway, USA, Brazil and France



Interview



Name and position:
Luiza Angheluta
Professor

Affiliation:
Njord & PoreLab

Been at UiO since: 2006
Been at Njord since: 2018

Luiza Angheluta

"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?

The physics we use in the Njord centre is grounded in statistical physics of complex systems. We aim to build a more fundamental understanding of the complexity of different geological processes using concepts of universality near critical phenomena in far-from-equilibrium systems. For this, we often construct minimal models of e.g. friction to study earthquakes or glacier surges, or plasticity to model how rocks deform. One golden thread that unites many of our research activities is the ultimate scope of shedding lights on how the passing of time have activated different kinds of rock deformations and fluid transports across lengthscales and timescales to shape the Earth's crust and create diverse patterns

imprinted on rocks. 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.

It is humbling when we realize that, in spite of all progress, we are light-years away from fully grasping Earth's complexity and what is ahead of us. For instance, fundamental geological processes are built on phenomena like friction, fracture, plasticity or turbulence which, each on its own merit, have the status of challenging unsolved problems in classical condensed matter physics. However, they are also very common phenomena in man-made systems and thus have immediate impact to industry and society; think of everything made around us that can break, get damaged or need to sustain some turbulent shakes. Therefore, engineers and material scientists have "adopted" these problems as their own to find different try-and-error solutions using empirical approaches and educated guesses. Meanwhile, statistical physicists have lost some momentum and interest in solving these problems as they got labeled as perhaps being "too engineering".

Njord centre provides a unique platform for statistical physicists to explore these basic phenomena of breaking, damaging deformation and nonlinear flow by doing fun experiments and building theoretical toy models that allow for making connections across different non-equilibrium phenomena in condensed matter physics, and asking fundamental questions in statistical physics pertaining to the nature of non-equilibrium systems and their non-conventional states of matter.

What are your current research project(s)?

I have broad interests in emergent phenomena, transport and pattern formation in non-equilibrium and complex systems, and use theoretical and computational methods to model them. My main current research is pivoted on understanding the evolution of complex fluids and solids as a kind of defected matter. When defects are topologically protected (like the hole in a donut), the specific details and heterogeneities in the system become largely unimportant in the scheme of large things, and the governing evolutionary principles are determined by the dynamics and interactions between topological defects. Systems with topological defects are characterized by a global symmetry that is broken at the defect core. For example, vortices break rotational symmetry in superfluids in a similar way as dislocation break the translational and rotational symmetry in perfect crystals. Topological defects are commonly present in many exotic states of matter from superfluid, superconductors, topological insulators and all the way to cosmological strings.

For now, I am mainly interested in the understanding how topological defects drive large-scale properties in the context of Bose-Einstein superfluids, plasticity of crystals and hydrodynamics of active matter. The kind of questions that guide our research deal with e.g.: i) how defects, like vortices and dislocations are being nucleated by external forces, ii) how defects cluster into high-level organizational structures or patterns (like subgrains boundaries in crystals) due to their long-range elastic interactions, iii) how is yield stress related to dislocation density and their mobility; iv) how is the turbulence cascades dictated by the interactions between clustered vortices, etc.

"Feynman's defiance of proclaimed authority has definitely stuck a personal chord having struggled with it myself as I grew up in a culture dominated by communist ideologies where respect and obedience was/is demanded by positions of power. Feynman is, in this respect, my hero for debunking and breaking loose from unearned authority."

In parallel, I am also interested in anomalous transport in porous media which currently is a project part of Porelab. We are using minimal models to predict different subdiffusive regimes of Brownian meanderings in labyrinth patterns with scale-free branch size distributions. Recently, we have also started new projects trying to understand statistical properties of self-propelled Brownian particles in confined space or interacting with a spatial quenched disorder. This is a minimalistic theoretical formulation of how active matter (like microbes and other living biological matter, but also microrobots) behave in complex environments.

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

I am interested in diverse topics in statistical and condensed matter physics and several of them fall under Njord's umbrella. Even the more exotic topics like superfluid Bose Einstein condensates bring home concepts from turbulence in classical fluids and ties in nicely with other fluid dynamics projects at Njord. The project on dislocation dynamics in crystals is addressing fundamental questions of low-temperature plasticity in rock deformations. Anomalous transport in porous media is another topic central to Porelab. We have also initiated new projects on the hydrodynamics of active matter and anomalous transport of self-propelled Brownian particles, that challenge Njord to expand its horizon by to include also the complexity of the bio-sphere under its umbrella.

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

Talking about complexity, the first references that come to mind is Anderson's short paper "More is different" and Per Bak's classical book on "How nature works". There are few

inspirational scientists of all times that have also kindled my fascinations for how to do physics. Niels Bohr and Richard Feynman are perhaps my top favorites who continue to inspire me with their unconventional way (at that time) of doing physics and living life; both following, in very distinct ways, their "gut feeling" for researching which led them to develop a genuine intuition about how nature works and formulate physical theories and mathematical models that paved the way on how we now understand the quantum world and how light interacts with matter. Feynman's defiance of proclaimed authority has definitely stuck a personal chord having struggled with it myself as I grew up in a culture dominated by communist ideologies where respect and obedience was/is demanded by positions of power. Feynman is, in this respect, my hero for debunking and breaking loose from unearned authority.

What do you think your research can do beyond academia?

I consider myself a theoretical physicist doing basic research in statistical and con-

densed matter physics. From that side of things, I am an advocate of a curiosity-driven way of thinking and researching where applications come as an unexpected bonus, aka discovery, but do not make much sense for research when they are demanded a priori. The proclaimed authority of the societal importance of applications bothers me. That is not to say that I do not see or appreciate the importance of applications. It is the order in which things are done that is upsetting to me. Niels Bohr did not obsess over quantum mechanics because of the need to invent quantum computers, and Leonardo Da Vinci did not fiddle with conceptualizing turbulence to control the airflow around cars or airplanes. I think that we tilted the balance too much towards investing into "usefulness" and applicable science, and that we need to step back and give more space and ground to playfulness and aimless research in science, since it does pay back in true discoveries and surprises, in the long run.

The proclaimed authority of the societal importance of applications bothers me. That is not to say that I do not see or appreciate the importance of applications. It is the order in which things are done that is upsetting to me. Niels Bohr did not obsess over quantum mechanics because of the need to invent quantum computers, and Leonardo Da Vinci did not fiddle with conceptualizing turbulence to control the airflow around cars or airplanes.

Interview

Fabian Barras and
Gaute Linga

Name and position:
Gaute Linga
Postdoctoral fellow

Affiliation:
PoreLab, Njord

Been at UiO since: April 2019
Been at Njord since: April 2019



Name and position:
Fabian Barras
Postdoctoral fellow

Affiliation:
Njord

Been at UiO since: September 2019
Been at Njord since: September 2019



"We are fortunate to work on a subject that sits at the interface between different research topics of Njord. For example, the past year we have been discussing fluid in fracture during geology field trips in Lofoten, during a workshop about magmatic dyke intrusions but also in relation to current physics experiments investigating the fluid cavitation at the tip of dynamic cracks. We could perhaps be viewed as a pair of shared electrons between PGP and PoreLab."

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

Fabian: I did a master in civil engineering at EPFL in Switzerland. Gaute you told me that you also are a civil engineer!?

Gaute: Well, I am what is called *sivilingenior* in Norway. But explaining that would take too long ... I did my Master's in Physics and Mathematics at NTNU, where I specialized mostly in fluid mechanics and statistical physics. Growing up in Bergen, becoming interested in fluid mechanics was not really a choice. Due to the atmospheric conditions you are forced to deal with every aspect of droplets and turbulent fluid flows on a daily basis. This, combined with an interest in mathematics and programming, in addition to a curiosity for how things work both in technology and nature has laid the path clear, I think. After my MSc I worked at SINTEF on fluid dynamics and thermodynamics for carbon capture and storage. I then did my PhD at NBI, Uni Copenhagen, on fluid flow in complex geometries, such as fractures and pores. After that, and a short stop back at SINTEF, I was happy to join Njord and PoreLab. Being interested in a lot of different things, I have not really stayed in one scientific lane, and the environment at Njord allows me to work with very physically and intellectually interesting problems, which can also have

a place in securing a sustainable future. **Fabian:** I completed my master thesis on exchange at the University of Illinois at Urbana-Champaign, where I worked on the simulation of dynamic fracture. Being rather clumsy, I have always been interested and sometimes pissed off by how things break. Numerical models were finally a way to study fracture safely. Back in EPFL for my PhD thesis, I studied the dynamic failure of frictional interfaces. I particularly enjoyed being part of a multidisciplinary group where friction was studied with different approaches and at various scales, from nanotribology to the earthquake dynamics. This experience certainly ignited my interest for a multidisciplinary group built around the topic of geophysics processes. Having grown up in the Alps, the prospect of cold and snowy winter was definitely the icing on the cake.

What are your current research projects together and separate?

Gaute: Together, we are working on a project that combines our respective experiences: modeling the interplay between fluid flow and dynamic rupture. To put it simply, Fabian is responsible for the solid part, and I am responsible for the fluid part. **Fabian:** Such coupling is important in the problem of seismicity induced by under-

ground fluid injection but also during natural earthquakes that impact fluid migration in the crust. In this context we have been part of an initiatory field trip to observe fossil earthquakes in Lofoten, as can be seen on the picture. More information about our project can be found later in the report. **Gaute:** We still need to write that part! **Fabian:** Right. Let's then talk about our separate projects. It is time to confess if you dared work with someone else over the past year!

Gaute: In general I work on problems where fluid flow and geometry has some sort of complex interplay. Mainly, apart from the joint project with Fabian and others, I am working on how mixing, that is, stretching, folding and dispersion of solutes in fluids, takes place in porous media under steady and unsteady flow conditions. On the side of that, transition to turbulence in pipe flow, microfluidics and a little bit of pattern formation/active matter/infectious disease modelling on the side of that again... with collaborators at NBI, University of Rennes, University of Illinois, to name a few. I have told Fabian about this, and he is OK with it. **Fabian:** Well, I should also admit some infidelities over the past year. I am also working on projects about frictional ruptures, which mediate how existing faults reactivate, for example in the neighborhood of fluid injection. In this context, I am collaborating with external researchers from University College London and EPFL conducting frictional experiments. I am also part of a project about slip pulse, an important type of frictional rupture, with Kjetil Thøgersen and François Renard, and Einat Aharonov who visited Njord last year.

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

Fabian: We are fortunate to work on a subject that sits at the interface between different research topics of Njord. For

example, the past year we have been discussing fluid in fracture during geology field trips in Lofoten, during a workshop about magmatic dyke intrusions but also in relation to current physics experiments investigating the fluid cavitation at the tip of dynamic cracks. We could perhaps be viewed as a pair of shared electrons between PGP and PoreLab. **Gaute:** Yes, it is interesting to see that the fluid intrusion problem occurs so many places – both in Njord's core areas and beyond. I think this project fits right in the middle, fluid and fracture meeting at the pore scale.

What do the two of you agree upon, and what do you disagree on?

Gaute: I think we agree on most things... **Fabian:** I disagree; look at our headgears in the picture! **Gaute:** I agree. We are usually very different when it comes to headgear. **Fabian:** Also, we had some tough disagreements regarding the ordering of cinnamon and sugar on top of the risgrøt... **Gaute:** Yes, do not get me started. But scientifically [and to some extent politically?], I mean, we mostly end up agreeing? **Fabian:** I disagree.

What do you think your research can do beyond academia?

Gaute: Tough question. On a day-to-day basis, I am mostly concerned with the curiosity driven "intellectual thrill" of solving problems, getting to the bottom of things and understanding how nature works... and doing mostly basic science means, on one hand, that we contribute piece by piece the puzzle of knowledge of the world. On the other hand, being interested in a lot of different things, I think we have a particular responsibility of directing our interests where we think our efforts can do good. And there is no contradiction



between that and being, say, curiosity-driven. We currently have a big crisis where geophysical systems and porous media play a role both in the problem and in the solutions. **Fabian:** Are you referring to the Swiss-cheese model for mitigating Covid spread? **Gaute:** Well, that too! So two of our most pressing issues – covid and climate – are related to porous media. So for me, this responsibility that I mentioned, implies directing efforts toward, but not limited to, fundamental research on the prerequisites of safe and scalable CCS as well as new and emission-free energy resources like geothermal, "blue energy", etc. **Fabian:** I would be very happy if it could bring a tiny contribution in mitigating the effect of induced seismicity currently preventing the development of technologies such as deep geothermal energy. Another

aspect that I wish to explore in the future is how to communicate and give back a bit of our research to the general public that finances it. Gaute, I heard you wrote an article for a popular media about the spreading of covid and also received offers for one of your artwork during PoreLab exhibition, what is your secret for communication? **Gaute:** What can I say? Great science is often beautiful... **Fabian:** My dream, though, is to find a way to distribute cinnamon more evenly on top of the risgrøt. The way it works now is just too... bursty. You can suddenly have chunks of cinnamon that blows up in your nose, and that triggers sneezing. This is not good for our covid times. I hope to have solved this before the next pandemic. **Gaute:** Have you tried putting on the cinnamon *before* the sugar?

Interview

Name and position:
Marthe Grønlie Guren
PhD research fellow

Affiliation:
Njord & PGP

Been at UiO since: August 2012
Been at Njord since: January 2018



Marthe Grønlie Guren

"My motivation is boosted after discussions, which could be discussions at conferences or at work. I get most excited about my work when things are working and I get results. The results are sometimes expected or un-expected, but both outcomes increase my motivation."

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

My master project was with molecular dynamics simulations of melting relations in the lower mantle, and I wanted to find a group at the University of Oslo that was working with this type of simulations at geological materials. Luckily, I found Henrik Sveinsson, Anders Malthe-Sørenssen and François Renard which have a great working environment on molecular dynamics simulations of geological processes.

What is your current research project(s)?

My PhD-project is on nanoscale imaging and modeling of mineral-water interfaces, where I use both experimental and numerical approaches to study what happen at the boundary layer between a solid and a liquid phase. Right now, I work on developing a python code that reproduce dissolution rates of carbonate minerals, measured in experiments. In addition, I work on a project where we study how cracks develops and proceeds in alpha-quartz.

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

My most recent publication was about the behavior of a confined water film between periclase or brucite surfaces under conditions for reaction-induced fracturing. The motivation for these simulations was to test a hypothesis by Xiaojiao Zheng (previous

PhD-student at Njord) and her co-authors. They hypothesized that the water film was squeezed out of the grain-grain boundary when the normal stress exceeded 30 MPa. We used the same conditions and studied the removal of water.

The processes happening at small scale are important for what we observe on the larger scale. For examples, the interactions between minerals and fluids could result in transformation from one rock type to another. Whether these reactions occur, depend on the nanoscale mechanisms controlled by the fluid-rock interactions since it is the fluids that control the transport of chemical components to and from the grain surfaces where the reactions occur.

I have also been part of a project where we collaborate with Christine Putnis at the University of Münster. In this project, we studied the interactions between calcite and chromium using atomic force microscopy. These experiments complement previous work by Christine and François.

What motivates you in your research?

My motivation is boosted after discussions, could be discussions at conferences or at work. I get most excited about my work when things are working and I get results. The results are sometimes expected or un-expected, but both outcomes boost my motivation. When I meet challenges,

I definitely prefer solving them with others. It could be by sitting together to solve it, or have a discussion to come up with different approaches to try. During the last year, I have met several challenges and they usually occurs when we are setting up new simulations. The approach is often to search for similar setups of methods, reproduce their work and the adapt it to our system.

Where do we usually find you?

I am usually found in my office in front of my computer, often accompanied by Henrik, discussing some unexpected behaviors in the simulations. We usually discuss politely, but I can be slightly frustrated when Henrik use a few minutes to solve the problems I have spent days trying to figure out... The discussions usually starts with either a short question, a new result or a coffee break, and ends up in hour long discussions, but it is always very helpful and provide a lot of ideas on how to proceed or interpret the results. When working from home, we have had some meetings on zoom, which works fine, but it is more rewarding to meet in real life.

Interview

Name and position:
Joachim Falck Brodin
PhD

Affiliation:
Njord & PoreLab

Been at UiO since: 2019 (2015 as student)
Been at Njord since: 2019



Joachim Falck Brodin

"Being a physicist is something of a midlife-crisis-project for me, as I only started to study physics after working for about fifteen years with quite different things. I could not decide whether to choose studies or just going surfing, so I settled on doing both"

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

Being a physicist is something of a midlife-crisis-project for me, as I only started to study physics after working for about fifteen years with quite different things. It stood between studying or just going surfing, so I settled on doing both. During the bachelor and master I developed a need to confront the increasingly outlandish claims made by theoretical physics, in addition much of it was also abstract for me to connect it directly with physical reality, going on in one dimension in reciprocal space and such, it therefore made sense to pursue experimental work. This also gives well with me as the lab is a welcome break from the computer, which seems to be the main tool, also for an experimentalist. I was drawn to PoreLab in particular because of the format of the lab-work, with table-top experiments, a do-it-yourself mentality, a very friendly working community, and a vast supply of appropriately outlandish phenomena to study.

What are your current research projects?

My main topic of research is two-phase flow in porous media, but this work also involves quite a few other topics, such as optics and computer science. The work is in a framework that have been actively studied at UiO at least since the eighties, but most of the experimental work has been conducted on

2D-systems. The first task I have dealt with is coming up with a working model for these types of experiments in 3D. We chose an approach through index-matching of porous media and immiscible fluid phases, which in turn are scanned by dyeing the fluids with fluorescent dyes and scanning through with a 2D laser-sheet. This is now up and running and we are doing experiments. Currently there are two main avenues I am working on. The first is approaching two phase flow at its most fundamental level, reviewing and expanding on the findings of the last decades, that are mainly from 2D investigations, and seeing how they hold up and what new can be learned in a 3D scenario. The other is investigating the spread of pollutants within a complex network, through secondary transport mechanisms, such as capillary pumping and diffusion.

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

I like to think of my self as someone that goes his own ways and is not afraid of sticking out. Unfortunately, my research still lies smack in the center of Njord's other activities. I investigate processes that both are fully in the domain of solid-state physics, and that are also of great relevance in understanding geological processes. However, I eagerly await the day inspiration strikes, and that my rebellious nature can bloom in a more subversive (as in actually rebellious) direction!

Where do we usually find you? (In the lab, out in the field, in your office, in meetings, drinking coffee in the kitchen. Please explain what you to where you are.)

I am a very restless person, so I need a lot of variation, both in what I am doing and in where I am. I don't much like to sit at home with the computer. I would much rather be in the lab, combining the writing of papers and dealing with correspondence and such, with tinkering with experiments and practical challenges. I also try to get out and do "field work" at least a day a week, to investigate for instance skis flow through complex networks of tracks and stacks of powder.

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 the education at all levels at their respective department.

Laboratory work is an important part of our research based teaching, and is a substantial part of the activities in the master level courses GEO4131 (Geomechanics), GEO4190 (Hydrogeology), GEO4151 (Earthquake and Volcano Processes), and FYS4420 (Experimental techniques in Condensed Matter Physics), 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 2020, Njord staff is responsible for the following courses:

Introduction to Physics
FYS1001

The course gives an introduction to fundamental concepts within a wide range of topics in physics. There is an emphasis on understanding, applications, good knowledge of units, physical argumentation and the use of mathematical and numerical methods.

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.

Oscillation and Waves
FYS2130

The course introduces oscillations and waves using analytical and numerical techniques. A large part of the course is devoted to applying the theory of oscillations and waves to phenomena such as resonance, sound, water waves and optics.

Thermodynamics and Statistical Physics
FYS2160

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

Experimental Techniques in Condensed Matter Physics
FYS4420/FYS9420

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

Disordered Systems and Percolation
FYS4460

This course consists of four projects with several aims, like to provide experience with developing various codes relevant for problems in statisitcal physics, to use the codes to develop 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.

Mineralogy
GEO2110

This course provides an introduction to the crystallographic, physical and optical properties of the commonest minerals. It teaches about atomic bonds, different mineral groups and the classification of minerals.

Petrology and Geochemistry
GEO2150

This course provides an introduction to equilibria between minerals, and between minerals and different fluids and melts. The course takes you through thermodynamic principles behind the construction and interpretation of phase diagrams, and how these can be used to understand the formation conditions for the common metamorphic and magmatic rocks.

Cross-disciplinary education in action: training a computational physicist on how to recognize fossil earthquakes in the field. Nustfjord, Lofoten Archipelago, June 2020.



Geomechanics
GEO3131/GEO4131

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

Earthquake and Volcanic Processes
GEO4151/GEO9151

This course focuses on the physics of Earthquake and Volcanic processes, which are both important endogenic processes accommodating the deformation of the Earth’s crust.

Floods and Landslides
GEO4171

The course is split into three parts focusing on the most common geohazards in Norway: floods, landslides and avalanches. The course includes 1-day field trips to selected sites and a 3-days excursion.

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

The course gives a basic introduction to the optical properties of crystalline matter and to the polarizing microscope for optical mineral identification.

Advanced Petrology
GEO4860/GEO9860

The course examines the processes leading to the formation of magmatic and metamorphic rocks, where the students are trained in: Phase equilibria and phase diagrams, thermobarometry, magmatic differentiation, magma migration, reaction kinetics, and the role of fluids during metamorphism.

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, pollutants and hydrocarbons in porous and fractured rocks, carbon sequestration and storage, avalanche dynamics, earthquakes and other geohazards. This makes our research relatable to the public.

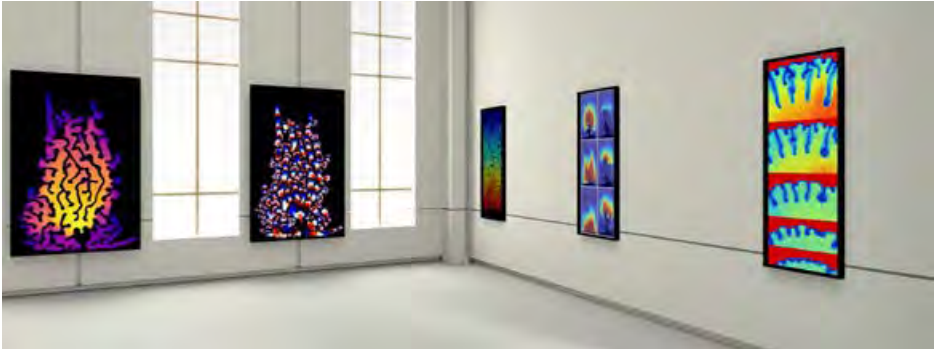
Physicist Anja Røyne is one of our highly productive researchers, especially with outreach work and science communication. Her talent as a science communicator was confirmed when she won “Brageprisen” for the best popular science book in 2018. The year of 2020 has been no exception for her and in December she was awarded the Communication Award from Titan. The Dean at the Faculty of Mathematics and Natural Sciences said the following about Røyne: “What you have accomplished within the field of science communication is impressive. When we add it together with what you contribute with in research and as a teacher for the Physics students you have shown yourself to be a multi-talented scientist.”

In 2020 Røyne published two(!) new popular science books, “Physics simply explained” and “Hot planet, cool minds”. In the book “Hot planet, cool minds” Røyne suggests ways to meet the challenges posed by climate change, and what these solutions would actually mean to us. Her popular science book from 2018 “The elements we live by” has been sold to 11 countries, including

the USA, Lithuania and South-Korea, and will be translated to 10 languages. Røyne is also regularly broadcasted on the national radio show Ekko, she has been interviewed on several podcasts, national newspapers and magazines, and she has given popular science talks to students and others.

At Njord we strive towards cultivating curiosity. As the first interstellar object ever observed, the phenomenon ‘Oumuamua has sparked a lot of curiosity since it was observed in 2017. Prompted by our free ranging curiosity, Njord researchers Eirik Grude Flekkøy and Renaud Toussaint, and astronomer Jane Luu, developed a theory to explain how ‘Oumuamua could have a porous structure that makes it so light that even sunbeams can push it around. PoreLab coined the nickname “cosmic dust bunny” for this unidentified object. The studies by Flekkøy et al. have so far been reported in around 100 popular science journals, both in

Top: Røyne presents to us some of the solutions for how we can meet the challenges caused by climate change and how the solutions will effect us. Bottom: Art is science, and science is art. PoreLab CoE invites you in the the beautiful and colorful world of our research.



Is Europe prepared for a volcanic eruption? This picture shows Gunnuhver on Iceland. This area on the peninsula Reykjanes has a high amount of geothermic activity. Iceland's airport Keflavik and the capital Reykjavik is close by. Photo: Olivier Galland

"We aim to convey our knowledge and to increase appreciation and understanding of science through our outreach projects."

Norway and around the globe, including Pour la Science, Aftenposten, Fox News, Popular Science and the Norwegian magazine Fra fysikkens verden.

Njord’s geoscientist Olivier Galland is becoming one of Norwegian media’s favorite volcano-experts, and probably the one favorite. In 2020 he wrote articles for Aftenposten Viten and Aftenposten Junior, and appeared in NRK News’ newsletter. In these media appearances Galland asks if Europe is prepared for the effects that a possible eruption could have. We know that clouds of ash from volcanos on Iceland can migrate to Europe if the wind conditions are right. It has been ten years since Eyjafjallajökull in Iceland erupted causing ash pollution that led to tremendous challenges for air traffic in major parts of Europe, and volcanic activity on Iceland suggests that the volcano borbjörn might erupt soon. Are we prepared this time?

At Njord we also find importance in sharing knowledge and encouraging peers within our own community and spreading knowledge to the public. Physicist Marcel Moura contributes significantly to this goal. In 2020, Moura and other scientists initiated the

Porous Media Tea Time Talks with early career peers from all over the world. The Tea Time Talks is a bi-weekly event, sent via YouTube, and it has been very much welcomed by the community.

In 2020 Moura also arranged a Career Development Event at the international Inter-Pore Conference. The event was a chance for early career researchers from all fields related to porous media to listen to talks and interact with established scientists who have followed very different career paths, both in academia and industry. One of the speakers focused on the massive problem of gender imbalance and biases in STEM fields. Moura and the other organizers intend to give more focus to this topic in the future. Moura was also interviewed on Brazilian television in 2020, where he shared knowledge with their viewers about one of the most common sights this year – the face cover- explaining how airflow through the cover really is a problem of flow in a porous medium.

Albert Einstein himself once said “The greatest scientists are artists as well”. Over the years we have in PoreLab come across a tremendous collection of striking visual patterns, stunning compositions of matter and motion brought to us by nature itself. So it was with great pleasure PoreLab in 2020 opened a virtual exhibition with some of the most beautiful moments. Even though the pictures carry a good amount of scientific information, they are presented in the gallery quite simply as beautiful collages of shape

and color. And maybe are the most intriguing pieces of art also the most intriguing pieces of science?

The pandemic has been present in all our lives in 2020, and because of this, it has become visible in our work as well. In April of 2020, Kristian Stolevik Olsen and Gaute Linga published an article in the Danish newspaper Weekendavisen, “Vejen til Frihed” (“The Road to Freedom”), about possible strategies for Denmark to handle the reopening of the community after the first lockdown. Others at Njord have been in the media with more research about or related to the pandemic. Henrik Sveinsson and Kjetil Thøgersen developed simulations for an article in the Norwegian newspaper Aftenposten about a near-fatal incident triggered partly because of coronavirus regulations.

It has become clear in 2020 that not even a pandemic can slow us down. In addition to all of the aforementioned activities, we have also had several other popular science contributions, like Joanna Dziadkowiec’s ‘Crystals: From rock candy to rock(et) science’ (with Haffner and Couturier) in Espurlette and Coline Bouchayer’s talk ‘Un an en Antarctique’ at APECS France Polar Week for kids between the ages of 7 and 12 years.

In 2021 we will continue to aim 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. It 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, and especially on our fieldwork because of heavy restrictions on travelling. Luckily, we have been able to do some fieldwork while keeping safe, both in Lofoten and the Faroe Islands.

In June, Luca Menegon, François Renard, Fabian Barras, Kristina Dunkel, Gaute Linga and master student Elizabeth Scheller conducted fieldwork in western Lofoten. 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 as witnessed by the article published in Nature Communication this year with Lucy Campbell, Luca Menegon and Åke Fagereng as authors.

Previous studies have found both well-preserved pseudotachylytes and those that are strongly deformed in different areas of western Lofoten. One purpose of this field trip was to combine the observations from two localities, Nusfjord and Reine, and to find any potential missing link between them. The questions addressed include the extent to which seismic and aseismic deformation are connected and whether both modes of deformation occurred during the same seismic cycle.

The second purpose of the fieldwork involves cyclicity in deformation: Fresh pseudotachylytes associated with deformed ones are used to investigate questions regarding

the rheology of pseudotachylytes and the mechanisms, inducing deep earthquakes.

On this trip, the group investigated the extent of seismic deformation in different lithologies by exploring additional areas in Lofoten. Preliminary field studies were conducted in the two most southern islands of the Lofoten archipelago, Værøy and Røst. Rocks from shear zones were collected and samples were scanned in 3D using synchrotron X-ray microtomography.

Also in June, a field trip to the Faroe Islands was carried out by Bjørn Jamtveit, master students Marija Rosenqvist and Max Meakins, and collaborators Sverre Planke and Hans Jørgen Kjøl. The trip was part of a project focused on the possibility of permanent storage of large quantities of CO₂ in basalts along the North Atlantic margin. Although the long-term plan is to investigate the possibility of CO₂ sequestration in suboceanic basalt, the Faroe Islands represent an excellent on-land analog. Marija and Max are doing their master thesis on this project and conducted a sampling and drone imaging program in the Faroe basalt sequences and interlayered sedimentary rocks. The core shed of the Faroe geological survey was also visited. At the end of 2020, samples were analysed for permeability and porosity structures, and will be analysed to test reactivity with CO₂ bearing fluids.

Left The Malinsfjall mountain, on the island of Viðoy, Faroe Islands. The mountain is composed of horizontal flows of basalt.

Right and below: Field work in the Lofoten Archipelago to search for the origin of fossil lower crust earthquakes, May 2020.



Laboratories

Njord's researchers from both Departments of Physics and Geosciences use five laboratories facilities: the four experimental rooms of the Centre of Excellence PoreLab, the two rooms of the FrictionLab, the Oslo Analogue Lab, the three rooms of the FlowLab and the two rooms of the LaglivLab, which all are equipped with state-of-art techniques and apparatuses.

PoreLab laboratories at UiO specializes 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 has acquired a Carbide Shapeoko XL CNC milling machine and two Formlabs Form 3 3D printers that are based on a new Low Force Stereolithography (LFS) technology. 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 has also a high-resolution FLIR SC300 infrared camera used for real-time measurements of heat dissipation and a wide variety of DSLR cameras and accompanying optics. Microscale experiments can be imaged via far field microscopy using a Zeiss Stemi 2000-C distortion-free stereomicroscope that couples to our high-speed and high-resolution cameras. Flicker-free 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 provide the highest performing non-contact surface measurements. We have a CT5000 in-situ testing stage from Deben, which can be mounted on the X-ray microtomograph at the National Science Museum in Oslo for imaging samples during deformation. We have developed triaxial rock deformation apparatus, the

HADES rig and KORE rig, which are installed at the beamline ID19 at the European Synchrotron Radiation Facility. These rigs allow imaging rocks during deformation using dynamic X-ray microtomography. We have also developed three rock core holders that can reach up to 10 MPa confining pressure. These core holders are installed on neutron sources (Institut Laue Langevin in Grenoble and Paul Scherrer Institute in Villigen near Zürich) for neutron tomography imaging of fluid flows in rocks.



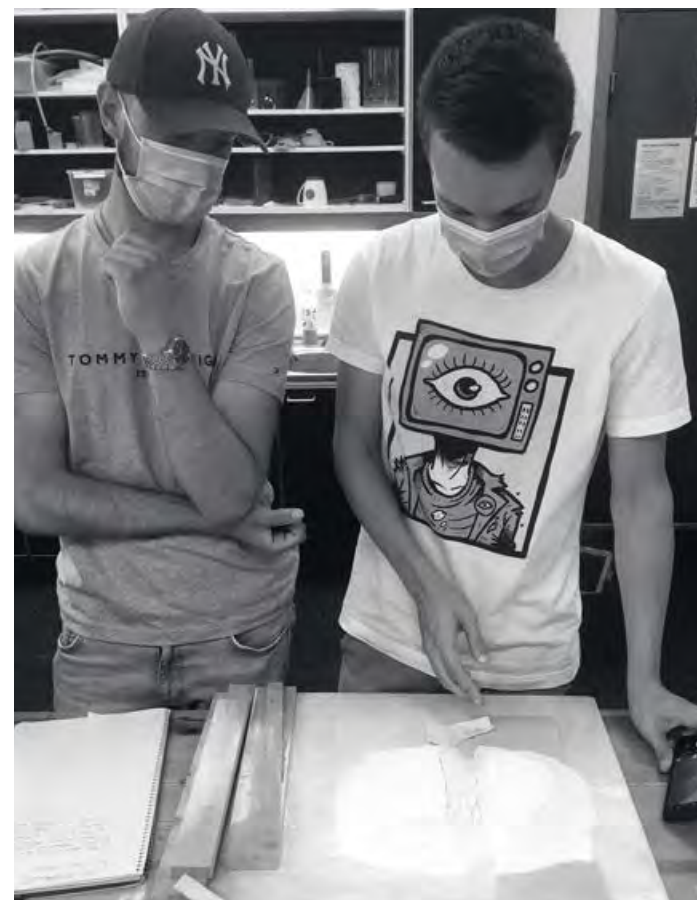
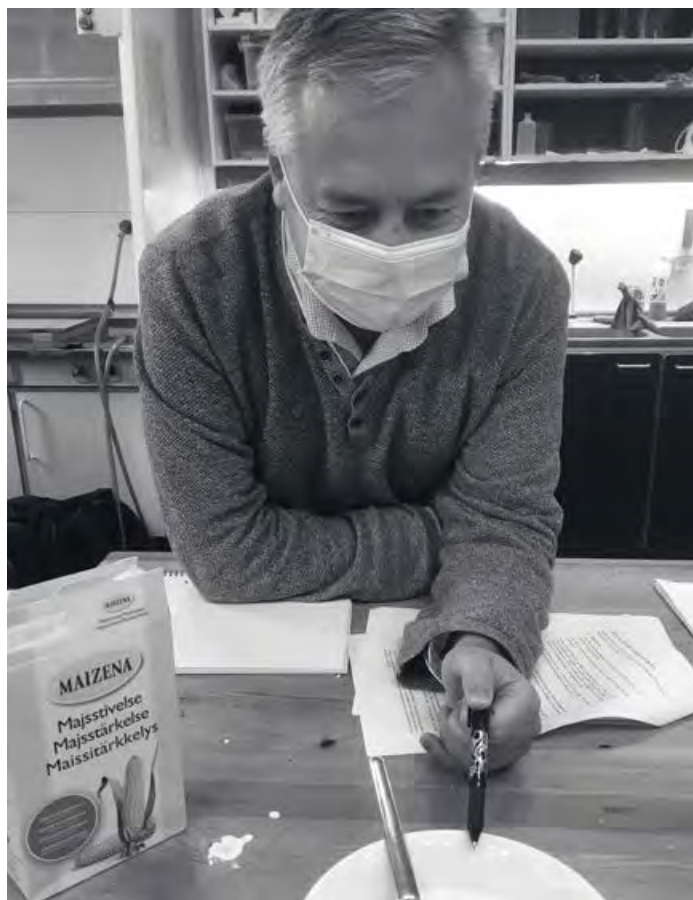
At **FlowLab**, we have a Surface Forces Apparatus (SFA 2000) equipped with a Spectrometer IsoPlane SCT320 that enables directly measurements of the static and dynamic forces between surfaces. Surface forces can also be measured using our Atomic Force Microscope (JPK Nanowizard 4), mounted on an inverted microscope, used for force spectroscopy and nanoscale imaging in air and liquids. This is also used for Magnetic Force Microscopy to image magnetic nanoparticles in bacteria. We have a whole set of photolithographic equipment that can fabricate microfluidic channels.

The whole system includes UV-KUB 1, photo resist spinner model 4000, Zepto from Diener plasma surface technology and Graphtec CE 6000. The experiments can be imaged via different sets of microscopes mounted with high-resolution cameras both Andor and iDS. Olympus upright microscope BX 62, Olympus inverted microscope GX 71, Olympus PMG 3, Olympus IX 81 and Olympus IX 83 are installed in different labs for imaging collection and processing. We also have a white light interferometer microscope, NT1100.

Top: The newly renovated Oslo Analogue Lab. In this picture it is set up for running stick-slip experiments to model earthquake statistics.

Below left: PoreLab researcher Marcel Moura shows a fractal pattern resulting from a fluid displacement experiment in a custom-built transparent porous medium.

Below right: Detail of the Krüss DSA25 drop shape analyzer. This device is used to measure the surface tension between a liquid and the surrounding air. During a measurement, a tiny liquid drop hangs from the central needle and its geometry is extracted to back-calculate the surface tension.



Training students on the rheology of geomaterials during the pandemic. Master course in Geomechanics (GEO4131) at the OsloAnalogueLab, UiO, September 2020.

"In 2020 the University of Oslo received 20,3 million of NOK from the Research Council of Norway based on the 2018 call for National Research Infrastructures. This funding will establish the geochronology part of the Goldschmidt Laboratory, a national infrastructure for geochemical, microstructural, and geochronological characterization of solid Earth materials."



The new established **LagLivLab** is partially in the Njord laboratories, and supported by both the physics department and a hybrid technology hub. The laboratory is equipped to build lab-on-a-chip and study cell biology. We have a clean room which is dedicated for cell culture and contains a MARS Class II biological safety cabinet and a PHCBI CO₂ incubator which is used to grow cells.

The **OsloAnalogueLab** (previously Volcano-Lab) has been relocated to a fully renovated room thanks to a support from the Physics Department. This laboratory focuses on the quantitative simulations of various geological-scale processes, including magma transport through, and emplacement within, the Earth's crust on various scales, caldera collapse, tectonic processes, and shear localization in brittle fault zones. An important aspect of the analogue laboratory is imaging through high-resolution/precision monitoring tools and cutting-

edge laboratory materials of variable and controlled rheology.

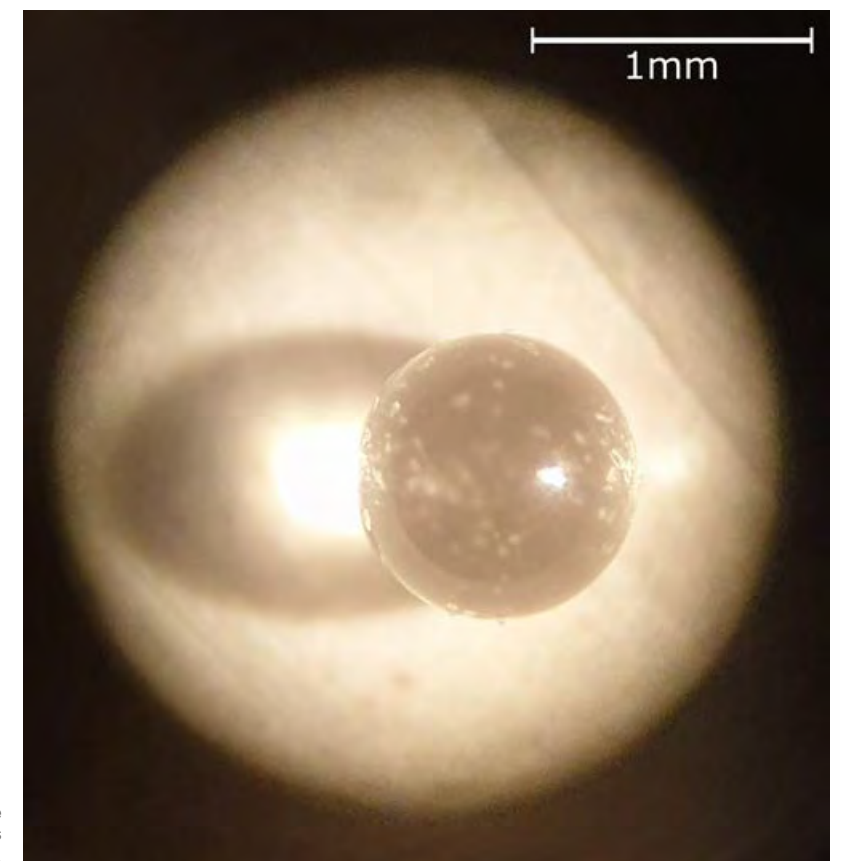
In 2020 the University of Oslo received 20,3 million of NOK from the Research Council of Norway based on the 2018 call for National Research Infrastructures. This funding will establish the geochronology part of the **Goldschmidt Laboratory**, a national infrastructure for geochemical, microstructural, and geochronological characterization of solid Earth materials. The Goldschmidt Laboratory is coordinated by the Department of Geosciences, and Njord has a leadership role in it. The geochronology part, which is referred to as "Goldschmidt I", will consist in a new isotope dilution thermal ionization mass spectrometry laboratory (ID-TIMS) at, UiO, and a new Noble gas mass spectrometer (NGMS) at the Geological Survey of Norway in Trondheim. In November 2020, the Department of Geosciences has submitted the "Goldschmidt II" proposal, which aims



An experiment demonstrating how a source of pollution can permeate through a porous medium. This model gives a direct visualization of what happens for example when polluted water is spilled on the soil.

to establish the main component of the infrastructure: a state-of-the-art laboratory for micro- and nanoscale studies of Earth materials and of other solid materials of high research and industrial relevance.

Njord is playing a leading role in the UiO's participation in the H2020 INFRAIA "EXCITE" project, which has been funded in 2020. EXCITE aims at establishing a European expert community in electron and X-ray microscopy for structural and chemical imaging techniques for Earth materials.



A close-up view of a single glass bead, the building block of many of PoreLab's porous media experiments.

Njord and COVID-19

The year of 2020 has certainly been different for us and it is impossible to talk about 2020 without mentioning the Coronavirus. The pandemic has had a huge impact on many aspects of our lives and impacted the work of everybody in Njord. 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 cancelled seminars, trips, fieldwork and parties. We have been denied many of the social arenas that we find important for meaningful collaboration with colleagues. These informal arenas that contribute to holding our diverse group together are important foundations for the synergy and innovation we have in our group.

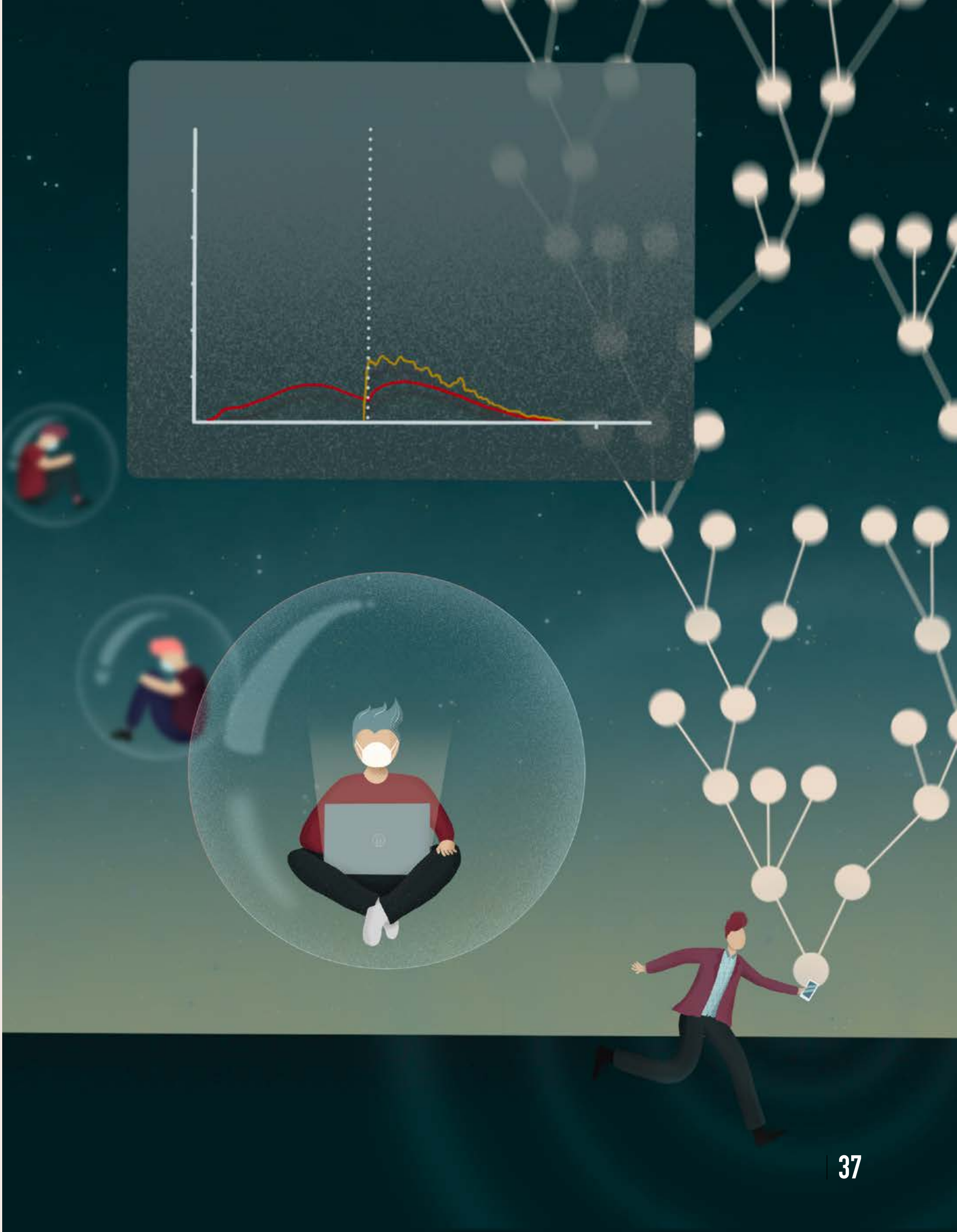
To keep the wheels turning we have had to rethink what we do and how we do it. We have managed this reimagining with regular, informal morning meetings on Zoom. We have successfully organized virtual seminars with external and international guests on Zoom, and even a 2-day hybrid workshop combining physical and virtual presence. Other initiatives have been instigated within our group, including the Porous Media Tea Time Talks, a bi-weekly digital event, an idea born under the pandemic.

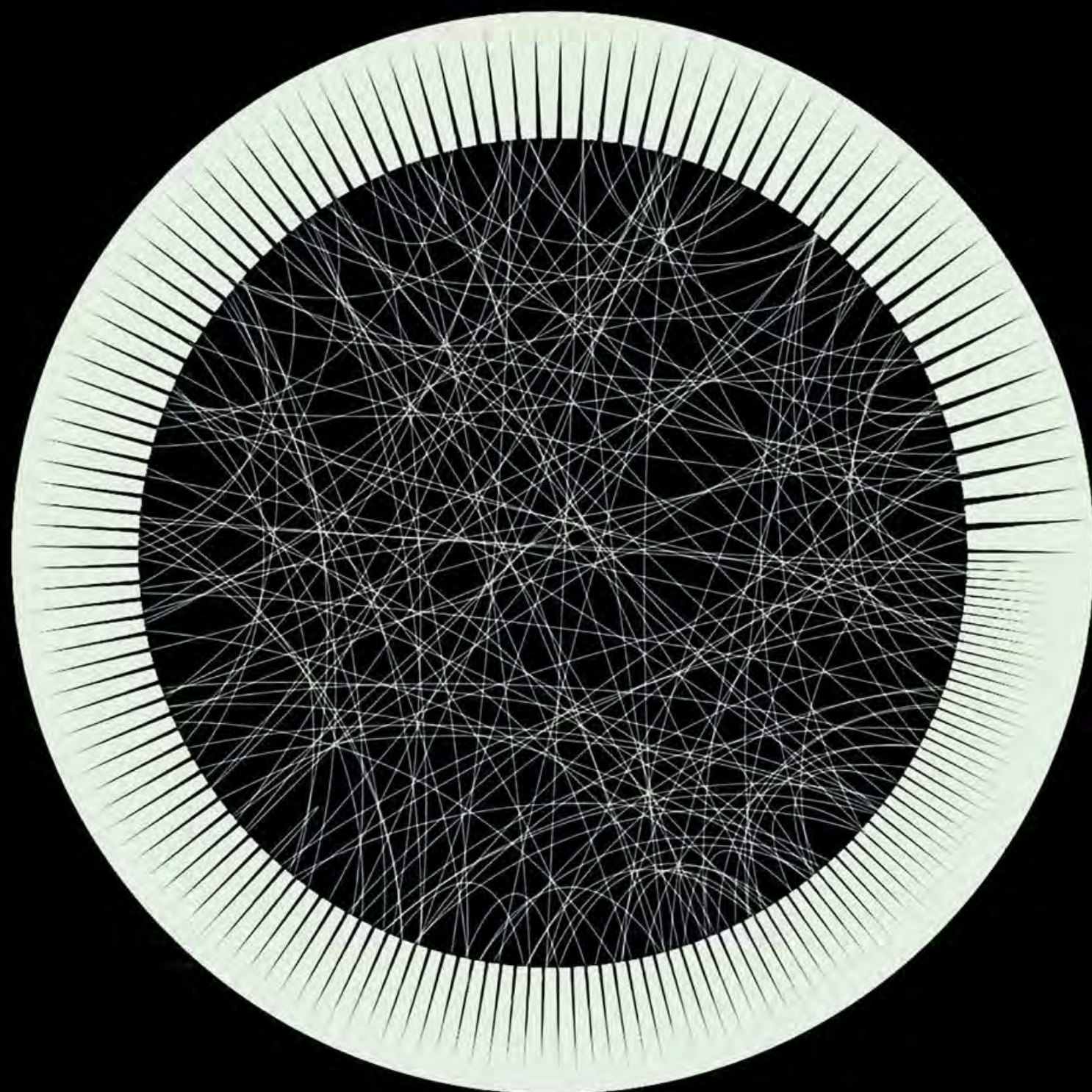
We have communicated research related to the pandemic to the public, like Moura's appearance on Brazilian TV about breathing through a face cover, like Stølevik and Linga's article in the Danish newspaper Weekendavisen about how to handle the spreading of the virus in Denmark and Thøgersen and Sveinsson's simulations for a newspaper article with an incident related to the pandemic.

The fact that the pandemic put such heavy restrictions on 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 have been denied many of the social arenas that we find important for meaningful collaboration with colleagues. These informal arenas that contribute to holding our diverse group together are important foundations for the synergy and innovation we have in our group."

"Virtual meetings have limitations, but they have also opened a world of new possibilities for easier and cheaper communication and interaction around the globe"





03

Research Projects

Introduction

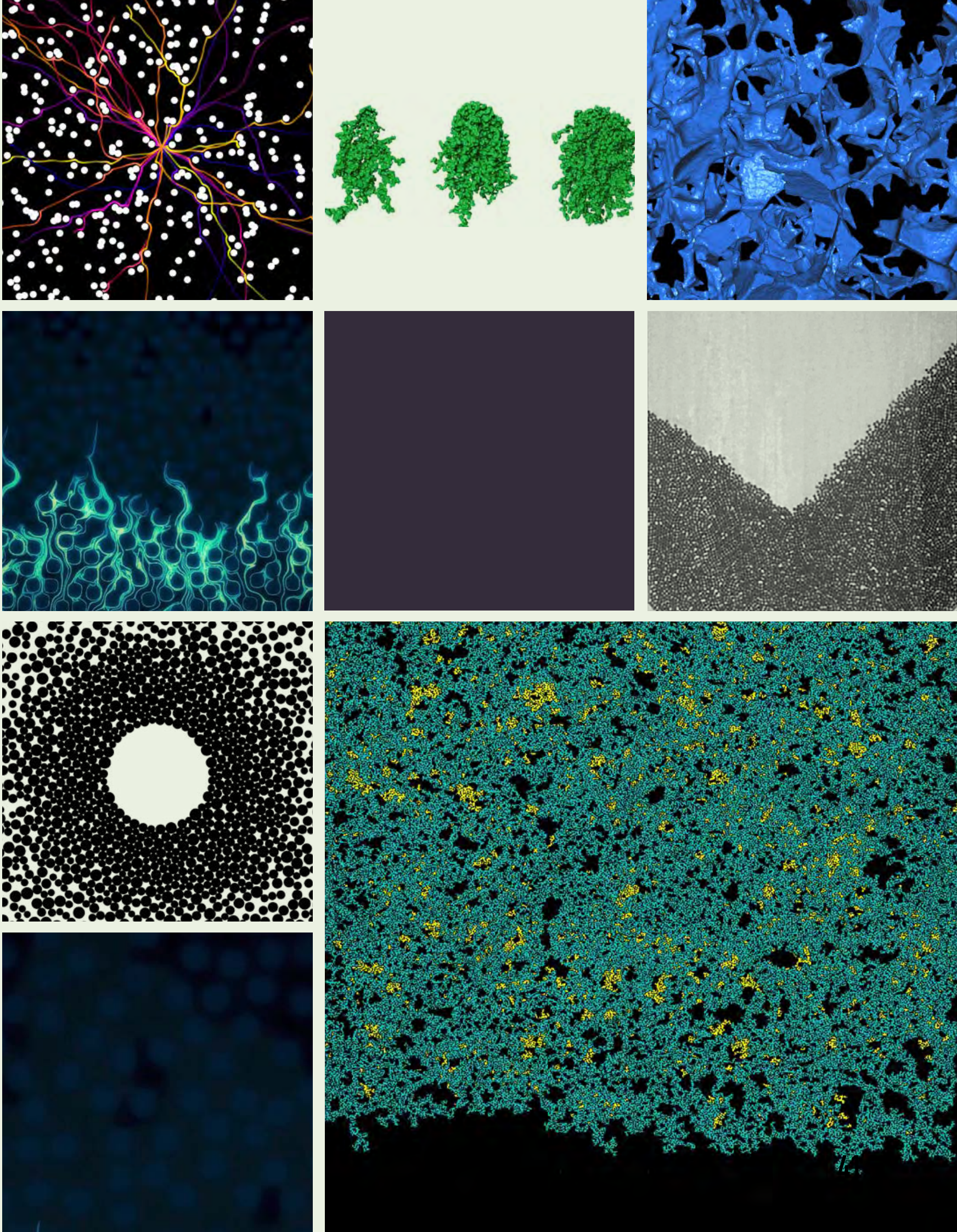
Many of the researchers at the Njord Centre focus on the dynamics of fluid migration through porous materials and geological or biological media. Some of them focus on single or multi-phase fluid dynamics in the confinement of a complex pore space where fluid-solid interactions vary along the interfaces. In other situations, the solid confinement is deformable and changes shape as a response to the forces imposed by fluid pressure gradients or to external forces. Another level of complexity, very often realized in geological systems, arises if the solid interact 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.

About Chapter 3

Fluids often enter the solids through fractures. Hence, the physics of fracturing is a central Njord activity. In natural systems, fracturing is often associated with displacement along the fracture surface and the frictional properties of fractured surfaces are important. This situation applies both to the slow slip encountered in aseismic faults and volcanos and to the high slip rates associated with natural earthquakes.

Finally, most of the systems studied at Njord evolve far from equilibrium and are often characterized by nonlinear relations between forces and fluxes and the emergence of ‘self-organized’ patterns. Such patterns may contain valuable information about underlying processes. This is particularly relevant in geoscience, where the only sources of information to understand ancient processes are the patterns left in rocks. It is also relevant for porous materials where emergent structures are often observed to arise as numerous processes act in concert. Pattern-formation is perhaps the common denominator for all senior researchers currently working at Njord.

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Fluid Flows in Complex Media

- 1 Advanced X-ray and neutron imaging of fractured and porous rocks
- 2 Two-phase flow in 3D porous media – an experimental approach
- 3 EarthFlows
- 4 Steady-state flow in 2D porous media
- 5 Physics of volcanic plumbing systems
- 6 Impact of volcanism on the petroleum system
- 7 Slow drainage experiments in porous media: what happens in your facemask while you sleep
- 8 Fluid saturation behind gravitational stabilized invasion fronts in porous media
- 9 Modelling and imaging flow in rocks across scales

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The Research Council of Norway,
(project ARGUS)

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Advanced X-ray and neutron imaging of fractured and porous rocks

Pollution of soil and ground water is a serious health threat where heavy metals express one of the highest hazards. Cadmium (Cd) is a resilient heavy metal which is among the top six pollutants worldwide. Therefore, understanding and quantifying the retention and sorption mechanisms of cadmium in rocks is of tremendous importance for both risk preparedness and hazardous waste treatment.

We use in-situ neutron imaging of Cd-doped flow experiments in limestone and sandstone samples. While the Fontainebleau sandstone was completely washed and no traces of cadmium remained in the rock, the Indiana limestone has demonstrated a real potential in retaining cadmium due to two different porous network sizes and permeabilities. At the end of the experiment about 30% of the injected cadmium remained in the rock, unevenly distributed in the rock, highlighting some areas of stagnant fluids. It provides a potential new perception of the capture of pollutants where only a fraction of the rock structure contributes to the sorption of heavy metals. The first year of this project investigated the project feasibility through fast 2D radiographies. Successful results already provided a first publication and motivation for advanced techniques. Accordingly we addressed this year the development of fast 3D tomography with scattering correction in order to quantitatively better image the small variations of our pollutant tracer and localize them in a three dimensional space.

Additional measurements will be performed next year and use all the previously gained experience for a dedicated study on pollutant fluid transport in 3D and real time. Through a collaboration with Prof. Fang Xia at the Murdoch University in Australia, we have imaged chemical processes occurring

during the leaching of ore minerals (Fig. 1). We also continued our developments of X-ray imaging processes using the Hades rig and developed several data processing tools to image and predict fracturing processes in rocks.

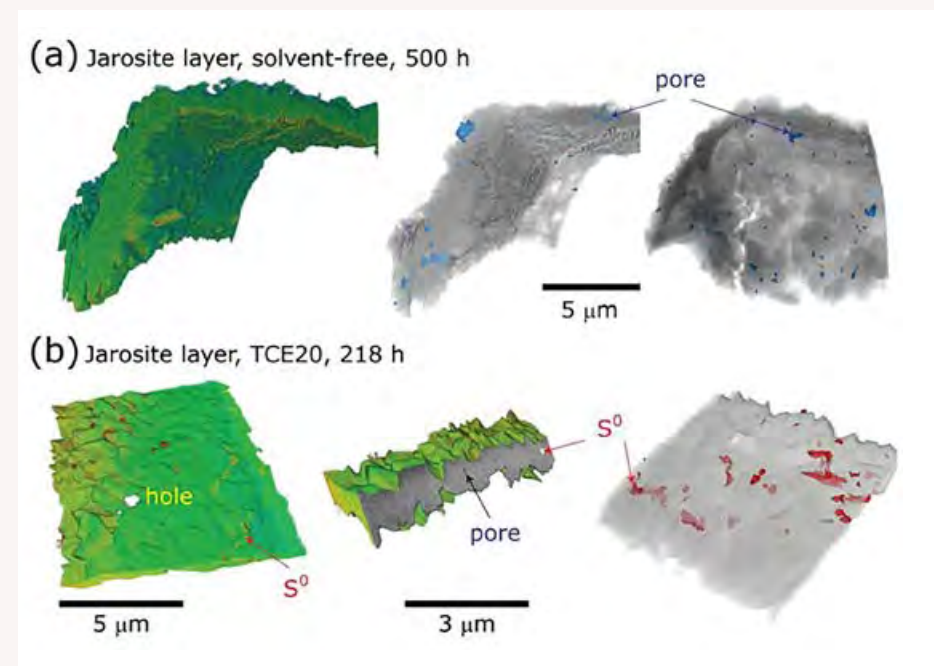


Figure 1: FIB-SEM tomography data of jarosite, $\text{KFe}_3+3(\text{OH})_6(\text{SO}_4)_2$, shells from (a) solvent-free experiment at 500 h, showing porosity, and (b) with TCE20 solvent experiment at 218 h, showing holes and embedded sulphur. The green-yellow-red and grey coloured isosurfaces represent the outer and inner surfaces of the jarosite shell. The grey colour is semi-transparent to reveal the pores (a) and embedded sulphur (b) in jarosite.

Products in highlight

McBeck, J., Mathiesen, J., Aiken, J. M., Ben-Zion, Y., & Renard, F. (2020). Deformation precursors to catastrophic failure in rocks, *Geophysical Research Letters*, *Geophysical Research Letters*, 47, e2020GL090255.

McBeck, J., Aiken, J. M., Ben-Zion, Y., & Renard, F. (2020). Predicting the proximity to macroscopic failure using local strain populations from dynamic in situ X-ray tomography triaxial compression experiments on rocks. *Earth and Planetary Science Letters*, 543, 116344.

Kartal, M., Xia, F., Ralph, D.E., Rickard, W., Renard, F., & Li W. (2020). Enhancing chalcopyrite leaching by tetrachloroethylene-assisted removal of sulphur passivation and the mechanism of jarosite formation, *Hydrometallurgy*, 191, 105192.

Two-phase flow in 3D porous media – an experimental approach

We are pursuing tabletop experiments on two-phase flow in 3D porous media with the use of an optical laser-fluorescence set-up, developed by us. Our starting point is the extensive research and accumulated insight gained from previous, 2D experiments [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].

We are also studying steady-state regimes in two-phase flow in porous media in a 3D scenario, where we aim to quantify how fluid densities, viscosities, wetting conditions, capillary effects and flow rate affect relative fluid saturations and transport.

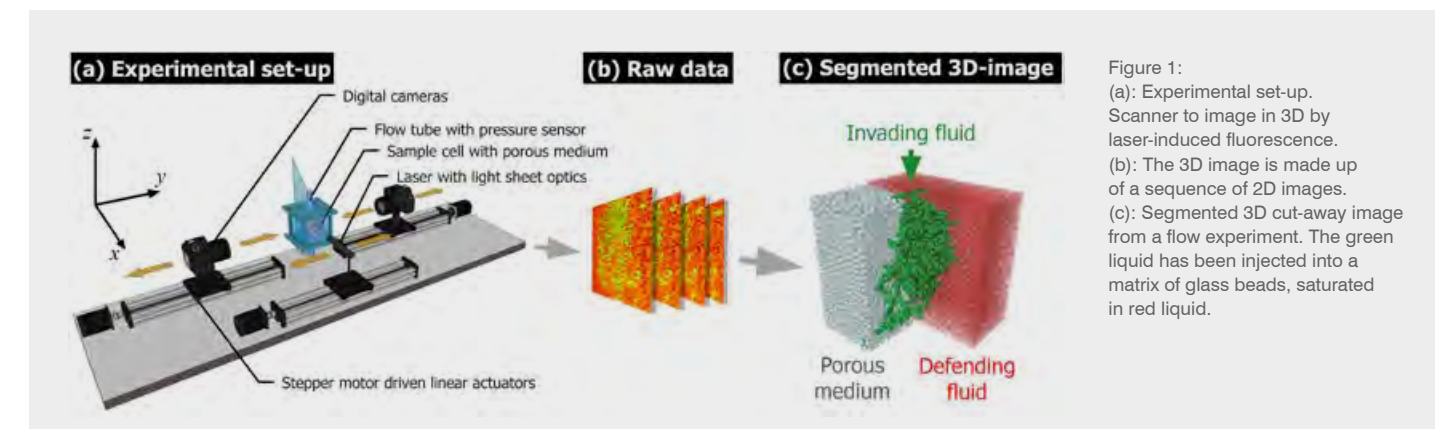


Figure 1: (a): Experimental set-up. Scanner to image in 3D by laser-induced fluorescence. (b): The 3D image is made up of a sequence of 2D images. (c): Segmented 3D cut-away image from a flow experiment. The green liquid has been injected into a matrix of glass beads, saturated in red liquid.



Figure 2: Images of the 3D configuration of a green liquid invading a less dense and less viscous liquid in a porous medium, from the top, captured at percolation. Flow rates increase from left to right. The structures consist of a compact region, surrounded by thin fingers. The compact centers grow with increasing flow rates, and with time.

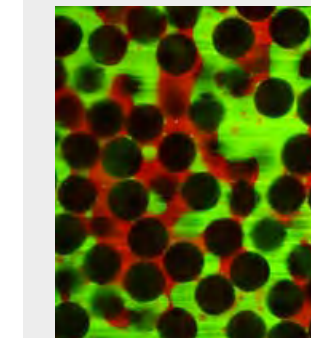


Figure 3: Raw image from a 3D experiment showing complex fluid dynamics in two-phase flow in a porous medium. The dark patches are uniform 3 mm diameter glass beads, the green fluid is glycerol, and the red is rapeseed oil.

Products in highlight

Birovljev, A., Furuberg, L., Feder, J., Jssang, T., Måløy, K. J., & Aharony, A. (1991). Gravity invasion percolation in two dimensions: Experiment and simulation. *Physical Review Letters*, 67(5), 584.

Løvoll, G., Méheust, Y., Måløy, K. J., Aker, E., & Schmittbuhl, J. (2005). Competition of gravity, capillary and viscous forces during drainage in a two-dimensional porous medium, a pore scale study. *Energy*, 30(6), 861–872.

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 Univeristy of Oslo, Strategic Research Initiative	Participants Luiza Angheluta^{1,4} (PI), Francois Renard^{1,2} (PI), Bjørn Jamtveit^{1,2} (former PI) Supervisors: Anders Malthe-Sørenssen^{1,4}, Anja Røyne^{1,4}, Knut Jørgen Måløy^{1,4}, Olivier Galland^{1,2}, Joe LaCasce², Andy Kääh², Karen Mair^{1,2}, Atle Jensen³, Kent A. Mardal³, Thomas V. Schuler², Andreas Carlson³, Luca Menegon^{1,2} Post-doctorate fellow: Kjetil Thøgerson^{1,4} Current PhDs: Ole Rabbel^{1,2}, Vidar Skogvoll^{1,4}, Coline Bouchayer², Torstein Sæter³ Graduated PhDs: Petter Vollestad³, Xiaojiao Zheng^{1,2}
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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 and near-surface environments. Geophysical flows include water and air, magma, as well other complex fluids such as hydrocarbons, CO₂-water mixtures, and fluid-solid mixtures. Even solid rocks can behave like fluids on geological timescales. Ice is a great example of a material with solid behavior on short timescales and fluid behavior on longer time scales. The relaxation timescales differentiate between solid and fluid-like matter, and often both states of matter coexist through the formation of interfaces between them, which can be highly complex and have punctuated dynamics. Nonlinear physical processes like friction, fracture and plas-

ticity in complex materials are example of processes that occur along interfaces, grain boundaries or mediated by defects. Understanding these processes requires a between understanding of the interfacial dynamics with which they couple.

The EarthFlows is a strategic initiative at UiO that promotes a new 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 on tipping points dynamics 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 nonequilibrium phase transitions and critical phenomena.

Highlighted projects:

Fracture network in low-permeable rocks under stress

Rapid generation of hydrocarbons in organic-rich, low-permeable shale leads to pore fluid overpressure and eventually fracturing of the rock. This mechanism is especially relevant in shale formation experiencing strong heating due to magmatic intrusions, because the time required for hydrocarbon generation is reduced from millions of years to only a few months or years. The newly established fracture networks then control migration of the hydrocarbons, and therefore represent a key factor in understanding both volcanically influenced petroleum systems and past

climate crises triggered through methane release related to magmatic intrusions. In our study, we use numerical modelling to analyze this type of fracture network evolution. We focus especially on how the phases of fracture network evolution can be identified in a set of geometrical parameters (crack opening, length, growth orientation, connectivity), and how these can be related to the stress state of the model and fluid expulsion behavior. We found that after an initial phase of fracture growth dominated by far-field stresses, local stress redistribution due to fracture interaction controls the coalescence of fractures, allowing for fluid expulsion in a pulse-like fashion.

Dislocation dynamics in low-temperature plasticity

The existence and mobility of dislocations are essential contributors to the strength and ductility of crystalline materials. Thus, understanding the mechanisms behind their creation and motion is a fundamental step in modelling plastic deformation of crystalline rocks. At sufficiently low temperature, edge dislocations move primarily through glide motion in the slip plane. Increasing temperature activates climb motion cross different slip planes. We model low-temperature plasticity within the phase field crystal modelling approach in which dislocation reactions and kinematics are

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emergent from a more fundamental level of description of the crystal lattice through a crystal density field that minimizes a suitable free energy. By a dynamical coupling of the phase field crystal density to an external stress field, we show that the model is able to spontaneously nucleate

a pair of edge dislocations with opposite Burgers vectors (dislocation dipole) in a two-dimensional hexagonal lattice. From the phase field density, one can derive an expression for the lattice incompatibility field that quantifies the local mismatch of the crystal structure, which accurately

predicts the nucleation location and the type of dislocation dipole that spawns. The incompatibility field calculated from the phase-field crystal density generalizes to three dimensional systems and similar calculations can be extended to body-centered cubic and face-centered cubic lattices.

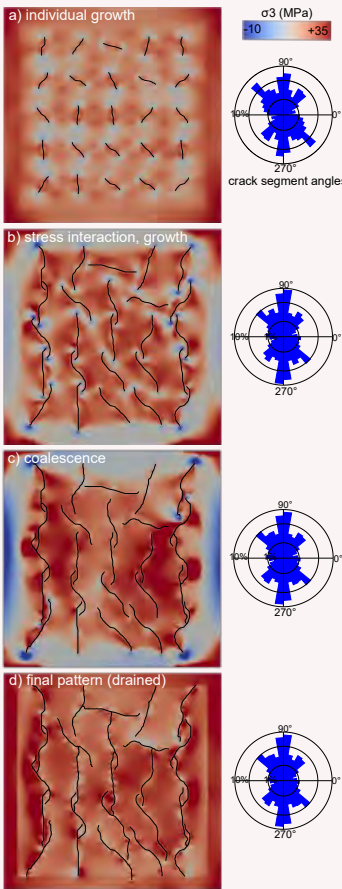


Figure 1: Visualization of a simulated growing fracture network under anisotropic external stress, with colors representing least principal stress magnitude. Each image corresponds to a distinct phase of the growth. Individual growth controlled by far-field stresses (a), continuing growth controlled by stress interaction between fractures (b), coalescence phase (c) establishing the final fracture network (d).

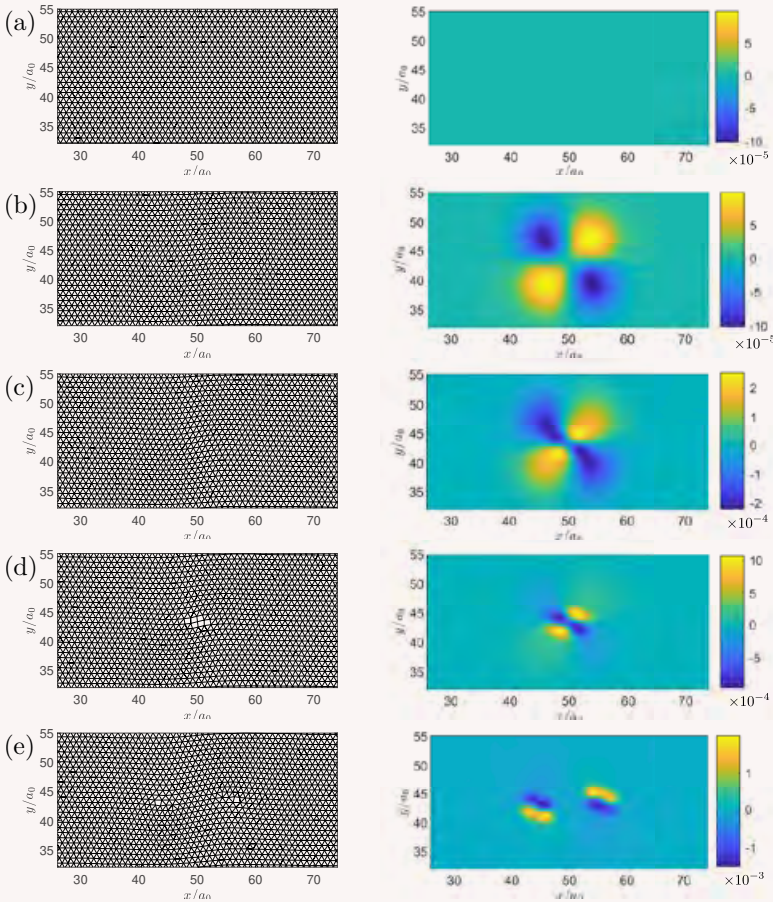


Figure 2: Snapshots of the simulation at increasing values of the external stress amplitude σ_0 (in units of shear modulus). a) $\sigma_0=0$, b) $\sigma_0=0.05$, c) $\sigma_0=0.08$, d) $\sigma_0=0.081$ – a dislocation dipole forms and e) $\sigma_0=0.081$ after the nucleation of the dislocation dipole. Left column: phase-field crystal density shown as lines connecting adjacent peaks in the density profile. Right column: the incompatibility field quantifying the local mismatch of the crystal structure.

Funding

The Research Council of Norway, Center of Excellence (Porous Media Laboratory)

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- ⁸⁾ University of Le Mans, France
- ⁹⁾ Uppsala University, Sweden

Steady-state flow in 2D porous media

The simultaneous flow of immiscible fluids in a porous medium occurs in many situations, but there is little fundamental research on the topic. Some experimental work has focused on such flows, however mainly in horizontal Hele-Shaw cells where gravity can be neglected. During previous experiments, a persistent steady-state configuration was reached for the fluids and the flow could be characterized statistically. This experimental project further explores steady-state flow in porous media, where we tilt the cell at various angles to systematically play with the influence of gravity. By conducting experiments at various flow rates, we investigate the fluid distribution in the medium and the dynamics as function of gravity and flow rates. The wetting (water-glycerol) and the non-wetting (air) phases are injected simultaneously from alternating inlet points into a Hele-Shaw cell containing one layer of randomly distributed glass beads, initially saturated with wetting fluid. We capture high resolution images in time-lapse series, and record the pressure at several locations in the cell. The image and pressure data yields detailed information about the flow dynamics, mechanical processes and statistics. At this point we have obtained systematic data sets with three different flow rates and four different tilting angles. Based on analysis of this initial data, we will identify the best flow rates and tilting angles to use in the planned follow-up set of experiments. In another part of this project, we design and 3D print porous Hele-Shaw cells for experiments that are optimized for the study of pore-scale and sample scale fluctuations of pore-pressure and fluid saturation. In addition to conduct fundamental



experiments, the goal of this project is to give experimental input to numerical and theoretical efforts to develop of a scale-up theory for steady state two-phase flow in porous media, i.e. to provide a link between the pore-scale physics and the macro scale flow behavior.

Figure 1: Photograph of the experimental setup, showing the liquid saturated porous Hele-Shaw cell at a 45 degrees tilting angle. The fluids are injected simultaneously into the cell inlet (bottom right) at a constant flow rate, while the outlet (top left) is open to the atmosphere. This tilting angle introduces an approx. 0.7 G gravitational component against the flow direction.

Physics of volcanic plumbing systems

This project implements multi-disciplinary research that integrates quantitative field observations, geological and geophysical subsurface data, and laboratory modelling, numerical and theoretical modelling to reveal the dynamics of volcanic plumbing systems.

Selected topics

Dyke emplacement mechanism

Igneous dykes are the main magma transport channels through the crust and the main feeder structures of volcanic eruptions. Common models of dyke emplacement systematically assume a linear elastic host rock deformation and tensile opening. However, field observations show that non-negligible plastic deformation and shear failure of the host rock can accommodate the emplacement of felsic magmas. We integrated quantitative field observations at the southwestern peninsula of Hovedøya, Oslofjord (Poppe et al., 2020) and quantitative 2D laboratory modelling (Guldstrand et al., in press) to infer the dynamics of dyke emplacement in the Earth's crust. Our study highlights two drastically different modes of emplacement, which assume contrasting failure modes of the host rock: when magma is emplaced in tough rocks, dykes are continuous sheets that propagate by fracturing, whereas when magma is emplaced into weak rocks, dykes are discontinuous finger-shaped that propagate by indenting the host rock.

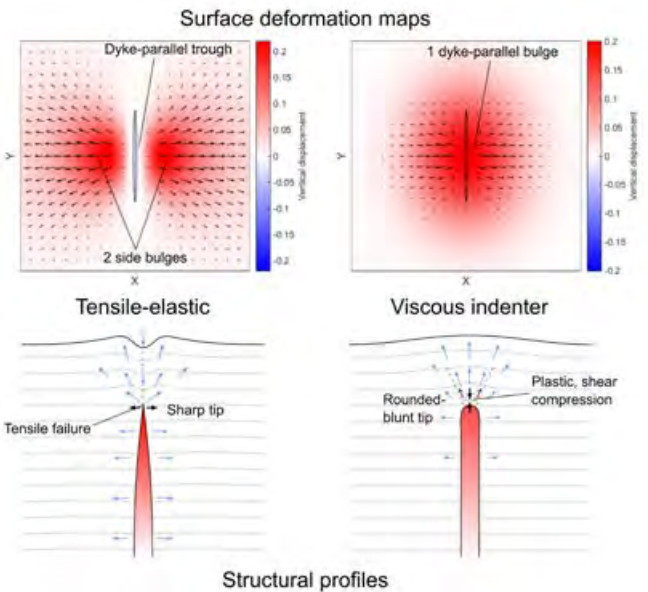


Figure: Summary of dyke propagation mechanisms and associated characteristic surface deformation (from Bertelsen et al. accepted). Top row: surface deformation maps associated with tensile elastic (left) and viscous indenter (right) dyke propagation mechanisms. Bottom row: characteristic structural cross sections of tensile elastic dyke (left) and viscous indenter dyke (right).

Implications of dyke emplacement mechanism for volcano geodesy

We study the implications of these two contrasting emplacement mechanisms on dyke-induced surface deformation. We performed two 3D laboratory experiments of dyke intrusion: in one experiment the host material is elastic gelatine, whereas in the other experiment the host material is cohesive Coulomb granular material (Bertelsen et al., 2021). We show that even is both experiments produce dykes, their

emplacement mechanisms are different and the resulting surface deformation are drastically different. Our results have significant implications for volcano geodesy, as the most established geodetic models used to invert geodetic data are based on purely elastic behaviour of the crust. Our experiments show that the Coulomb properties of crustal rocks are equally important to interpret geodetic signals at active volcanoes.

Products in highlight

Galland, O., Mescua, J., Palma, O., Marín, G., & Albino, J. (2020). A Fresh Perspective on Intricate Volcanic Plumbing Systems. *EOS – Science News by AGU*, December 16.

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? Invited research article in *Journal of Volcanology and Geothermal Research*, 107153.

Poppe, S., Galland, O., de Winter, N., Goderis, S., Claey, P., Debaille, V., Boulvais, P., & Kervyn, M. (2020). Structural and Geochemical Interactions Between Magma and Sedimentary Host Rock: The Hovedøya Case, Oslo Rift, Norway. *Geochemistry, Geophysics, Geosystems*, 21, doi: 10.1029/2019GC008685.

Guldstrand, F.B.B., 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*, submitted.

Mattsson, T., Petri, B., Almqvist, B., Chadima, M., Burchardt, S., Palma, J. O., Hammer, Ø., & Galland, O. Magnetite distribution anisotropy, mineral shape fabrics, and the associated AMS, AARM and AIRM fabrics. *Journal of Geophysical Research*, submitted.



Products in highlight

Eriksen, F. K. (2019). Impact of gravity on pore-scale steady state flow patterns. *International Workshop on Non-Equilibrium Thermodynamics in Porous Media*. August 29, Trondheim, Norway

Eriksen, F. K. (2020). Tuning the flow rate and gravity in steady-state flow experiments. *Knut Jørgen's 60 years Anniversary Conference*. January 28, Courmayeur, Italy

Funding The University of Oslo Participants Olivier Galland^{1,2}, Ole Rabbel^{1,2}, Karen Mair^{1,2}, Jose Mescua³, J. Octavio Palma⁴, Alain Zanella⁵, Dougal Jerram⁶, Lars Eivind Augland⁷, Héctor J. Villar⁸, Sverre Planke^{7,9}, Adrian Medialdea¹⁰, Ivar Midtkandal², Juan Spacapan¹⁰, Kim Senger¹¹	Affiliation ¹⁾ The Njord Center, University of Oslo, Norway ²⁾ Department of Geosciences, University of Oslo, Norway ³⁾ CONICET Mendoza, Argentina ⁴⁾ Y-TEC, Argentina ⁵⁾ University of Le Mans, France	⁶⁾ DougalEarth, UK ⁷⁾ CEED, University of Oslo, Norway ⁸⁾ GeoLab Sur, Buenos Aires, Argentina ⁹⁾ VBPR, Oslo, Norway ¹⁰⁾ YPF, Argentina ¹¹⁾ UNIS, Longyearbyen, Svalbard		Funding The Research Council of Norway, Center of Excellence (Porous Media Laboratory)	Participants Marcel Moura¹, Knut Jørgen Måløy¹, Eirik Grude Flekkøy¹ and Renaud Toussaint^{1,2}	Affiliation ¹⁾ PoreLab, The Njord Centre, University of Oslo, Norway ²⁾ University of Strasbourg, Strasbourg, France
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Impact of volcanism on the petroleum system

Numerous sedimentary basins in the world host voluminous igneous sill-complexes, i.e. stacking of sills that are emplaced in different levels of the sedimentary sequence. When sills are emplaced in organic-rich sedimentary formations, they can considerably affect the thermal and maturation history of the hydrocarbon source rock and can be highly relevant elements of the petroleum system. We performed ambitious research in the Neuquén basin, Argentina, to study a world-class igneous petroleum system, in cooperation with the Argentinian oil company YPF. Our study show that: (1) the main hydrocarbon maturation in producing oil fields was dominantly triggered by the heat provided by the cooling of the igneous sills, (2) the igneous sills are fractured reservoirs for the hydrocarbons, (3) contact metamorphism lead to the deposition of iron sulphides which are expressed as low-resistivity zones on both contacts of the intrusions (Spacapan et al., 2020a,b,c).

In order to capture the complex processes at work in igneous petroleum systems, we carried out an extensive field mapping of an exceptional field analogue of a petroleum system, in the northern Neuquén Basin, Argentina (Rabbel et al., submitted). There we identified the numerous types of fractures and their associated processes, and we discuss their implications for fluid migration.

In March 2019, Galland lead a field expedition in southern Mendoza province, Argentina, to study the peculiar Cerro Alquitrán, an igneous andesitic conduit at the rims of which large volumes of petroleum are seeping out (Galland et al., in prep.) (Figure). Field observations show

that magmatic fractures and breccia within the conduit serve as migration pathways. Cerro Alquitrán is an exceptional field case study highlighting that igneous intrusions have major impact on fluid migration in sedimentary basins.

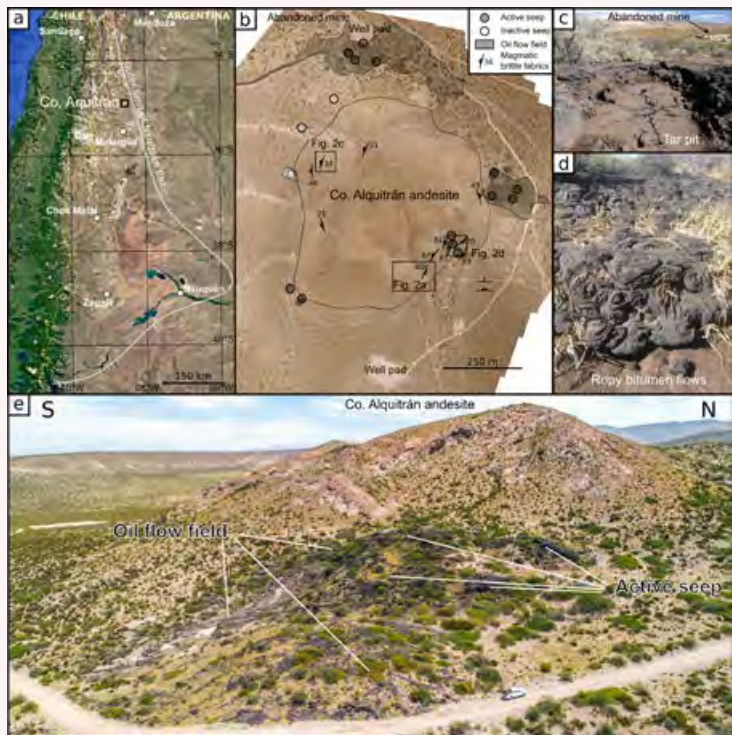


Figure summarising field observations of petroleum seeps around the Cerro Alquitrán andesitic plug, Mendoza province, Argentina (Galland et al., in prep.)

Products in highlight

Galland, O., Mescua, J., Jerram, D., Augland, L.E., Villar, H.J., Zanella, A., Planke, S., Medialdea, A., Midtkandal, I., & Palma, J.O. Implications of felsic igneous intrusions on fluid migration. *Geology*, in preparation.

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

Spacapan, J.B., Ruiz, R., Manceda, R., D'Odorico, A., Roxha, E., Rojas Vera, E., Medialdea, A., Cattaneo, D., Palma, O., Leanza, H.A., & Galland, O. (2020). Chapter 20 – An Igneous Petroleum System within the Vaca Muerta Formation. *Minisini, D., Fantin, M., Lanusse, I., and Leanza, H.A., eds., Integrated geology of unconventional: The case of the Vaca Muerta play, Argentina: AAPG Memoir 120.*

Spacapan, J., D'Odorico, A., Palma, J.O., Galland, O., Senger, K., Ruiz, R., Manceda, R., & Leanza, H.A., (2020). Low resistivity zones at contacts of igneous

intrusions emplaced in organic-rich formations and their implications on fluid flow and petroleum systems: A case study in the northern Neuquén Basin, Argentina. *Basin Research*, 32, 3–24, doi: 10.1111/bre.12363.

Spacapan, J., D'Odorico, A., Palma, J.O., Leanza, H.A., Ruiz, R., Medialdea, A., Galland, O., & Manceda, R. (2020). Igneous petroleum systems in the Malargüe fold and thrust belt, Río Grande Valley area, Neuquén Basin, Argentina. *Marine and Petroleum Geology*, 111, 309–331, doi: <https://doi.org/10.1016/j.marpet-geo.2019.08.038>.

Slow drainage experiments in porous media: what happens in your facemask while you sleep

You arrive home after another day of socially distanced interactions with your fellow colleagues. Had this been another year, you could grab some snack, open a beer and jump on the sofa straight away. But this is 2020, so the first thing you do is remove and wash your reusable facemask, this life-saving, COVID-blocking porous medium. After a thorough wash, you decide to hang it on a string, to let it dry overnight, such that tomorrow this porous medium can go back to its heroic mission of preserving life on Earth as we know it. But what is really happening inside that mask while you sleep (or drink your beer)?

The drying mask is nothing but the most common 2020 realization of a porous medium slow drainage experiment. As gravity

and evaporation work their ways, the water in the mask gives room for the surrounding air, which creeps into the mask, filling in the voids between the fibers of the tissue. This process, which seems rather smooth and continuous, is actually far from that. It occurs as an interesting succession of fast invasion events, some very small, with just one pore getting dry, others much larger, with air invading and drying several pores at once. This interesting intermittent dynamics is not exclusive to drying facemasks. It occurs in many natural and engineered settings and porous media scientists have kept a close eye on it over the years. By using artificially designed transparent porous networks, we can see very well the evolution of the air invasion dynamics. We show the result of one of those experiments

on the right side of the figure. In this experiment, air invaded a porous network that was initially filled with a liquid (much like the process of the drying of a facemask on a string, as shown on the left of the figure). The different colors were randomly placed to help us see the different air invasion bursts, i.e., different portions of the medium that get dry. We have found that this drying occurs in an intermittent manner, with a wide distribution of invasion events, some small and some very large. It is interesting to notice how even such an apparently simple phenomenon, the drying of a piece of tissue, can present very interesting dynamics if we look close enough.

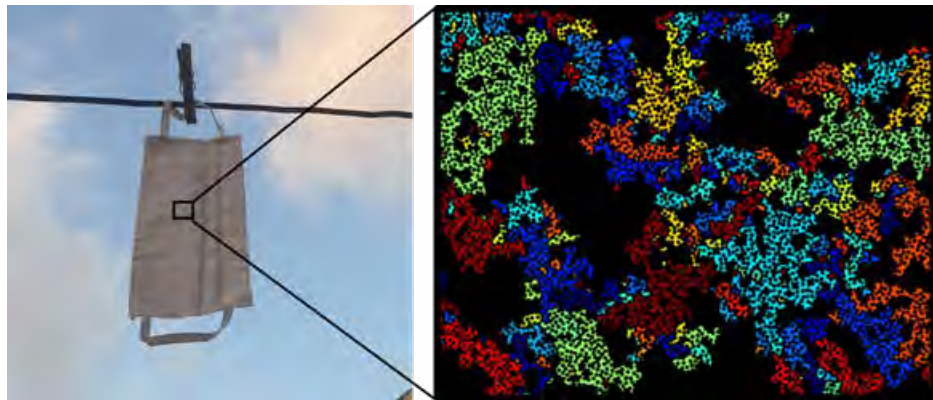


Figure: A drying facemask (left) is an example of a slow drainage experiment in a porous medium. Although the process of drying seems very slow and continuous, it actually presents an interesting intermittent invasion dynamics, in which portions of the wet porous medium are successively invaded by the surrounding air. The invasion bursts can be well seen in our experiments, using artificial transparent porous network. In the experiment shown on the right, a viscous liquid is removed from the right side while air enters from the left. The different invasion bursts are colored randomly, to aid visualization. We see a wide distribution of air invasion events, some very small and some very large. The circular black dots are the porous matrix, in this case a monolayer of glass beads.

Products in highlight

Moura, M., Måløy, K. J., Flekkøy, E. G., & Toussaint, R. (2020). Intermittent dynamics of slow drainage experiments in porous media: characterization under different boundary conditions. *Frontiers in Physics*, 7, 217.



Funding The Research Council of Norway, Center of Excellence (Porous Media Laboratory)	Participants Monem Ayaz^{1,2}, Marcel Moura¹, Knut Jørgen Måløy¹, Renaud Toussaint^{1,2}, Gerhard Schäfer²	Affiliation ¹⁾ PoreLab, The Njord Centre, University of Oslo, Oslo, Norway ²⁾ University of Strasbourg, Strasbourg, France	Funding Equinor (Akademia, project MODIFLOW), Swiss National Science Foundation, The Research Council of Norway, Center of Excellence (Porous Media Laboratory)	Participants Gaute Linga¹, Fabian Barras¹, François Renard¹, Bjørn Jømtveit¹, Eirik Grude Flekkøy², Luiza Angheluta¹, Joachim Mathiesen^{3,1}, Tanguy Le Borgne^{4,1}	Affiliation ¹⁾ The Njord Center, University of Oslo, Norway ²⁾ PoreLab, The Njord Center, University of Oslo, Norway ³⁾ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark ⁴⁾ Université de Rennes 1, Rennes, France
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Fluid saturation behind gravitational stabilized invasion fronts in porous media

When a non-wetting fluid displaces a wetting fluid in a gravitational field, the gravity will stabilize the fluid front and pockets of trapped fluid will be left behind the front. It is of particular interest to know how the saturation behind the advancing front depends on the fluid properties like surface tension, densities and viscosities, and the local geometry of the porous medium, and if the trapped fluid behind the front is stable or if it will be drained on large time scales. Can we understand the dependence between the measured pressure in the fluid and the fluid saturations?

We have experimentally and numerically studied the influence of gravity on the pressure-saturation relationship in a given porous medium during slow drainage. The effect of gravity was systematically varied by tilting the system relative to the horizontal configuration. The use of a quasi two-dimensional porous media allowed for direct spatial monitoring of the saturation. Exploiting the fractal nature of the invasion structure, we obtained a relationship between the final saturation and the strength of the gravity using percolation theory. Moreover, the saturation, pressure, and gravity field were functionally related, allowing for pressure-saturation curves to collapse onto a single master curve. This allows to upscale the pressure-saturation curves measured in a laboratory to large representative elementary volumes used in reservoir simulations. The large-scale behavior of these curves follows a simple relationship, depending on the density

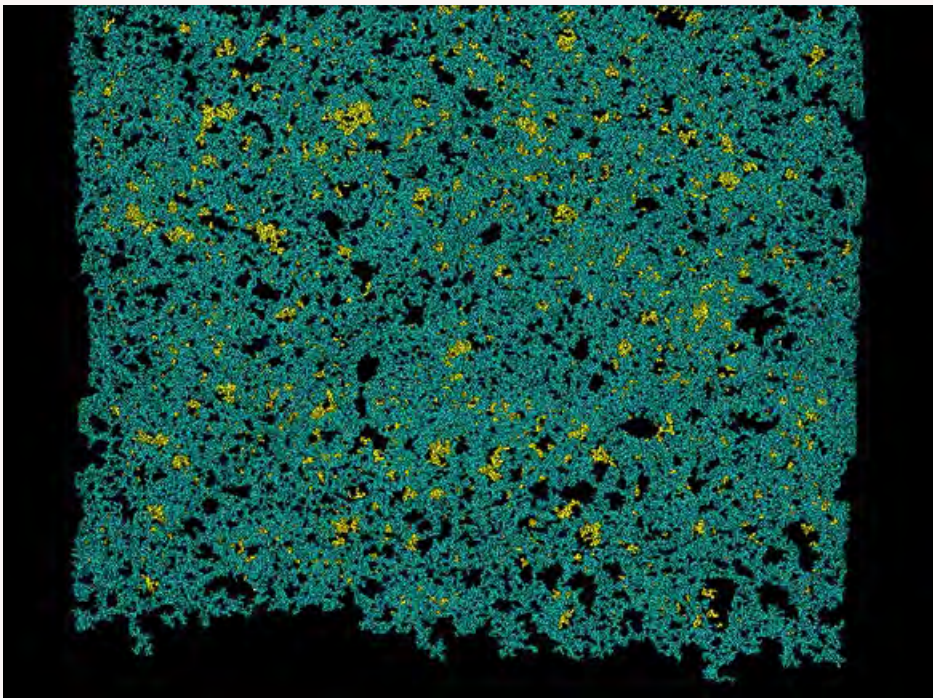


Figure: The picture shows a gravity stabilized front where air (in green) invades a glycerin/water solution (in black). The cluster left behind invaded by film flow at large times are seen in yellow.

difference, the gravity field, and on the flow direction. The size distribution of trapped defending fluid clusters is also shown to contain information on past fluid flow and can be used as a marker of past flow speed and direction.

We have further studied the effects of connectivity enhancement due to film flow phenomena on the drainage and the relative

influence of gravity for such effects. Our setup allows us to directly visualize the dynamics of the flow and, in particular, to pinpoint which pore invasion events are due to film flow phenomena. We have observed the formation of an active zone behind the liquid-air interface, inside which film flow drainage events are more likely to occur.

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 fluid is naturally present (earthquakes, magmatic intrusions, aquifers) or artificially injected in the subsurface, as in the process of carbon capture and storage or the exploitation of geothermal reservoirs. This project tackles the modeling 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, and found that flow intermittency significantly enhances transverse spreading as well as the folding and stretching of fluid filaments that is a hallmark of chaotic mixing. We have developed a numerical framework to compute stretching and folding of strips and sheets to reveal possibly chaotic mixing properties of real porous rock.

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. CO₂, hydrogen). We have designed a numerical method solving the coupled dynamics of fluid flow and fracture growth. The picture below displays the sudden burst of a fluid-saturated crack.

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).

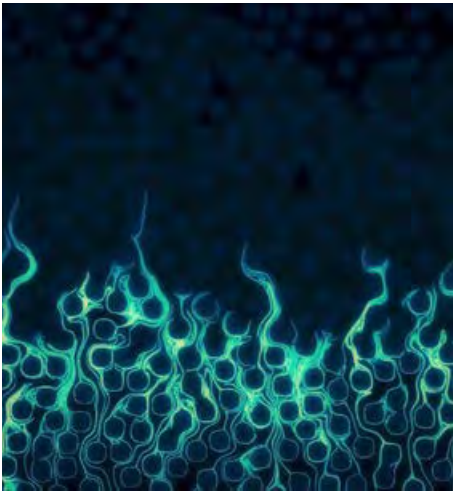


Figure 1: Stretching and folding of a line of tracer dye during two-phase porous media flow.

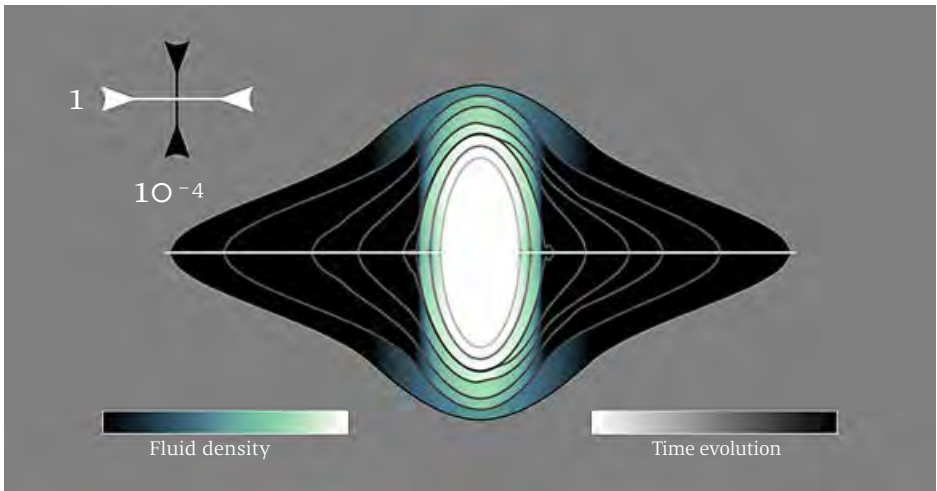


Figure 2: Fluid-depleted zone emerging during the rapid growth of a fluid-driven crack.

Products in highlight

Passelègue, F. X., Almakari, M., Dublanchet, P., Barras, F., Fortin, J., & Violay, M. (2020). Initial effective stress controls the nature of earthquakes. *Nature Communications*, 11, 5132.



Barras, F., Aghababaei, R., & Molinari, J. F. Onset of sliding across scales: How the contact topography impacts frictional strength. *Physical Review Materials*, accepted.

Rezakhani, R., Barras, F., Brun, M., & Molinari, J. F. (2020). Finite element modeling of dynamic frictional rupture with rate and state friction. *Journal of the Mechanics and Physics of Solids*, 141, 103967.

Linga, G., Mathiesen, J., Renard, F., & Le Borgne, T. (2020). Stretching and Folding in Intermittent Two-Phase Porous Media Flows. *Bulletin of the American Physical Society*, November 23.

Linga, G., Moyner, O., Nilsen, H. M., Moncorgé, A., & Lie, K. A. (2020). An implicit local time-stepping method based on cell reordering for multiphase flow in porous media. *Journal of Computational Physics*: X, 100051.

Products in highlight

Ayaz, M., Toussaint, R., Schäfer, G., & Måløy, K. J. (2020). Gravitational and Finite-Size Effects On Pressure Saturation Curves During Drainage. *Water Resources Research*, 56(10), e2019WR026279.

Moura, M., Flekkøy, E. G., Måløy, K. J., Schäfer, G., & Toussaint, R. (2019). Connectivity enhancement due to film flow in porous media. *Physical Review Fluids*, 4(9), 094102

Funding
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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.

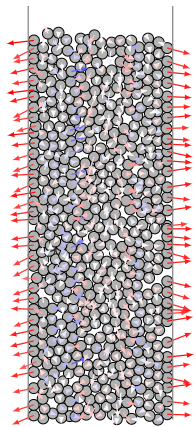


Figure 1:
Local forces in a magnetic Janssen configuration.

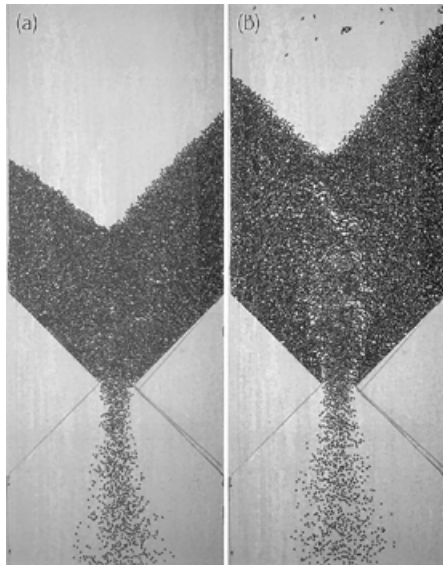


Figure 2: Discharge of a 2D-silo without magnetic field (a), and with a strong magnetic field normal to the plan (b).



Figure 3: Trigger of the bulldozing instability using ferromagnetic interactions.



Products in highlight

Thorens L., Måløy, K. J., Bourgoïn, M., & Santucci, S. Magnetic Janssen Effect. In review.

Thorens L., Måløy, K. J., Bourgoïn, M., & Santucci, S. Tamming the Janssen Effect. *Powders and Grains*, in review.

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

Thorens L., Viallet, M., Måløy, K. J., Bourgoïn, M., & Santucci, S. Discharge of a 2D magnetic silo. *Powders and Grains*, in review.





Pattern Formation and Dynamical Systems

- 1 Transition from viscous fingers to compact invasion patterns during drainage of porous media
- 2 A cosmic dust-bunny: 'Oumuamua as a space fractal
- 3 Labyrinthine structures in seal noses
- 4 Active matter in disordered environments
- 5 Hyper-ballistic super diffusion
- 6 Flows in networks
- 7 Dislocation dynamics and plasticity in small crystals

Transition from viscous fingers to compact invasion patterns during drainage of porous media

Immiscible fluid displacement is unstable when a less viscous fluid invades a more viscous fluid inside a porous medium, resulting in characteristic flow patterns that depend on the flow rate (or overpressure) of the invading fluid. For low flow rates, the capillary forces dominate and the invading fluid forms an invasion percolation type of pattern, while for higher flow rates viscous forces dominate such that the invading fluid forms a dendritic viscous fingering type of pattern. This cross-over from capillary to viscous fingering depends on the viscosity contrast between the fluids in addition to the flow rate. In recent experiments we inject air at a constant overpressure into the center of a circular Hele-Shaw cell filled with a monolayer of glass beads, initially saturated with a viscous liquid. To explore invasion patterns in the parameter space of viscosity and overpressure, we conduct sets of experiments for different overpressures and repeat the experiment for 10 different glycerol-water solutions. For higher overpressures and lower viscosity contrasts, we have observed the emergence of more stable and dense invasion patterns. These patterns are seen in the regime where the patterns are expected to be unstable and dendritic according to the Saffman-Taylor instability. 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, a process that is neither understood nor previously described.

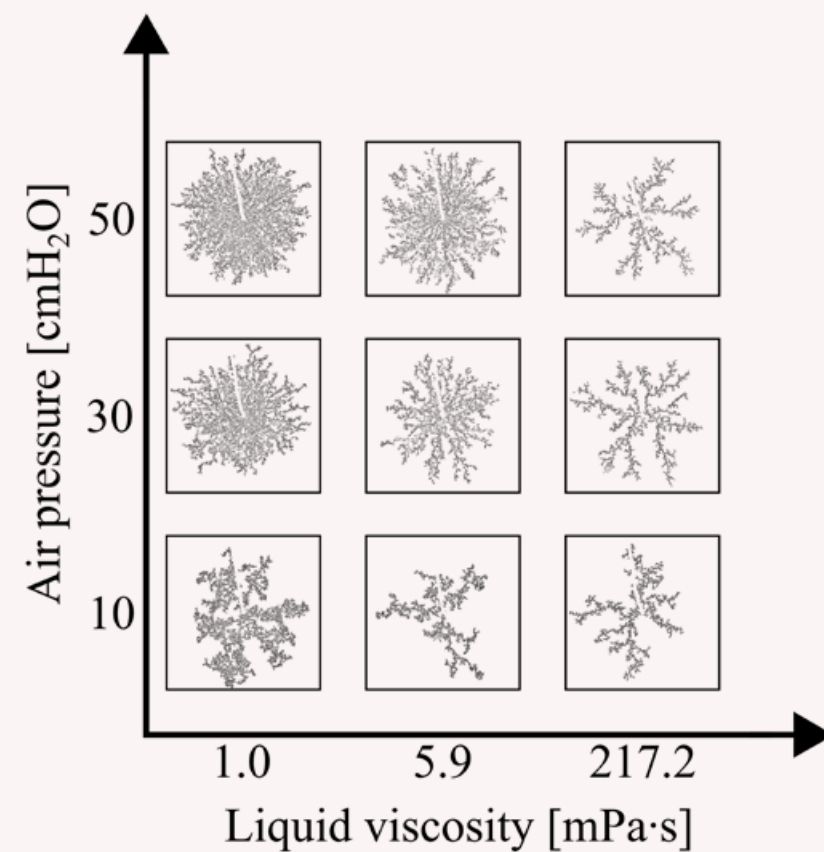


Figure: Examples of final patterns and how they change with injection pressure (increases upwards) and liquid viscosity (increases towards right). The pattern clearly becomes compact for higher pressures and lower viscosity (top left), while increasing viscosity leads to viscous fingers (top right). Also note that the capillary fingering regime is approached for low pressure and viscosity (bottom left).

A cosmic dust-bunny: 'Oumuamua as a space fractal

The first known interstellar object was discovered in 2017 and named 'Oumuamua, Polynesian for visitor from afar. Passing through our solar system it was observed to be highly elongated and about the size of a large ship. It displayed such unusual properties that its origin remains a subject of much debate. Among the most puzzling observation was its acceleration, which could not be explained by gravity alone. We proposed that 'Oumuamua's properties could be explained as those of a fractal dust aggregate (a "dust bunny")

which was formed in the inner coma of a fragmenting comet orbiting around a distant star, and then escaped to interstellar space. Such a fractal can be light enough for the suns radiation pressure to explain the extra-gravitational acceleration. The formation of the fractal is made possible by two important factors: 1) the presence of cometary fragments as accretion sites, and 2) the fractal's ability to absorb impacts during the accretion process. After forming, the fractal eventually separates from the fragment due to hydrodynamic

stress, then is ejected into interstellar space by radiation pressure. Our model predicts the short dimension of 'Oumuamua, and the object's elongated shape (although the model cannot distinguish between a cigar or disk shape). The model could also explain the discovery rate of 'Oumuamua, depending on the number of fragments produced per comet. Finally, it predicts the existence of fractal bodies in the solar system, which may one day be identified.

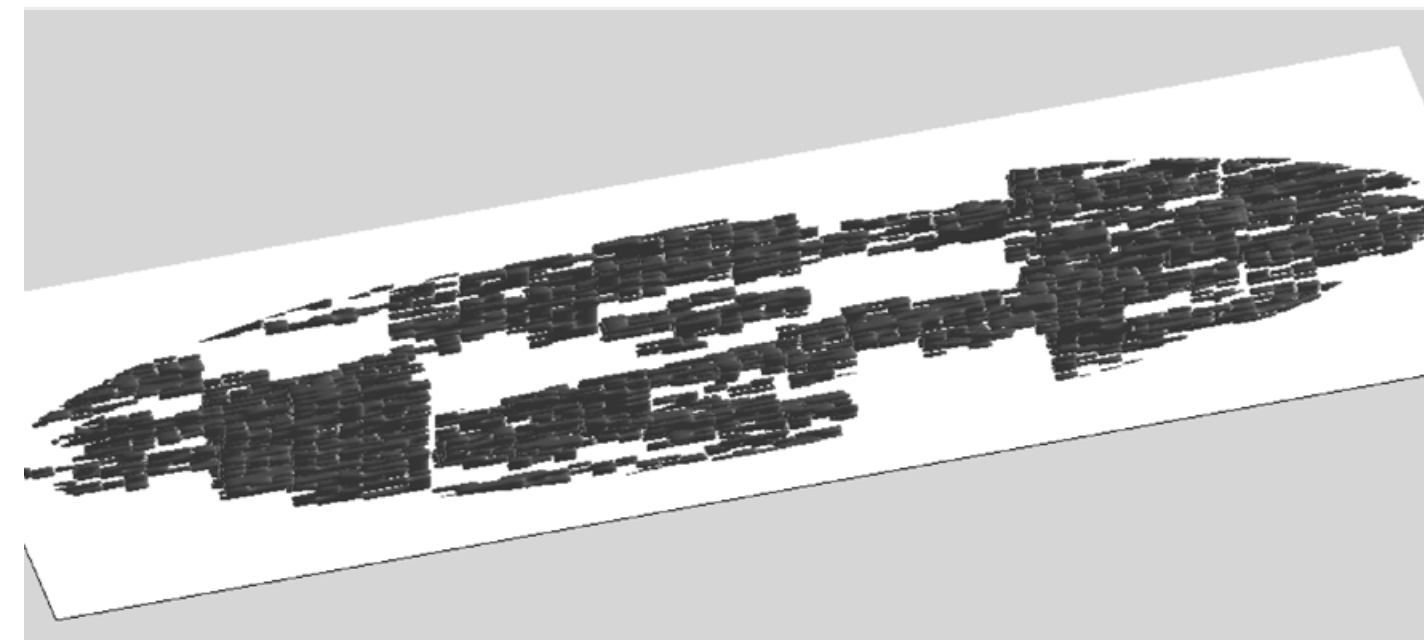


Figure: Dust bunny – a conceptual model of a fractal cometary aggregate.

Production in highlights

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

Funding
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Labyrinthine structures in seal noses

Seals have a heat exchanging organ in their noses that resemble the labyrinthine structures seen in our frictional fluids experiments and simulations.

We use images of the convoluted nose structure of a variety of seal species, and argue that the observed internal structure in these nose turbinates, may be predicted from a thermodynamic analysis. In particular, we predict the channel length and width of the nose organ, so-called maxilloturbinates. The analysis is based on the condition that the nose must act as an exchanger of both a heat- and water. The evolution of the nose structure may thus be understood from the seals need to conserve body heat and water. This theory is supported by the fact that maxilloturbinates are much more developed in arctic seals than in seals that live in warmer environments.

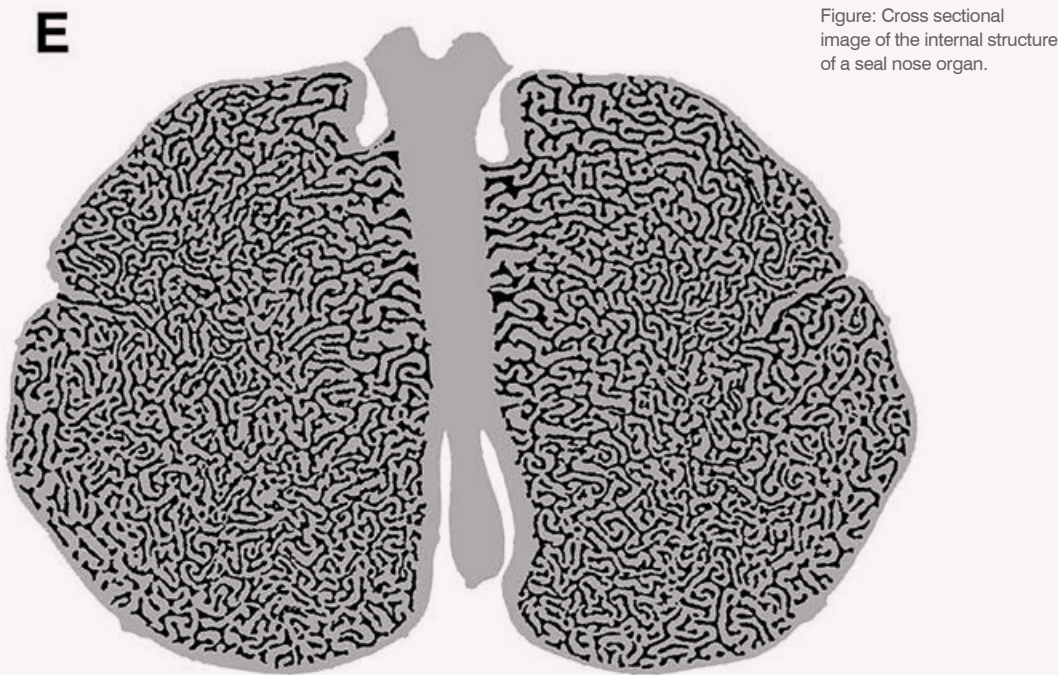


Figure: Cross sectional image of the internal structure of a seal nose organ.

Active matter in disordered environments

A defining feature of living systems is their ability to absorb free energy from the environment and use it to perform useful tasks, like generating motion or self-healing. Active matter is a class of non-equilibrium systems that mimics these properties by allowing selfpropelled particles to convert environmental energy into directed motion (which is why they are self-propelling). This mimics for example how bacteria or cells use energy to move through fluids and complex media. While theoretical models of active matter have had great success when applied to homogeneous or open systems, most realistic scenarios have some degree of spatial complexity. This extra level of complexity may be of a spatial or temporal nature and includes for example bacterial motion through soil or cell migration in tissue. Temporal disorder includes for example time-dependent swimming mechanisms that allows bacteria to effectively navigate a complex landscape.

In this project we aim to improve our understanding about such active systems in the presence of disorder or spatial confinement. Our methods rely on a microscopic description of the individual particles, which can be studied through numerical simulations. Effective models for the behavior on large spatial and temporal scales can be compared to the more detailed simulations to gain insights into the most relevant aspects of the system.

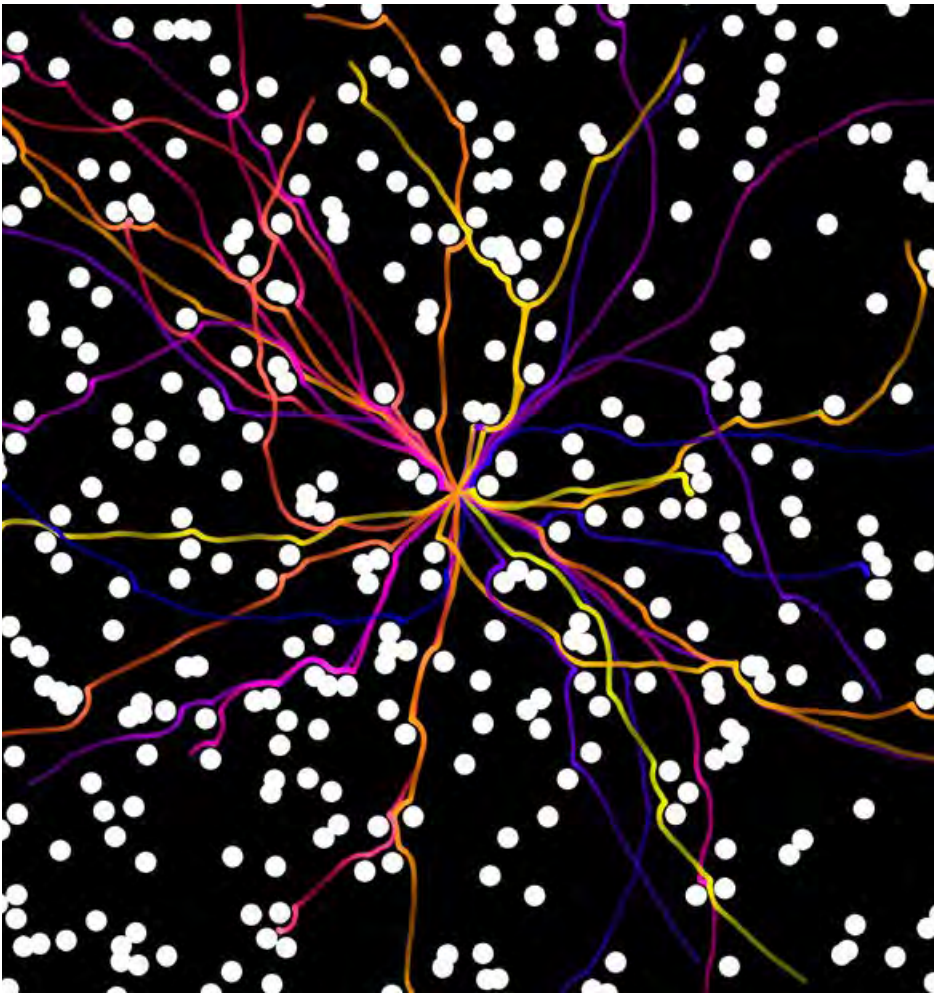


Figure: Simulation of the trajectories of active particles moving through a two-dimensional random porous media. Many open questions remain regarding swimming strategies and the search for optimal paths to navigate such environments, for example in the search for nutrients.

Production in highlights

Olsen, K. S., Angheluta, L., & Flekkøy, E. G. (2020). Escape problem for active particles confined to a disk. *Physical Review Research*, 2(4), 043314.

Olsen, K. S., Angheluta, L., & Flekkøy, E. G. Active particles moving through disordered landscapes. *Soft Matter*, in press.

Olsen, K. S. (2020) Perturbative effective diffusivity of microswimmers in the presence of oscillating torques. *arXiv* (<https://arxiv.org/abs/2012.05415>).

Hyper-ballistic super diffusion

Super-diffusion is a subject treated by statistical physics, but is of general interest to a wider community because it arises in such different contexts as fluid dynamics, biological physics, and geophysics. We introduce a highly general model that is applicable to several of these areas, and it introduces exact solutions to the associated differential equation along with a

corresponding particle model. It also gives a classical basis for hyper-ballistic diffusion, a phenomenon, which has primarily been observed in quantum systems. The model is applicable in contexts including bacteria growth, granular media and the thermodynamics of frost heave. By means of a particle model that includes interactions only via the local particle concentration,

we show that hyperballistic diffusion may result. This is done by the exact solution of the corresponding non-linear diffusion equation, as well as by particle simulations. The connection between these levels of description is provided by the Fokker-Planck equation describing the particle dynamics.

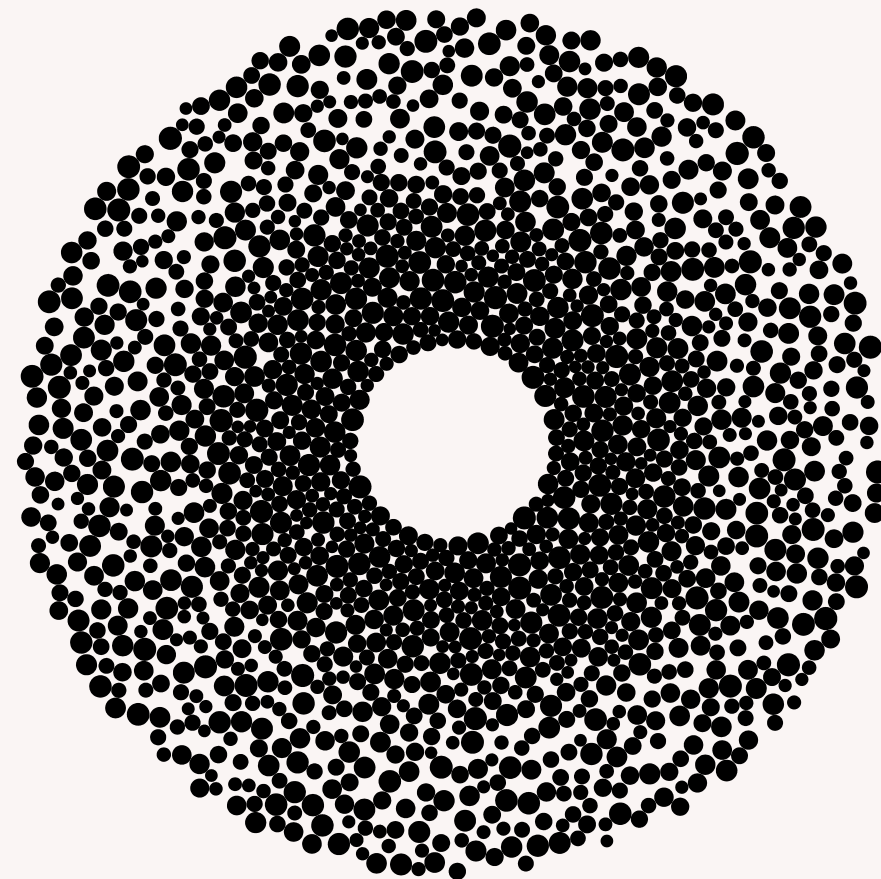


Figure: A candidate system for superdiffusive behavior, a simulation of a compactifying granular medium where the porosity may evolve superdiffusively.

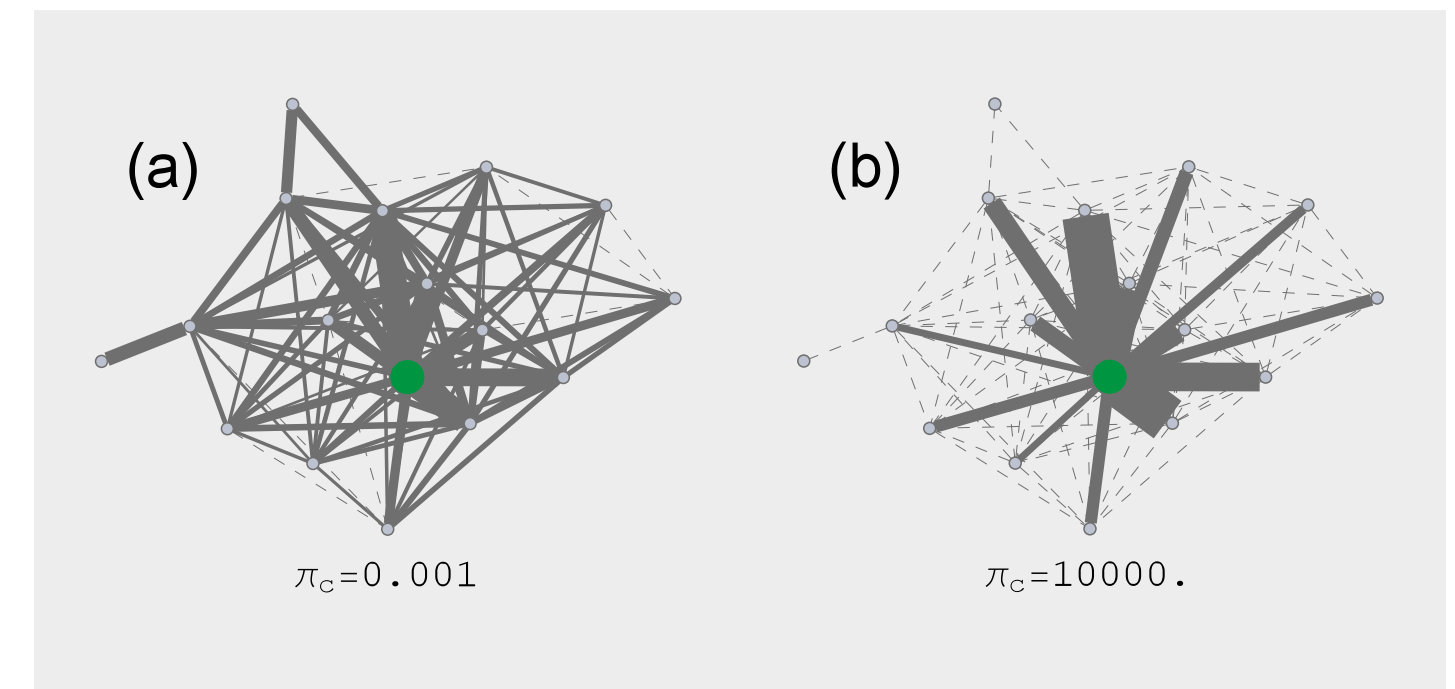
Flows in networks

The network-theoretical description of many-particle systems as *nodes* connected by *edges* has found diverse applications in science and technology, including flow 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. The flows 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. Grasp is quantified by flows between two nodes, in which random “walkers” have a tunable probability to “die” while traversing an edge. With a high death rate, only walkers proceeding

along geodesics survive, while with a low death rate, they spread over the whole network like an electrical current [1]. To quantify reach, one chooses a single node as a current source, while all other nodes are connected to ground by resistors. If the resistances to ground are high, the current persists far from the source (large reach), while small resistances limit the reach to the nearest neighbors of the source node [2]. We propose several new, grasp- and reach-parametrized centrality measures.



Figures: Extremes of reach, illustrated on a social network of kangaroos. Line thickness indicates current magnitude. Dashed edges carry negligible current. (a) Large reach, corresponding to low conductances to ground, π_C . (b) Small reach, corresponding to high π_C . From [2].

Production in highlights

Hansen, A., Flekkøy, E. G., & Baldelli, B. (2020). Anomalous Diffusion in Systems with Concentration-Dependent Diffusivity: Exact Solutions and Particle Simulations. *Frontiers in Physics*, 8, 523.

Production in highlights

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

2) Gurfinkel, A. J., & Rikvold, P. A. (2020). A Current-Flow Centrality with Adjustable Reach. *arXiv preprint*, arXiv:2005.14356.

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Dislocation dynamics and plasticity in small crystals

Each year, thousands of Minnesotans walks upon a frozen lake searching for fish. “Trusting [the lake] is less like buying gold than buying stock in an insurance company” (Laughlin, *A different universe*, 2008). Indeed, the rigidity of solid phases are organizational, caused by the emergent crystalline structures of many interacting particles. However, just as organizations are only as strong as their weakest links, so do solids break apart due to the motion of crystal defects such as dislocations.

The Phase-Field Crystal (PFC) is a meso-scale model of plasticity that attempts to bridge the gap between the microscopic description of colloidal particles with that of continuum plasticity. The dynamics of the model is given by minimizing the free energy which determines the crystal structure (Fig. 1). By coupling the evolution of the PFC to a mesoscopic stress field, we have developed a model which has been shown to effectively capture the character and motion of dislocations [1-3]. By imposing

an external stress field, we have induced the nucleation of a dislocation dipole in an otherwise perfect hexagonal lattice (Fig. 2) and have found sensitive stress-based diagnostics of the process [4]. In further research we will extend and apply the model to other crystal symmetries in 2 and 3 dimensions.

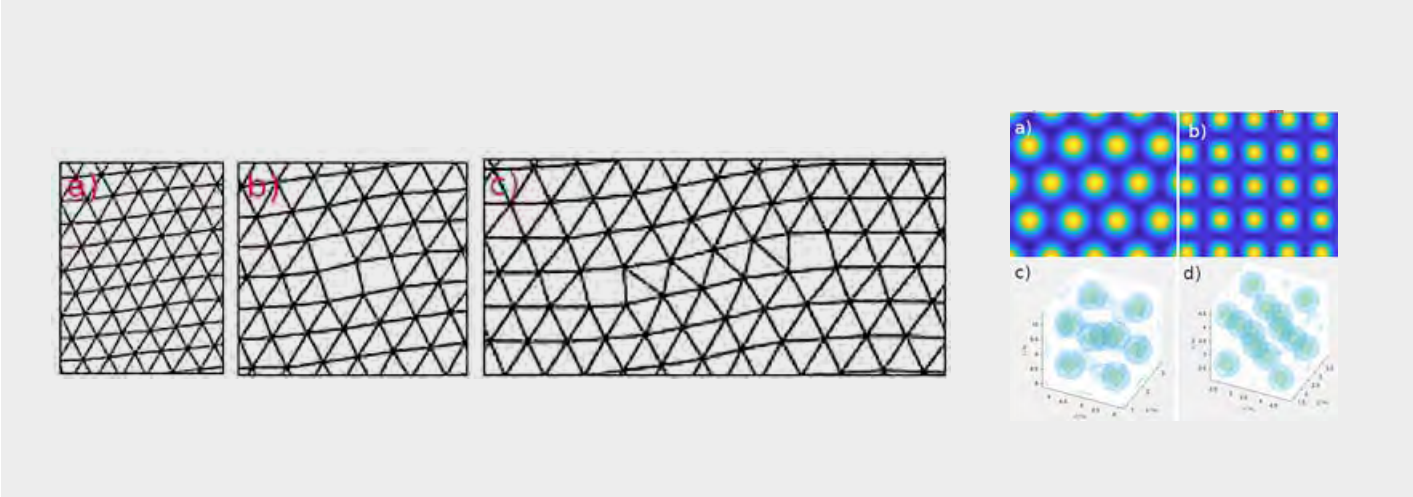


Figure 1: Different structures of the PFC.
a) 2D hexagonal,
b) 2D square,
c) 3D body-centered cubic,
d) 3D face-centered cubic,

Figure 2: Stress induced nucleation of a dislocation dipole in the hexagonal PFC.
a) The PFC (shown as lines connecting adjacent peaks in the density field) prior to nucleation,
b) the PFC at the nucleation instant,
c) moments after the nucleation of two distinct edge dislocations.

Production in highlights

1) Skaugen, A., Angheluta, L., & Viñals, J. (2018). Dislocation dynamics and crystal plasticity in the phase-field crystal model. *Phys. Rev. B*, 97(5), 054113.
2) Skaugen, A., Angheluta, L., & Viñals, J. (2018). Separation of elastic and plastic timescales in a phase field crystal model. *Phys. Rev. Lett.*, 121(25), 255501.

3) Salvalaglio, M., Angheluta, L., Huang, Z.-F., Voigt, A., Elder, K. R., & Viñals, J. (2020). A coarse-grained phase-field crystal model of plastic motion. *Journal of the Mechanics and Physics of Solids*, 137, 103856

4) Skogvoll, V., Skaugen, A., Angheluta, L., & Viñals, J. (2020). Dislocation nucleation in the phase field crystal model. ArXiv:2009.07524 [Cond-Mat]. *Phys. Rev. B*, accepted.



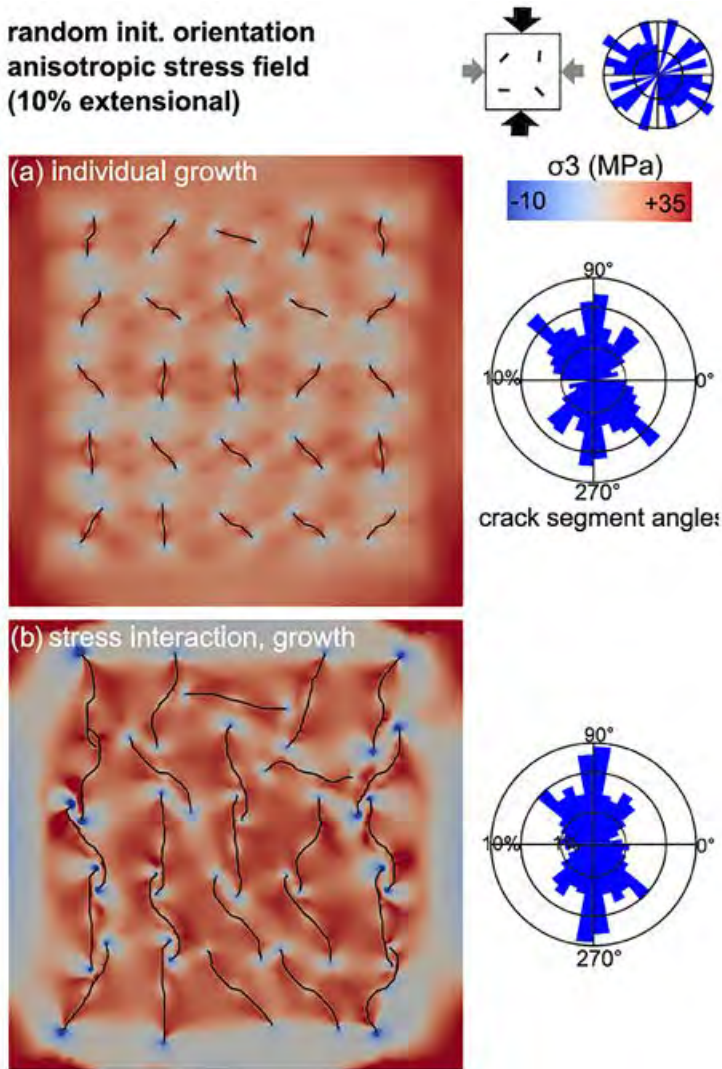
Fracture, Friction and Creep in Rocks and Materials

- 1 Growth of fracture network due to fluid generation
- 2 Emergent networks: Predicting strain localization and fracture network development
- 3 Brittle-viscous deformation cycles at the base of the seismogenic crust
- 4 The road to failure in rocks
- 5 Maturation and fracturing of organic-rich shale during primary migration
- 6 An origin of brittleness: a thermal point of view

Growth of fracture network due to fluid generation

When low-permeability and organic-rich rocks such as shale experience sufficient heating, chemical reactions including shale dehydration and maturation of organic matter lead to internal fluid generation. This may cause substantial pore fluid overpressure and fracturing. In the vicinity of igneous intrusions emplaced in organic-rich shales, temperatures of several hundred degrees accelerate these processes and lead to intense fracturing. The resulting fracture network provides hydraulic pathways, which allow fluid expulsion and affect hydrothermal fluid flow patterns. However, the evolution of these complex fracture networks and controls on geometry and connectivity are poorly understood. We performed a numerical modeling study based on the extended finite element method to investigate coupled hydromechanical fracture network evolution due to fast internal fluid generation. The results indicate a three-phase process including (1) individual fracture growth, (2) fracture interaction, and (3) expulsion phase. We additionally found that although the external stress field controls the overall fracture orientation distribution, local stress interactions may cause significant deviations of fracture paths and control the coalescence characteristics of fractures.

Figure: Time series and rose plots of the fracture network evolution for random initial fracture orientation and anisotropic stresses (10% extensional). The color code represents the smallest principal stress (from Rabbel et al., 2020).



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 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 tim-

ing 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.

This project started in September 2020, and has thus far yielded four submitted papers.

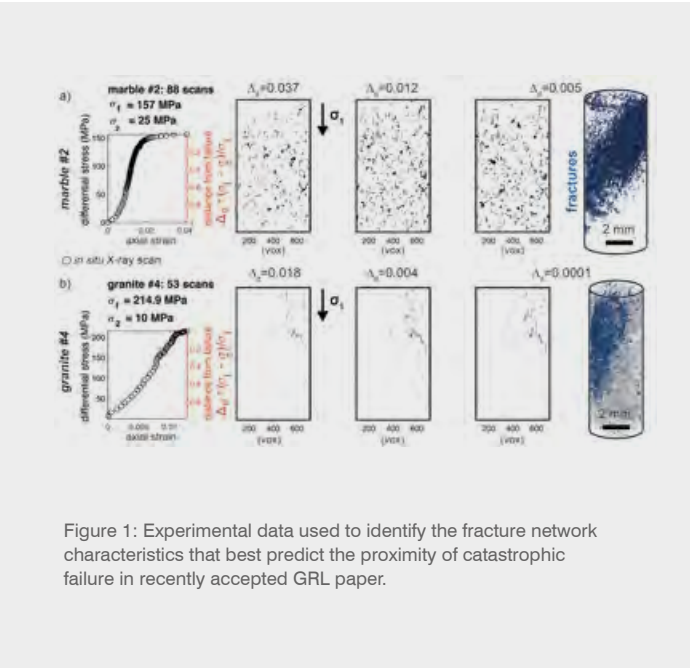


Figure 1: Experimental data used to identify the fracture network characteristics that best predict the proximity of catastrophic failure in recently accepted GRL paper.

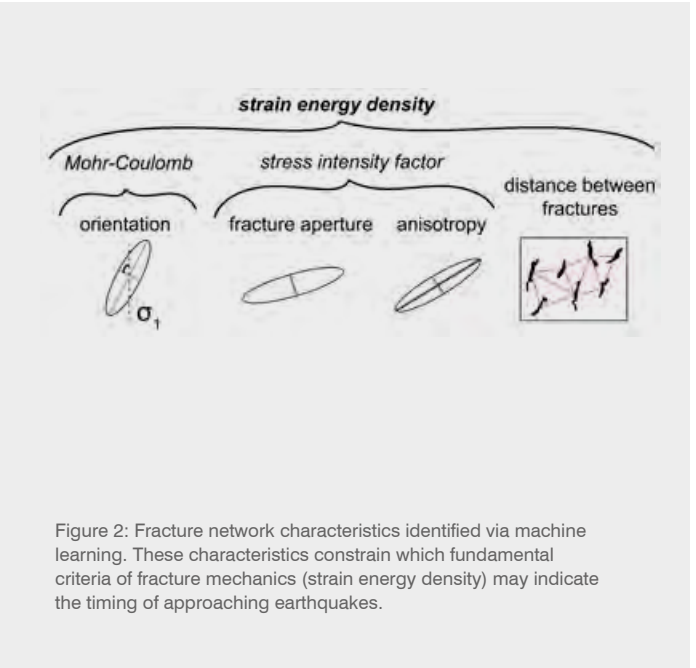


Figure 2: Fracture network characteristics identified via machine learning. These characteristics constrain which fundamental criteria of fracture mechanics (strain energy density) may indicate the timing of approaching earthquakes.

Production in highlights

Rabbel, O., Mair, K., Galland, O., Gröhser, C., Meier, T. (2020). Numerical Modeling of Fracture Network Evolution in Organic-Rich Shale With Rapid Internal Fluid Generation. *Journal of Geophysical Research*, 125.

Production in highlights

McBeck, J., Mair, K., & Renard, F. Decrypting healed fault zones: How gouge production reduces the influence of fault roughness. *Geophysical Journal International*, in press.

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

McBeck, J., Aiken, J., Mathiesen, J., Ben-Zion, Y., & Renard, F. (2020) Deformation precursors to catastrophic failure in rocks. *Geophysical Research Letters*, e2020GL090255.

McBeck, J., Zhu, W., & Renard, F. The competition between fracture nucleation, propagation and coalescence in the crystalline continental upper crust. *Solid Earth*, in review.

Funding Posiva Oy (Finland), University of Plymouth (UK), University of Bologna (Italy), University of Oslo	Participants Luca Menegon¹, Giulio Viola², Mark Anderson³, Paolo Garofalo², Jussi Mattila⁴, Francesca Prando³, Barbara Marchesini², Francesco Giuntoli², Alberto Vitale Brovarone²	Affiliation ¹⁾ The Njord Center, University of Oslo, Norway ²⁾ University of Bologna, Italy ³⁾ University of Plymouth, UK ⁴⁾ Rock Mechanics Consulting Finland Oy, Vantaa, Finland	Funding The Research Council of Norway (project HADES)	Participants François Renard¹, Benoit Cordonnier¹, Jess McBeck¹, Neelima Kandula¹, Bjørn Jamtveit¹, Jérôme Weiss², Wenlu Zhu³, Yehuda Ben-Zion⁴, Paul Meakin⁵	Affiliation ¹⁾ The Njord Center, University of Oslo, Norway ²⁾ University Grenoble Alpes, Grenoble, France ³⁾ University of Maryland, USA ⁴⁾ University of Southern California, USA ⁵⁾ Temple University, Pennsylvania, USA
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Brittle-viscous deformation cycles at the base of the seismogenic crust

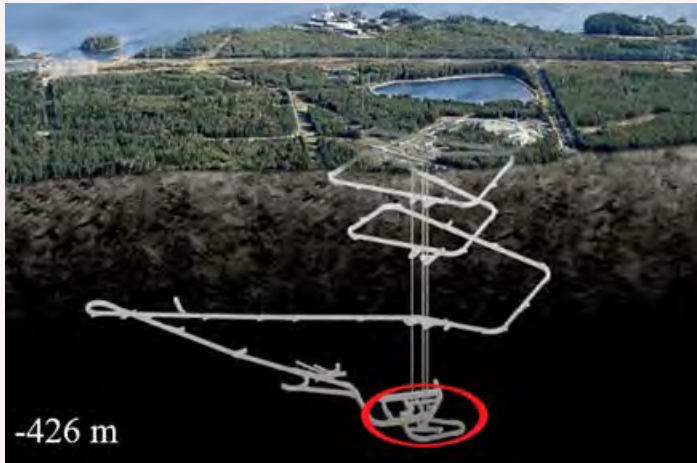
Most of continental earthquakes nucleate at the *brittle-viscous transition*, where the strength of crustal rocks is at its maximum. Crustal deformation near the *brittle-viscous transition* involves the competition between fracturing and viscous flow, and a prominent role of variations in fluid pressure 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 southwestern Finland. The study area is located in Onkalo, the site of a deep geological repository for high-grade nuclear waste.

The project aims to (i) determine the mechanical evolution of long-lived faults active at the *brittle-viscous transition*, (ii) determine the extent of fluid pressure oscillations during deep faulting, (iii) characterize the multi-scale fluid pathways of a fault system.

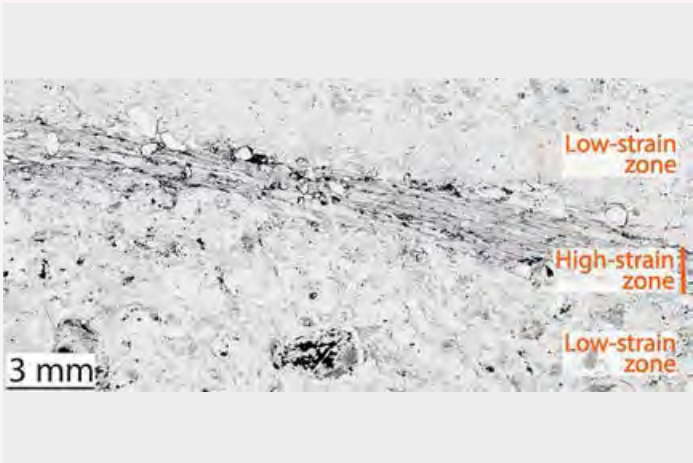
By combining fluid-inclusion studies with electron backscatter diffraction (EBSD) analysis of crystallographic orientations of minerals, we found out that: (i) transient fluid overpressure triggered a switch to brittle and seismic fault behavior in the deep, ‘ductile’ crust, and (ii) the stress history of the ductile flow of a fault can be preserved in its microstructure (for example, in the grain size of quartz). We

are currently investigating the distribution and interconnection of porosity in the fault rocks using Hg-porosimetry combined with x-ray microtomography. Another aspect of the project is the study of pathways for radionuclide migration via trace-element mapping of deformed sulphides found in the fault network in Onkalo.

Furthermore, a complementary case-study to Onkalo has focused on the feedback between deep carbon mobilization and deformation in the subduction channel. We demonstrated that fluid-mediated carbonate reduction has a positive effect on deformation localization in tremor-genic portions of the subduction zone.



(A) Panoramic photograph of the Onkalo site in SW Finland, with an overlay drawing of the underground infrastructure (photo courtesy of Posiva Oy). The red circle shows the depth location of the samples used in the project.



(B) Positive feedback between percolation of C-bearing fluids (to form graphite, the dark grey layers) and strain localization in deformed subducted carbonate rocks.

Production in highlights

Prando, F., Menegon, L., Anderson, M., Marchesini, B., Mattila, J., & Viola, G. (2020). Fluid-mediated, brittle-ductile deformation at seismogenic depth – Part 2: Stress history and fluid pressure variations in a shear zone in a nuclear waste repository (Olkiluoto Island, Finland). *Solid Earth*, 11(2), 489–511.

Giuntoli, F., Brovarone, A. V., & Menegon, L. (2020). Feedback between high-pressure genesis of abiogenic methane and strain localization in subducted carbonate rocks. *Scientific reports*, 10(1), 1–15.

The road to failure in rocks

Our main question is how to quantify the dynamics of microfractures in rocks to predict the onset of major rupture and earthquake nucleation.

We have developed a combined experimental and numerical approach to unravel how ruptures nucleate in rock samples, how earthquake may damage wall rocks in natural earthquakes, and whether precursory signals exist that would indicate the propagation of an earthquake before it happens. Using dynamic X-ray tomography imaging at the European Synchrotron Facility and a home-designed rock deformation apparatus, the Hades rig, we imaged in 4D the evolution of microfractures in rocks before system-size brittle failure. These microfractures represent precursory signals to the main rupture. We have analyzed and observed in 4D how slow slips in rocks may damage the surrounding volume, leading to the formation of a damage zone. Our experiments produce large amounts of data (more than 150 TB so far) and we have developed novel data processing techniques to follow the evolution of strain in a sample during deformation. Among these techniques, we have developed several machine learning workflows to unravel which parameters control the onset of system-size failure in rocks.

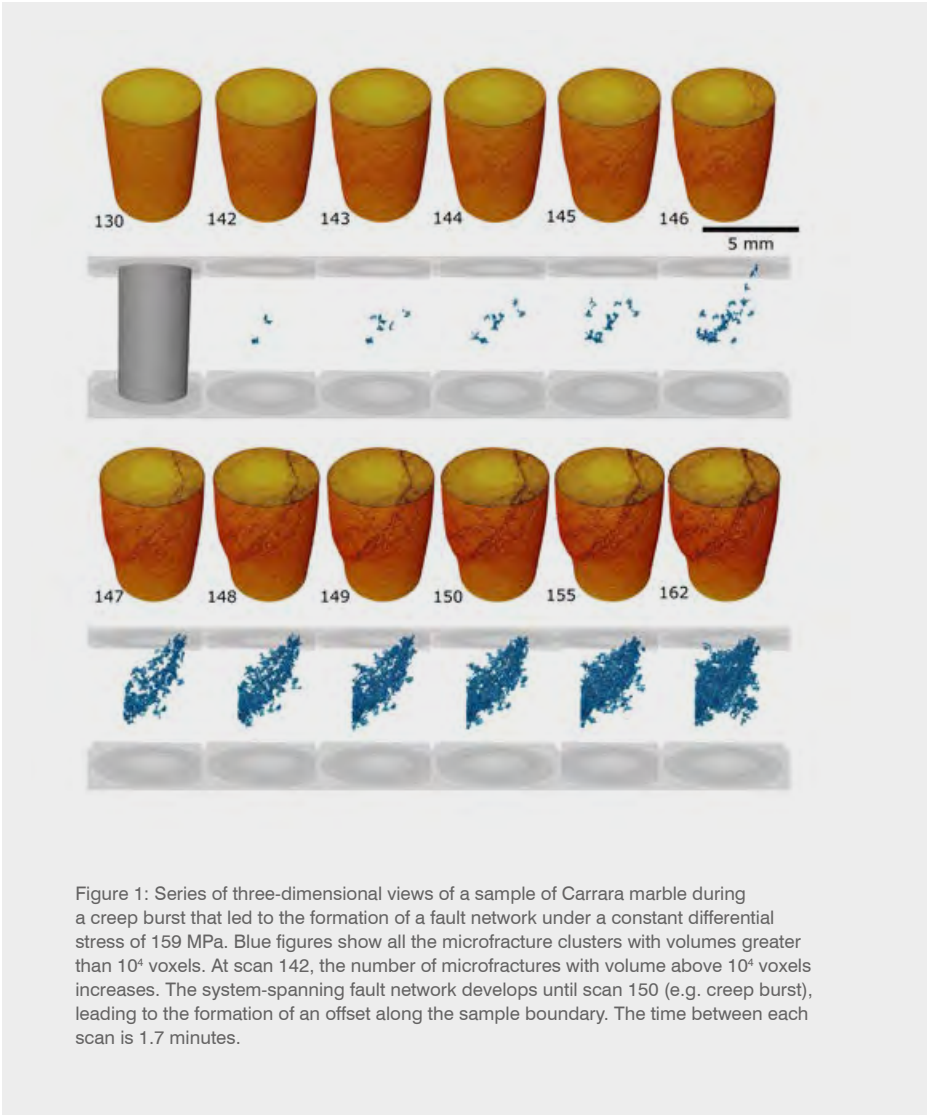


Figure 1: Series of three-dimensional views of a sample of Carrara marble during a creep burst that led to the formation of a fault network under a constant differential stress of 159 MPa. Blue figures show all the microfracture clusters with volumes greater than 10⁴ voxels. At scan 142, the number of microfractures with volume above 10⁴ voxels increases. The system-spanning fault network develops until scan 150 (e.g. creep burst), leading to the formation of an offset along the sample boundary. The time between each scan is 1.7 minutes.

Production in highlights

Renard F., Kandula, N., McBeck, J. A., & Cordonnier, B. (2020). Creep burst coincident with faulting in marble observed in 4-D synchrotron X-ray imaging triaxial compression experiments. *Journal of Geophysical Research: Solid Earth*, 125(9), e2020JB020354.

Heap, M. J., Baud, P., McBeck, J. A., Renard, F., Carbillet, L., & Hall, S. A. (2020). Imaging strain localisation in porous andesite using digital volume correlation. *Journal of Volcanology and Geothermal Research*, 404, 107038.

McBeck, J., Aiken, J. M., Ben-Zion, Y., & Renard, F. (2020). Predicting the proximity to macroscopic failure using local strain populations from dynamic in situ X-ray tomography triaxial compression experiments on rocks. *Earth and Planetary Science Letters*, 543, 116344.

Renard, F., McBeck, J., & Cordonnier, B. (2020). Competition between slow slip and damage on and off faults revealed in 4D synchrotron imaging experiments. *Tectonophysics*, 782–783, 228437.

McBeck, J., Ben-Zion, Y., & Renard, F. (2020). The mixology of precursory strain partitioning approaching brittle failure in rocks. *Geophysical Journal International*, 221, 1856–1872.

Funding The Research Council of Norway (project PROMETHEUS)	Participants François Renard ¹ , Maya Kobchenko ¹ , Benoit Cordonnier ¹ , Olivier Galland ¹ , Thomas Chauve ¹ , James Johnson ¹ , Nazmul Mondol ² , Luc Scholtès ³ , Frédéric Donzé ⁴ , Audrey Ougier-Simonin ⁵	Affiliation ¹⁾ The Njord Center, University of Oslo, Norway ²⁾ Department of Geosciences, University of Oslo, Norway ³⁾ University of Nancy, France ⁴⁾ University Grenoble Alpes, France ⁵⁾ British Geological Survey, Nottingham, UK	Funding University of Strasbourg, CNRS, IRP France-Norway D-FFRACT, The Research Council Norway CoE-program	Participants Tom Vincent-Dospital ^{1,2} , Renaud Toussaint ^{1,2} , Alain Cochard ² , Knut Jørgen Måløy ¹ , Eirik Grude Flekkøy ¹ , Marcel Moura ¹ , Stéphane Santucci ³	Affiliation ¹⁾ Porelab, The Njord Center, University of Oslo, Norway ²⁾ University of Strasbourg, France ³⁾ ENS de Lyon, University Claude Bernard, France
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Maturation and fracturing of organic-rich shale during primary migration

Our main question is how hydrocarbons are expelled from source rocks during burial control 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 propagation of hydraulic fractures.

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

The main outcome this year is an article in Journal of Geophysical Research (Chauve et al., 2020) that demonstrates how the initial sedimentary layering of shale controls microfracturing during the maturation of organic matter and primary migration.

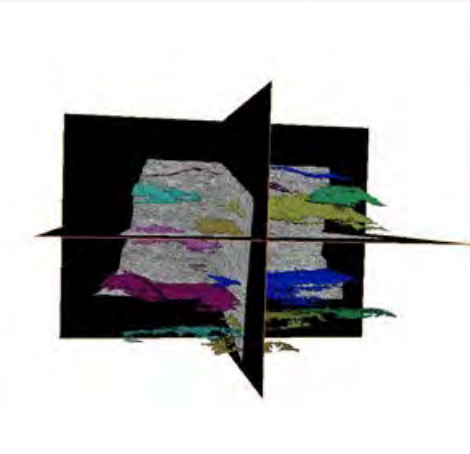
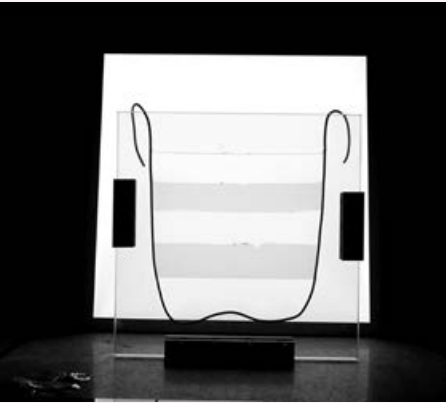
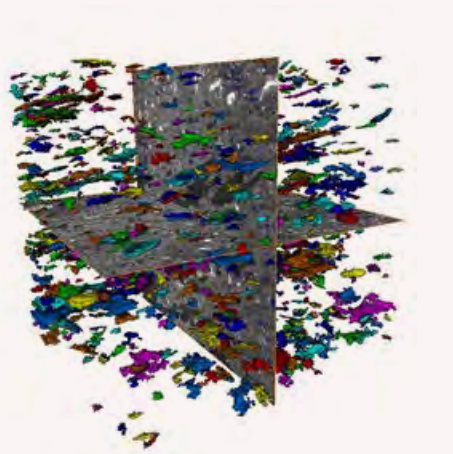


Figure: Left – Synchrotron microtomography images of a shale sample from a borehole in the Draupne formation, North Sea. A label analysis is carried out for all kerogen lenses and fractures, with examples two resolutions (6.63 μm – top; 0.7 μm – bottom). An analysis of size, shape, fabric, anisotropy, volume of total rock, and kerogen patch orientation is carried out for both, as well as how these parameters relate to one another. Right – Analogue modelling of primary migration in a gelatin system with five layers. The two darker layers have sugar/yeast representing organic content rich layers, while the three lighter layers do not content organic matter.



An origin of brittleness: a thermal point of view

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 cause, which is a positive feedback loop. For conditions where this reinforcement is sufficiently strong, it can lead to a jump to so called avalanches, where the rupture speed jumps to high values, and the material is thermally weakened.

We developed a model coupling mechanics, statistical physics and chemistry based on these elements. We showed that these elementary ingredients reproduce well the mechanical behavior of fracture in acrylic glass (PMMA), as well as the one of peeled tapes (i.e. the rupture of polymeric glue). (Vincent-Dospital et al., 2020a).

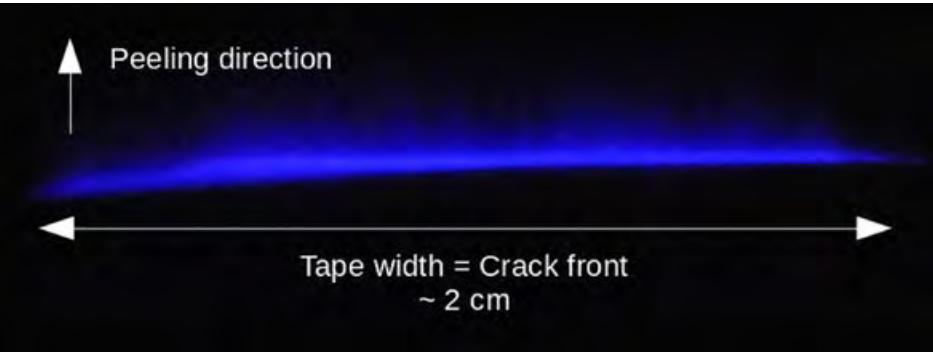
Figure: Blue radiation emission when a tape is peeled at a velocity above the stick-slip threshold, i.e. 15 cm/s for this standard office tape. Picture taken with a standard digital reflex camera, ISO: 25600, shutter speed: 1/2 s, focal length: 60 mm, aperture: f/4. Such fractoluminescence could be the mark of a very hot crack front, locally exceeding 1000 °C, when unrolling the tape. The intensity and spectral characteristics are compatible with blackbody radiation of the material with a thermal profile explained by the thermo-mechanical model (Vincent-Dospital et al. 2020a).

This also explains features such as fractoluminescence during fast rupture: when ordinary tape is peeled sufficiently fast, the velocity of the crack jumps for short periods to large values, higher than the externally imposed velocity, because of this instability – before the crack slows down until the tape is loaded again. This variation in speed is the cause of varying force in the tape, and of the noise emitted when tapes are peeled fast enough. If, on contrary, tape is peeled slowly, the front is in so-called stable creep, and the front speed corresponds to the imposed one: no noise is emitted in this case. Interestingly, during fast peeling with associated instability, the front emits a blue light during the fast stages: this is the so-called fractoluminescence mechanism. Our model explains this phenomenon as being a possible thermal radiation emitted by a nanometric size zone, hotter than 1000 °C, in the vicinity of the crack front. See figure.

This model also renders for a transition between brittle and ductile fracture mode, as observed under the brittle Earth crust, and explains this transition as a critical point (Vincent-Dospital et al., 2020b).

In a case where heating is negligible, we could also explain the distribution of local velocities (Vincent-Dospital et al. 2020c, Cochard et al., 2019) and the distribution of global velocities and jumps (Santucci et al., 2019).

The consequences of such model are numerous : for example, we show how following material creep allows to predict under which load the material will fail in a brittle way (Vincent-Dospital et al. 2020d). We also show that such processes can play a role in biomaterials, heat generation and conduction being compatible with the excitation of proteins transmitters activating the pain information process (2020e).



Production in highlights

Vincent-Dospital, T., Toussaint, R., Santucci, S., Vanel, L., Bonamy, D., Hattali, L., ... & Måløy, K. J. (2020). How heat controls fracture: the thermodynamics of creeping and avalanching cracks. *Soft Matter*, 16(41), 9590–9602.



Vincent-Dospital, T., Toussaint, R., Cochard, A., Måløy, K. J., & Flekkoy, E. G. (2020). Thermal weakening of cracks and brittle-ductile transition of matter: A phase model. *Physical Review Materials*, 4(2), 023604.

Vincent-Dospital, T., Cochard, A., Santucci, S., Måløy, K. J., & Toussaint, R. (2020). Thermally activated intermittent dynamics of creeping crack fronts along disordered interfaces. *arXiv*, preprint arXiv:2010.06865.

Vincent-Dospital, T., Toussaint, R., Cochard, A., Flekkoy, E. G., & Måløy, K. J. (2020). Is breaking through matter a hot matter? A material failure prediction by monitoring creep. *arXiv*, preprint arXiv:2007.04866.

Vincent-Dospital, T., & Toussaint, R. (2020). Thermo-mechanical pain: a hidden role for heat dissipation in biological tissues. *arXiv preprint*, arXiv:2005.04991.



Mechano-Chemical Processes from the Nanoscale to the Scale of Continents

- 1 Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity
- 2 Nanoscale imaging and modelling of mineral-water interface
- 3 Structural and metamorphic transformation processes in the lower continental crust and upper mantle
- 4 History-dependent friction
- 5 BioZement 2.0 – Systems analysis and fundamental control of bacterial processes in the production of bio-concrete for construction purposes

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

The overall strength of granular materials and porous rocks is often associated with processes that take place in fluid-filled contacts between individual solid grains. To recognize these processes and to be able to modify them, we need analytical methods that investigate the relevant interfaces at a nanoscale. In this experimental project, we study the interfaces with the Surface Forces Apparatus (SFA).

SFA measures surface forces acting at nanoscale surface separations between two macroscopic surfaces (a contact radius diameter is approximately 100 µm). An in-situ sensing SFA modification developed at the Vienna University of Technology allows monitoring of the measured forces in real-time, owing to the addition of strain gage-based force-measuring sensors. That expands the applications of the SFA and enables force measurements without bringing the surfaces out of contact.

In the first year of this project, we focused on the very composition of confined solid-solid interfaces filled with electrolytes or organic solutions. We showed that the binding of the soluble organic molecules could be modulated by the addition of inorganic ions, which have a different affinity to both adsorb onto the solid confining walls and to form complexes with the functional groups of the organics. Using the electrochemical SFA (EC-SFA), we further studied the transport of organic and inorganic ions

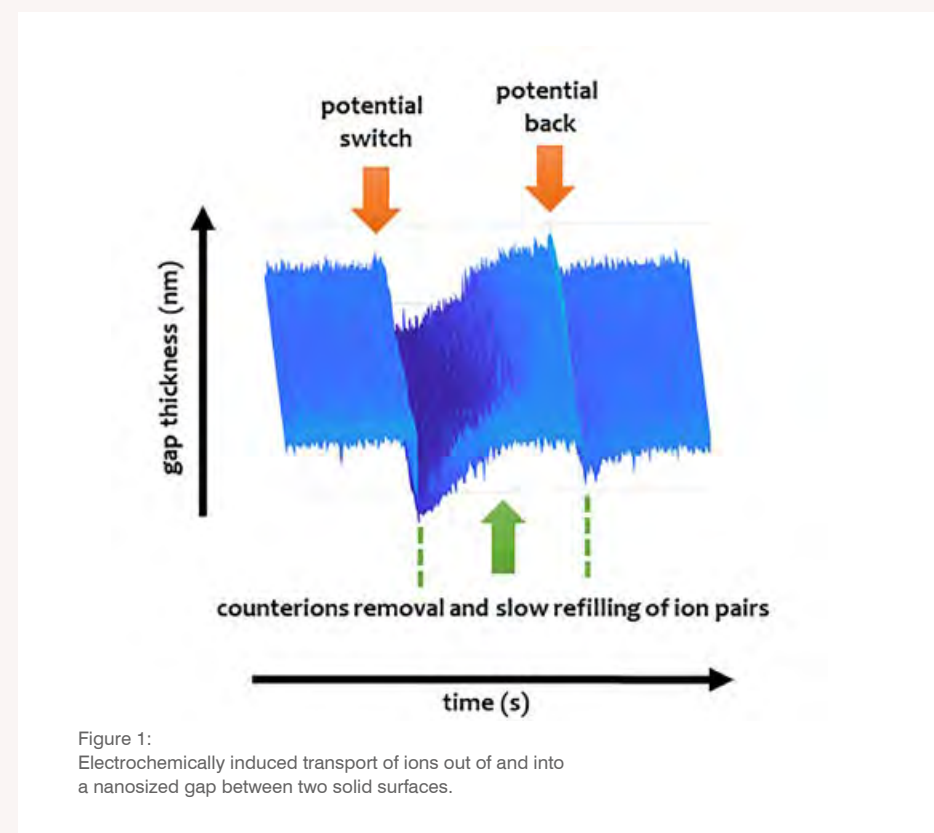


Figure 1:
Electrochemically induced transport of ions out of and into a nanosized gap between two solid surfaces.

into and out of a nano-sized confined gap. With the EC-SFA, we can rapidly change the surface charge of one of the confining surfaces and visualize how the ions are transported. In this work, we observed a

number of interesting metastable charge regulation pathways emerging before the charge equilibrium is achieved in a nano-sized gap between two solid surfaces.

Production in highlights

Dziadkowiec, J., & Røyne, A. (2020). Nanoscale Forces between Basal Mica Surfaces in Dicarboxylic Acid Solutions: Implications for Clay Aggregation in the Presence of Soluble Organic Acids. *Langmuir*, 49, 14978–14990.

Cheng, H.-W., Dziadkowiec, J., Wieser, V., Imre, M., Valtiner, M. Real-time Visualization of Metastable Charge Regulation Pathways in Molecularly Confined Slit Geometries. Under review.

Nanoscale imaging and modelling of mineral-water interface

Fluids control the transport of chemical components to and from the grain surfaces where the reactions occur and the supply rate of these components affects the overall rock transformation rate. The processes between mineral-fluid interfaces that occur at nanoscale can be studied by both experimental approaches and by modelling. Within this topic, our research includes experimental studies of incorporation of toxic elements into carbonate minerals and molecular dynamics simulations of the behavior of a confined water film between mineral surfaces.

Molecular dynamics simulations provide a deeper understanding of atom-scale processes that are not visible in experiments. By studying the behavior of a confined water film between two mineral surfaces, we provide insight about whether reactions,

or mineral transformation, requiring water can proceed or not under large stresses. Our simulations focus on a confined water film between two periclase or brucite surfaces under conditions for reaction-induced fracturing. The results show that when the pressure reaches a few tens of MPa, the water film collapses to one or two water layers. Figure 1 show the evolution of the thickness a water film until 3 ns. When the pressure is 15 MPa the water film remains stable, while at a pressure of 81 MPa the water film quickly collapses to one water layer.

Experimental methods are used to study the incorporation of toxic elements into a mineral, which have proven to be an effective technique to remove the toxic elements from aqueous solutions. Dissolution of carbonate minerals and precip-

itation of nanoparticles occurs easily on the mineral surfaces. This coupled dissolution-precipitation mechanism occurs in the boundary layer, a highly saturated layer, at the mineral-fluid interface. The formation of nanoparticles might contain contaminating elements (Figure 2a), immobilizing it from aqueous solution. Another way to immobilize the toxic elements is to let the host mineral grow in the presence of this element. The toxic oxyanions can then be incorporated into the crystal structure, observed by irregularities from the normal growth (Figure 2b). To study the interaction over time, we use atomic force microscopy and stirred flow-through reactors, and the analyze of the final products we use Raman spectroscopy, SEM and ICP-MS. These experiments are performed in collaboration with the Universities of Münster, Utrecht and Grenoble Alpes.

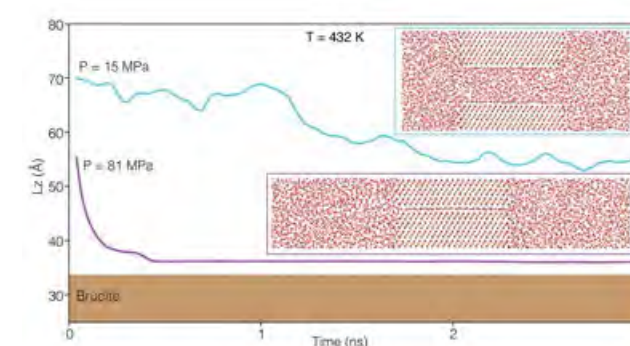


Figure 1: The lines represent the thickness (Lz) of the simulation domain in the z-direction as a function of time at two different pressures (15 and 81 MPa). The snapshots visualize the thickness of the water film between two brucite blocks at 3 ns.

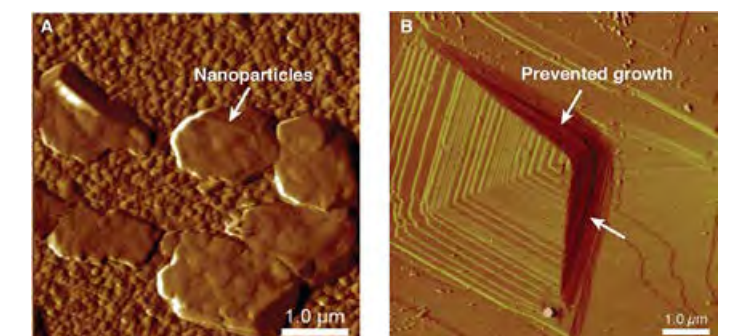


Figure 2: The effect of chromium-rich fluids on a calcite surface. A) Formation of nanoparticles. B) Growth of calcite hillocks where two of the sides are prevented from normal growth due to incorporation of chromate ions.

Production in highlights

Guren, M.G., Putnis, C.V., Montes-Hernandez, G., King, H., & Renard, F. (2020). Direct imaging of coupled dissolution-precipitation and growth processes on calcite exposed to chromium-rich fluids. *Chemical Geology*, 552, 119770.

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 for reaction-induced fracturing. *Geochimica et Cosmochimica Acta*, 294, 13–27.

Funding
European Research Council, UK Natural Environment Research Council (project DIME)

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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 absense 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).

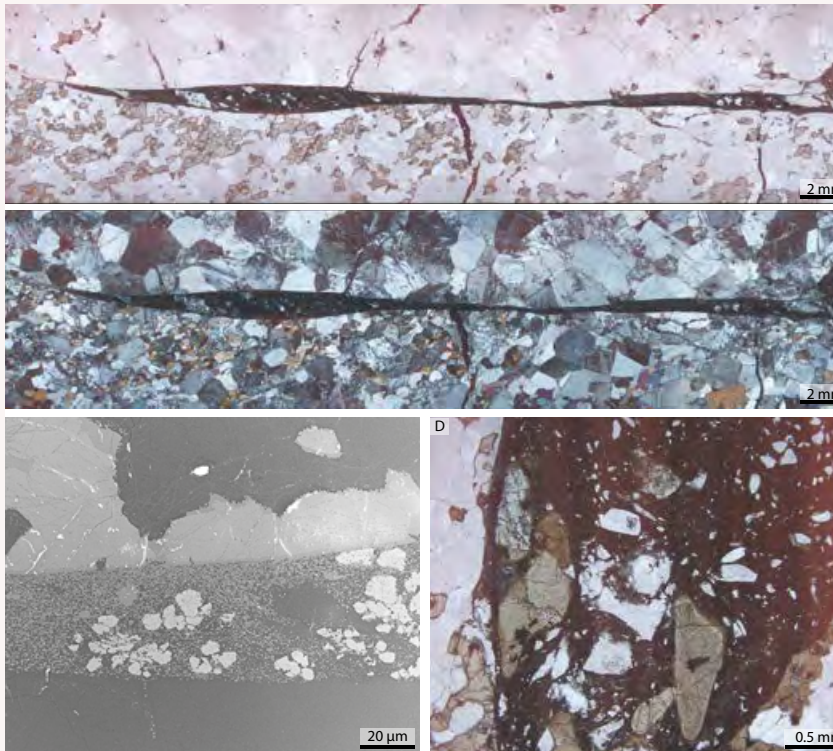
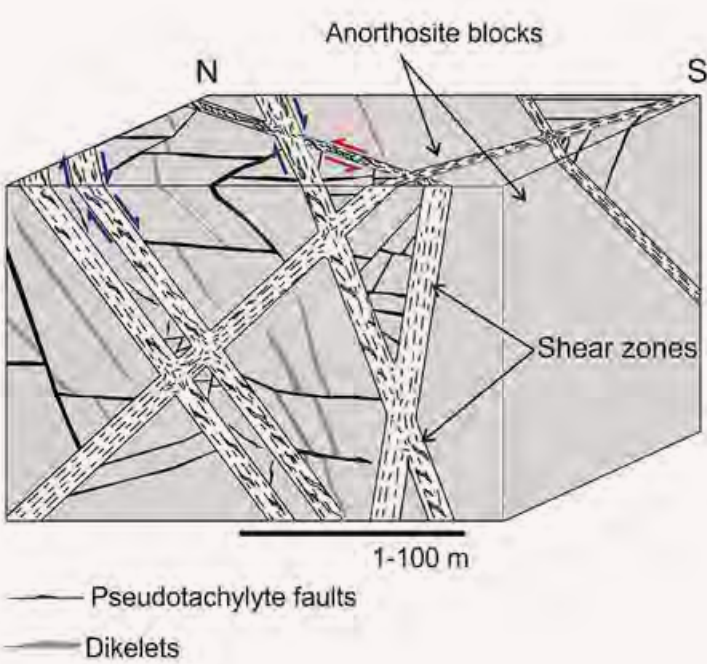


Figure 1: Dry Pseudotachylyte in amphibole-bearing paragneiss. Optical micrographs in plane polarized (a) and cross polarized (b) light showing a pseudotachylyte that juxtaposes pyroxene and amphibole-rich (bottom) and poor (top) host rock. There is no alteration zone around the pseudotachylyte. c) Backscatter 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).

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 postseismic 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 requires 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 (over-pressure) and hence reduce the frictional strength of the earthquake faults.

In a related 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 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 highlights

Campbell, L. R., Menegon, L., Fagereng, Å., & Pennacchioni, G. (2020). Earthquake nucleation in the lower crust by local stress amplification. *Nature communications*, 11(1), 1–9.

Menegon, L., Campbell, L.R., Mancktelow, N., Camacho, A., Wex, S., 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). Invited contribution to *Philosophical Transactions of The Royal Society A*, in press.

Dunkel, K.G., Zhong, X., Arnestad, P.F., Valen, L.V., & Jamtveit, B. (2020) Highly stressed lower crust: Evidence from dry pseudotachylytes in granulites, Lofoten Archipelago, Norway. *Geology*, 49.

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.

Incel, S., Renner, J., & Jamtveit, B. (2020) Fracturing wall rock damage and the onset of retrograde metamorphism in plagioclase rich rocks – Linking laboratory data to natural observations. *Geochemistry, Geophysics, Geosystems* 21.

Funding The Research Council of Norway	Participants Kjetil Thøgersen¹, Even Nordhagen¹, Henrik Andersen Sveinsson¹, Anders Malthé-Sørenssen¹, Evangelos Korkolis¹, Francois Renard¹, Julian Scheibert²	Affiliation ¹⁾ The Njord Center, University of Oslo, Oslo, Norway ²⁾ CNRS, Laboratoire de Tribologie et Dynamique des Systèmes, Ecole Centrale de Lyon, France	Funding The Research Council of Norway, Centre for Digital Life Norway	Participants Anja Røyne¹, Mohammad Amin Razbani¹, Alexander Wentzel², Emil Karlsen³, Eivind Almaas³, Jennifer Zehner³, Pawel Sikorski³, Harald Throne-Holst⁴, Anders Myhr⁵, Espen Jøttestuen⁶, Frida Røyne⁷, Simone Balzer Le², Dino van Disself²	Affiliation ¹⁾ The Njord Centre, University of Oslo, Norway ²⁾ SINTEF, Oslo, Norway ³⁾ NTNU, Trondheim, Norway ⁴⁾ Oslo Metropolitan University, Oslo, Norway ⁵⁾ Pure Logic, Lysaker, Norway ⁶⁾ NORCE, Stavanger, Norway ⁷⁾ RISE, Göteborg, Sweden
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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 where introduced by Amon-tons 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 pro-ject 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-de-pendent friction, test and apply this theory on atomic-, meso- and macroscopic scales and apply it to key problems in glaciology and geoscience.

In 2020, we have extended a one-dimen-sional model to address slip-pulse dynam-ics, which opens for new insights into how slip pulses affect friction and earthquake

processes. We have also extended a mo-lecular dynamics potential for the interac-tion of water and silicates and developed a machine-learning based approach to determine the model parameters under various geological conditions. The model is currently used to determine good pa-rameter values to address hydro-fracture processes under realistic geological con-ditions. Simultaneously, we have built a new high performance computing clus-ter with 1100 cores to effectively model water-silicate systems over nano-second to micro-second time frames. We expect these models to provide new insights into fracture and friction processes in dry and wet silicates in 2021.

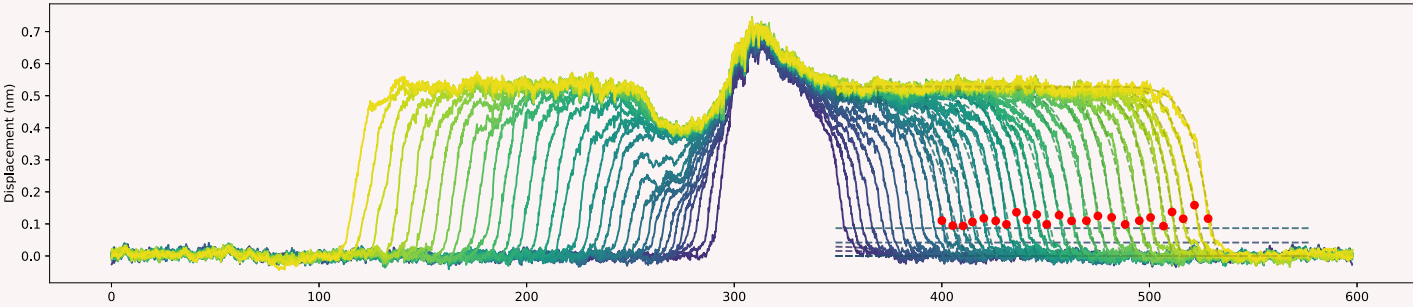


Figure: Illustration of a slip pulse in a molecular dynamics simulation shear rupture in silicate (SiO2). The top figure illustrates the displacement field and the bottom figures illustrates the propagation of the slip pulse by snap-shots of the local displacement over 4 picoseconds (Henrik Anderson Sveinsson).

Production in highlights

Thøgersen, K., Aharonov, E., Barras, F., & Renard, F. (2020). A minimal model for the onset of slip pulses in frictional rupture. *arXiv*, preprint *arXiv:2012.11199*.

Johansson, A., Sveinsson, H., Thøgersen, K., Hafreager, A., Aharonov, E., & Malthé-Sørenssen, A. (2020). Molecular Dynamics Simulations of Creep in Silica-Water Systems. *Bulletin of the American Physical Society*, 65.

Thøgersen, K., Andersen Sveinsson, H., Scheibert, J., Renard, F., & Malthé-Sørenssen, A. (2019). The moment duration scaling relation for slow rupture arises from transient rupture speeds. *Geophysical Research Letters*, 46(22), 12805–12814.

Production in highlights

Zehner, J.S., Røyne, A., Wentzel, A. & Sikorski, P. (2020) Calcium carbonate precipitation: An experimental toolbox for in situ and real-time investigation of microscale pH evolution. *RCS Advances* 10(35):20485–20493

Razbani, M.A., Zehner, J.S., Jøttestuen, E., Røyne, A., Sikorski, P., & Malthé-Sørenssen, A. (2019) A pore-scale model of microbially induced calcium carbonate precipitation. *InterPore2019*, 6–10.10.2019.

Røyne A, Phua YJ, Balzer Le S, Eikjeland IG, Josefsen KD, Markussen S, et al. (2019) Towards a low CO₂ emission building material employing bacterial metabolism (1/2): The bacterial system and prototype production. *PLoS ONE* 14 (4): e0212990. <https://doi.org/10.1371/journal.pone.0212990>

Myhr A, Røyne F, Brandtsegg AS, Bjørkseter C, Throne-Holst H, Borch A, et al. (2019) Towards a low CO₂ emission building material employing bacterial metabolism (2/2): Prospects for global warming potential reduction in the concrete industry. *PLoS ONE* 14(4): e0208643. <https://doi.org/10.1371/journal.pone.0208643>

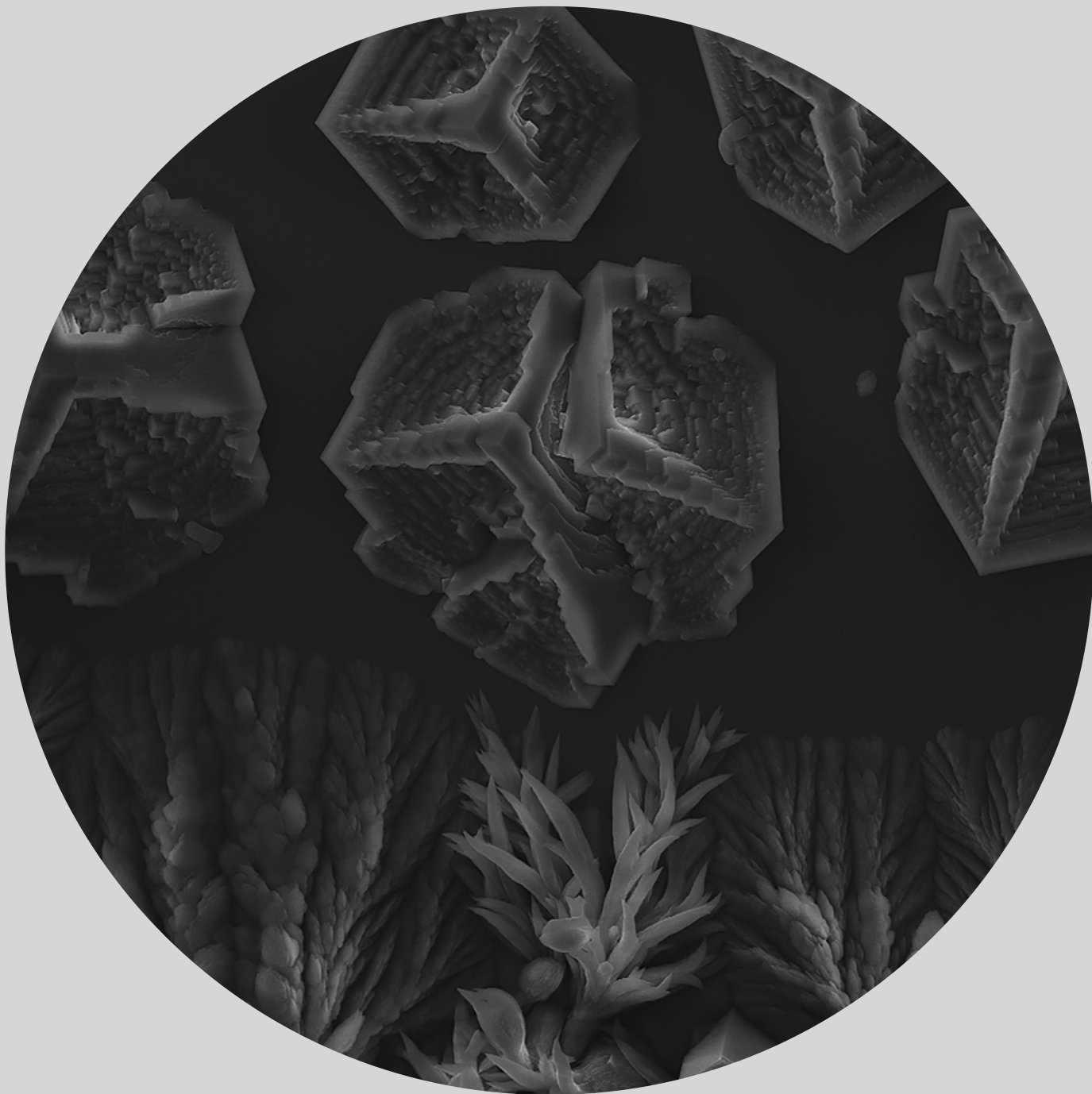
Karlsen, E., Schulz, C., & Almaas, E. (2018). Automated generation of genome-scale metabolic draft reconstructions based on KEGG. *BMC bioinformatics*, 19(1), 467.

By volume, concrete is the most important material in the world – more than twice as much concrete is produced every year as every other material combined. At the same time, the production of cement, which is the most important component of concrete, accounts for somewhere between 5 and 10 % of global, anthropogenic CO₂ emissions. The goal of BioZEment 2.0 is to develop the fundamental knowledge that is required for being able to produce concrete materials based on biotechnology. Biotechnology can allow us to produce materials with considerably lower energy use and CO₂ emissions than what we make today. In order to reach this goal, we have established a multidisciplinary consortium with expertise in microbiology, life cycle assessment, techno-economic analysis and research on consumers. Our results confirm that this type of material has the potential to make a significant difference in Norwegian and global CO₂-emissions, and that the attitudes of consumers in general are positive. We have established experimental and numerical models for understanding the biogeochemical couplings in the material on the microscale, coupled to a genetic



based metabolic model for the bacteria. We have also developed a production system for prototypes, that will be used to test material properties on a larger scale.

Figure: Prototype brick produced by bacteria at SINTEF (photo: Alexander Wentzel).



04

Appendices



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PhD projects

Candidate	Title/Topic	Supervisor(s)
Aspaas, Andreas	<i>Starting January 2021</i>	François Renard and Bernd Etzelmüller
Baldelli, Beatrice	<i>Gravity-stabilized flow on self-affine surfaces</i>	Eirik Grude Flekkøy, Knut Jørgen Måløy, Gaute Linga
Bouchayer, Coline	<i>Modelling transient velocity variations in glaciers</i>	Thomas V. Schuler, François Renard, Kjetil Thøgersen, Andreas Kääb
Brodin, Joachim Falck	<i>Experimental studies on flow in porous media in 3D</i>	Knut Jørgen Måløy, Eirik Grude Flekkøy, Marcel Moura
Guren, Marthe Grønlie	<i>Nanoscale imaging and modelling of mineral surfaces during mechano-chemical transformations</i>	François Renard, Anja Røyne, Anders Malthe-Sørenssen
Johnson, James Ronald	<i>Microfractures in organic shales and their transport properties</i>	François Renard, Nazmul Mondol
Kandula, Neelima	<i>X-ray micro tomographic studies on the precursors to failure in rocks at conditions relevant for earthquake nucleation</i>	François Renard, Dag Kristian Dysthe, Jerome Weiss
Michalchuk, Stephen	<i>Microstructural Analysis of Brittle Structures in Ductile Environments</i>	Luca Menegon, François Renard, Kristina Dunkel
Nordhagen, Even Marius	<i>History-dependent effects in atomic-scale friction</i>	Anders Malthe-Sørenssen, Henrik Sveinsson, Kjetil Thøgersen
Olsen, Kristian Stølevik	<i>Statistical physics for two-dimensional complex flow</i>	Knut Jørgen Måløy, Eirik Grude Flekkøy, Marcl Moura
Rabbøl, Ole	<i>Thermo-mechanical processes at the interface between igneous intrusions and organic-rich host rocks: Fieldwork, modelling and implications for resource exploration</i>	Olivier Galland, Karen Mair
Razbani, Mohammad Amid	<i>Numerical modelling of mineral-microbe interactions</i>	Anders Malthe-Sørenssen, Anja Røyne, Espen Jettestuen
Rønning, Jonas	<i>Turbulence in Bose-Einstein condensates and active matter</i>	Luiza Angheluta, Eirik Grude Flekkøy
Shafabakhsh, Paiman	<i>Starting January 2021</i>	François Renard, Gaute Linga, Tanguy Le Borgne
Skogvoll, Vidar	<i>Multiple scales modelling of crystal plasticity</i>	Luiza Angheluta, François Renard, Luca Menegon
Thorens, Louison	<i>Tunable interactions inside deformable porous media</i>	Knut Jørgen Måløy, Mickaël Bourgoin, Eirik Grude Flekkøy, Stéphane Santucci

Finished PhDs in 2020

Candidate	Title/Topic	Supervisor(s)
Aupart, Claire Olga Maryse	<i>Mechanochemical feedbacks during hydration of ultramafic rocks</i>	Bjørn Jamtveit, Håkon Austrheim, Anders Malthe-Sørenssen

Postdoc projects

Fellow	Title/Topic	Supervisor(s)
Barras, Fabian	<i>Modelling the interplay between earthquake rupture and fluid migration in the Earth's crust</i>	François Renard, Bjørn Jamtveit
Campbell, James Matthew	<i>Porous Media Physics</i>	Eirik Grude Flekkøy, Knut Jørgen Måløy
Chauve, Thomas	<i>Numerical modeling of primary migration in shale using Discrete Elements Method (DEM)</i>	Francois Renard
Cordonnier, Benoit	<i>Neutron imaging of pollutant flow within geological samples</i>	Francois Renard
Demurtas, Matteo	<i>Granular flow and mineral anistropy</i>	Karen Mair
Dospital, Tom-Vincent	<i>Starting January 2021</i>	Knut Jørgen Måløy
Dunkel, Kristina	<i>Interplay of earthquakes and metamorphism (with a focus on wall rock damage caused by lower crustal seismicity)</i>	Bjørn Jamtveit
Dziadkowiec, Joanna	<i>Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity</i>	Anja Røyne, Dag Kristian Dysthe, Markus Valtiner
Eriksen, Fredrik Kvalheim	<i>Deformation and flow in porous media</i>	Knut Jørgen Måløy
Guldstrand, Frank Bo Buster	<i>Laboratory modelling of the intrusion and emplacement of viscous fluids in cohesive mohr-coulomb hosts and the associated deformation applied to magmatic processes</i>	Olivier Galland
Kobchenko, Maya	<i>Primary migration in shales</i>	Francois Renard
Korkolis, Evangelos	<i>History-dependent friction</i>	Anders Malthe-Sørenssen, François Renard
Linga, Gaute	<i>Numerical modelling of the complexitiy of fluid flow in deforming porous media</i>	Francois Renard, Eirik Grude Flekkøy
Moura, Marcel	<i>Intermittent burst dynamics on porous media two-phase flow</i>	Eirik Grude Flekkøy, Knut Jørgen Måløy
Petley-Ragan, Arianne	<i>Earthquakes and Metamorphism in the Bergen Arcs, Western Norway</i>	Bjørn Jamtveit
Sveinsson, Henrik	<i>Polycrystals, fracture and plasticity. Mineral-water-deformation phenomena</i>	François Renard, Luiza Angheluta-Bauer
Thøgersen, Kjetil	<i>Friction controls on glacier motion</i>	Thomas Vikhamar Schuler, Anders Malthe-Sørenssen, Andreas Kääb

Guest talks, workshops and seminars

January 17 th	Sverre Holm, University of Oslo. "Waves with Power-Law Attenuation"	June 11 th –12 th	EarthFlows meeting 2020. "Complexitiy in Solid Earth and Geophysical Flows". Organizer: Francois Renard.
January 27 th –30 th	PoreLab Conference in Courmayeur, Italy. Organizer: Knut Jørgen Måløy	June 12 th	Håkon Fossen, University of Bergen. "Deformation bands: strain localization features in granular media"
February 7 th	Bjarne Frost Nielsen, University of Copenhagen. "How babies are made"	June 12 th	Andrew Putnis (University of Münster), Jo Moore, Håkon Austrheim, Andreas Beinlich. "Metamorphic differentiation and the evolution of a shear zone"
February 28 th	Wojciech Miloch, University of Oslo. "4DSpace group"	June 12 th	David Kammer, ETH Zürich. "Modelling arrest of large-scale laboratory earthquakes"
March 11 th	Thomas Combriat, University of Oslo. "The Song of Bubbles".	July 13 th – November 16 th	Porous Media Tea Time Talks. Biweekly event with talks from early career researchers. 10 events from July 2020 to November 2020. 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)
April 20 th –22 nd	SFF Geoextremes Workshop. Organizer: Francois Renard	September 2 nd	Magmatic Flows Workshop. Organizer: Olivier Galland
May 2 nd	Heidi Morstang, University of Plymouth. "The Documentary – Pseudotachylyte"	December 3 rd	EarthFlows December Meeting. Organizer: Francois Renard
June 11 th	Dan Henningson, KTH Stockholm. "Large scale numerical experiments of pitching wings and the role of laminar-turbulent transition"	December 3 rd	Anne Mangeney, Institut de Physique du Globe de Paris. "Seismic waves: a unique source of information on glaciers and landslides"
June 11 th	Ira Didenkulova, Tallinn University. "Extreme wave run-ups on a beach"	December 3 rd	Emile Okal, Northwestern University. "Tsunamis as coupling agents of eclectic Earth media"
June 11 th	Inga Berre, University of Bergen. "Physics-based modelling of injection-induced coupled processes and fracture deformation"		
June 11 th	Thomas Vikhamar Schuler, University of Oslo. "Mammamia, Corona and trajectories of future glacier evolution"		
June 11 th	Christine Putnis, University of Münster. "Mineral growth via non-classical pathways: observations using nanoscale imaging"		
June 11 th	Catherine Noiriel, University of Toulouse. "Exploring mineral reactivity in 4D"		

Production list 2020

Publications

- Aleksans, J., Koehn, D., **Toussaint, R.**, & Daniel, G. (2020). *Simulating Hydraulic Fracturing: Failure in soft versus hard rocks*. Pure and Applied Geophysics, 177(6), 2771–2789.
- Ayaz, M.**, **Toussaint, R.**, Schäfer, G., & **Måløy, K. J.** (2020). Gravitational and Finite-Size Effects On Pressure Saturation Curves During Drainage. Water Resources Research, 56(10), e2019WR026279.
- Barras, F.**, Aldam, M., Roch, T., Brener, E. A., Bouchbinder, E., & Molinari, J. F. (2020). The emergence of crack-like behavior of frictional rupture: Edge singularity and energy balance. Earth and Planetary Science Letters, 531, 115978.
- Ben-Zeev, S., Aharonov, E., **Toussaint, R.**, Parez, S., & Goren, L. (2020). Compaction front and pore fluid pressurization in horizontally shaken drained granular layers. Physical Review Fluids, 5(5), 054301.
- Bousmaha, M., Bensoula, M., & **Toussaint, R.** (2020). Mechanical instability of saturated soils sampled in the Oran coast, Algeria. Journal of Materials and Engineering Structures, 7(1), 5–14.
- Campbell, L. R., **Menegon, L.**, Fagereng, Å., & Pennacchioni, G. (2020). Earthquake nucleation in the lower crust by local stress amplification. Nature communications, 11(1), 1–9.
- Cao, P., Ning, F., Wu, J., Cao, B., Li, T., **Sveinsson, H. A.**, ... & Hyodo, M. (2020). Mechanical Response of Nanocrystalline Ice-Contained Methane Hydrates: Key Role of Water Ice. ACS Applied Materials & Interfaces, 12(12), 14016–14028.
- Cao, Y., Du, J., Park, M., Jung, S., Park, Y., Kim, D., ... & **Austrheim, H.** (2020). Metastability and Nondislocation-Based Deformation Mechanisms of the Flem Eclogite in the Western Gneiss Region, Norway. Journal of Geophysical Research: Solid Earth, 125(5), e2020JB019375.
- Ceccato, A., **Menegon, L.**, Warren, C. J., & Halton, A. M. (2020). Structural and metamorphic inheritance controls strain partitioning during orogenic shortening (Kalak Nappe Complex, Norwegian Caledonides). Journal of Structural Geology, 104057.
- Chauve, T.**, Scholtes, L., Donzé, F. V., Haque Mondol, N., & **Renard, F.** (2020). Layering in shales controls microfracturing at the onset of primary migration in source rocks. Journal of Geophysical Research: Solid Earth, 125(5), e2020JB019444.
- Chavez Panduro, E. A., **Cordonnier, B.**, Gawel, K., Børve, I., Iyer, J., Carroll, S. A., Walsh, S. D. et al (2020). Real time 3D observations of Portland cement carbonation at CO₂ storage conditions. Environmental Science & Technology, 54, 8323–8332, doi:10.1021/acs.est.0c00578.
- Di Chiara, A., Morris, A., Anderson, M. W., **Menegon, L.**, & Tremblay, A. (2020). Magnetic anisotropy reveals Acadian transpressional fabrics in an Appalachian ophiolite (Thetford Mines, Canada). Geophysical Journal International, 222(2), 1034–1045.
- Dumazer, G.**, Sandnes, B., **Måløy, K. J.**, & **Flekkøy, E. G.** (2020). Capillary bulldozing of sedimented granular material confined in a millifluidic tube. Physical Review Fluids, 5(3), 034309.
- Dunkel, K. G.**, **Zhong, X.**, **Arnestad, P. F.**, **Valen, L. V.** & **Jamtveit, B.** (2020). High transient stress in the lower crust: Evidence from dry pseudotachylytes in granulites, Lofoten Archipelago, northern Norway. Geology, v. 49, <https://doi.org/10.1130/G48002.1>
- Dziadkowiec, J.**, & **Royne, A.** (2020). Nanoscale Forces between Basal Mica Surfaces in Dicarboxylic Acid Solutions: Implications for Clay Aggregation in the Presence of Soluble Organic Acids. Langmuir, 49, 14978–14990.
- Fekak, F., **Barras, F.**, Dubois, A., Spielmann, D., Bonamy, D., Geubelle, P. H., & Molinari, J. F. (2020). Crack front waves: A 3D dynamic response to a local perturbation of tensile and shear cracks. Journal of the Mechanics and Physics of Solids, 135, 103806.
- Fondriest, M., Balsamo, F., Bistacchi, A., Clemenzi, L., **Demurtas, M.**, Storti, F., & Di Toro, G. (2020). Structural complexity and mechanics of a shallow crustal seismogenic source (Vado di Corno Fault Zone, Italy). Journal of Geophysical Research: Solid Earth, 125(9), e2019JB018926.
- Giuntoli, F., Brovarone, A. V., & **Menegon, L.** (2020). Feedback between high-pressure genesis of abiotic methane and strain localization in subducted carbonate rocks. Scientific reports, 10(1), 1–15.
- Giuntoli, F., **Menegon, L.**, Warren, C. J., Darling, J., & Anderson, M. W. (2020). Protracted Shearing at Midcrustal Conditions During Large-Scale Thrusting in the Scandinavian Caledonides. Tectonics, 39(9), e2020TC006267.
- Gloersen, Ø. N.**, Gilgien, M., **Dysthe, D. K.**, **Malthe-Sørenssen, A.**, & Losnegard, T. J. (2020). Oxygen demand, uptake, and deficits in elite cross-country skiers during a 15-km race. Medicine & Science in Sports & Exercise, 52, 983–992.
- Graziani, R., Montomoli, C., Iaccarino, S., **Menegon, L.**, Nania, L., & Carosi, R. (2020). Structural setting of a transpressive shear zone: insights from geological mapping, quartz petrofabric and kinematic vorticity analysis in NE Sardinia (Italy). Geological Magazine, 1–19.
- Guren, M. G.**, Putnis, C. V., Montes-Hernandez, G., King, H. E., & Renard, F. (2020). Direct imaging of coupled dissolution-precipitation and growth processes on calcite exposed to chromium-rich fluids. Chemical Geology, 552, 119770.
- 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 for reaction-induced fracturing. Geochimica et Cosmochimica Acta, 294, 13–27.
- Gurfinkel, A. J., & **Rikvold, P. A.** (2020). Absorbing random walks interpolating between centrality measures on complex networks. Physical Review E, 101(1), 012302.
- Gussone, N., **Austrheim, H.**, Westhues, A., & Mezger, K. (2020). Origin of rodingite forming fluids constrained by calcium and strontium isotope ratios in the Leka ophiolite complex. Chemical Geology, 119598.
- Heap, M. J., Baud, P., **McBeck, J. A.**, **Renard, F.**, Carbillet, L., & Hall, S. A. (2020). Imaging strain localisation in porous andesite using digital volume correlation. Journal of Volcanology and Geothermal Research, 404, 107038.
- Incel, S.**, Renner, J., & **Jamtveit, B.** (2020). Evolution of brittle structures in plagioclase-rich rocks at high-pressure and high-temperature conditions—Linking laboratory results to field observations. Geochemistry, Geophysics, Geosystems, 21(8), e2020GC009028.
- Jouniaux L., Allègre V., **Toussaint R.**, & Zyserman F. (2020). Saturation dependence of the streaming potential coefficient. Book chapter 5 In Seismoelectric Exploration: Theory, Experiments, and Applications. Edited by Grobde N., Revil A., Zhu Z. & Slob E., American Geophysical Union <https://doi.org/10.1002/9781119127383.ch5>
- Jung, S., Jung, H., & **Austrheim, H.** (2020). Microstructural evolution of amphibole peridotites in Åheim, Norway, and the implications for seismic anisotropy in the mantle wedge. Minerals, 10(4), 345.
- Kartal, M., Xia, F., Ralph, D.E., Rickard, W., **Renard, F.**, Li W. (2020). Enhancing chalcopyrite leaching by tetrachloroethylene-assisted removal of sulphur passivation and the mechanism of jarosite formation. Hydrometallurgy, 191, 105192, doi: 10.1016/j.hydromet.2019.105192.
- Katayama, I., Abe, N., Hatakeyama, K., Akamatsu, Y., Okazaki, K., **Ulven, O. I.**, **Cordonnier, B.**, ... & Godard, M. (2020). Permeability Profiles Across the Crust-Mantle Sections in the Oman Drilling Project Inferred From Dry and Wet Resistivity Data. Journal of Geophysical Research: Solid Earth, 125(8), e2019JB018698.
- Kirilova, M., Toy, V., Sauer, K., **Renard, F.**, Gessner, K., Wirth, R., & Xiao, X. (2020). Micro- and nano-porosity of the active Alpine Fault zone, New Zealand. Solid Earth, 11, 2425–2438.
- Koehn, D., Piazzolo, S., Sachau, T., & **Toussaint, R.** (2020). Fracturing and Porosity Channeling in Fluid Overpressure Zones in the Shallow Earth’s Crust. Geofluids, 2020, 7621759.
- Linga, G.**, Bolet, A., & **Mathiesen, J.** (2020). Transient electrohydrodynamic flow with concentration-dependent fluid properties: Modelling and energy-stable numerical schemes. Journal of Computational Physics, 109430.
- Luu, J. X., **Flekkøy, E. G.**, & **Toussaint, R.** (2020). 'Oumuamua as a Cometary Fractal Aggregate: The “Dust Bunny” Model. The Astrophysical Journal Letters, 900(2), L22.
- Malvoisin, B., **Austrheim, H.**, Hetényi, G., Reynes, J., Hermann, J., Baumgartner, L. P., & Podladchikov, Y. Y. (2020). Sustainable densification of the deep crust. Geology, 48 (7): 673–677.
- Marchesini, B., Garofalo, P. S., **Menegon, L.**, Mattila, J., & Viola, G. (2019). Fluid-mediated, brittle-ductile deformation at seismogenic depth-Part 1: Fluid record and deformation history of fault veins in a nuclear waste repository (Olkiluoto Island, Finland). Solid Earth, 10(3), 809–838.
- Mattsson, T., Burchardt, S., **Mair, K.**, & Place, J. (2020). Host-rock deformation during the emplacement of the Mourne Mountains granite pluton: Insights from the regional fracture pattern. Geosphere, 16(1), 182–209.
- McBeck, J. A.**, Aiken, J. M., **Mathiesen, J.**, Ben-Zion, Y., & **Renard, F.** (2020) Deformation precursors to catastrophic failure in rocks. Geophysical Research Letters, e2020GL090255.
- McBeck, J., Aiken, J. M., Ben-Zion, Y., & **Renard, F.** (2020). Predicting the proximity to macroscopic failure using local strain populations from dynamic in situ X-ray tomography triaxial compression experiments on rocks. Earth and Planetary Science Letters, 543, 116344.
- McBeck, J.**, Ben-Zion, Y., & **Renard, F.** (2020). The mixology of precursor strain partitioning approaching brittle failure in rocks. Geophysical Journal International, 221(3), 1856–1872.
- McBeck, J.**, Cooke, M., & Fattaruso, L. (2020). Predicting the propagation and interaction of frontal accretionary thrust faults with work optimization. Tectonophysics, 228461.
- McBeck, J.**, Cooke, M., & **Renard, F.** (2020). How the energy budget scales from the laboratory to the crust in accretionary wedges. Earth and Planetary Science Letters, 541, 116276.
- Montes-Hernandez, G., & **Renard, F.** (2020). Nucleation of Brushite and Hydroxyapatite from Amorphous Calcium Phosphate Phases Revealed by Dynamic In Situ Raman Spectroscopy. The Journal of Physical Chemistry C, 124(28), 15302–15311.
- Montes-Hernandez, G., Bah, M., & **Renard, F.** (2020). Mechanism of formation of engineered magnesite: A useful mineral to mitigate CO₂ industrial emissions. Journal of CO₂ Utilization, 35, 272–276.
- Montes-Hernandez, G., **Renard, F.**, Auzende, A. L., & Findling, N. (2020). Amorphous Calcium-Magnesium Carbonate (ACMC) Accelerates Dolomitization at Room Temperature under Abiotic Conditions. Crystal Growth & Design, 20(3), 1434–1441.
- Moore, J., Beinlich, A., Piazzolo, S., **Austrheim, H.**, & Putnis, A. (2020). Metamorphic Differentiation via Enhanced Dissolution along High Permeability Zones. Journal of Petrology, ega096.
- Moore, J., Beinlich, A., Porter, J. K., Talavera, C., Berndt, J., Piazzolo, S., **Austrheim, H.**, & Putnis, A. (2020). Microstructurally controlled trace element (Zr, U-Pb) concentrations in metamorphic rutile: An example from the amphibolites of the Bergen Arcs. Journal of Metamorphic Geology, 38(1), 103–127.
- Moura, M.**, **Måløy, K. J.**, **Flekkøy, E. G.**, & **Toussaint, R.** (2020). Intermittent dynamics of slow drainage experiments in porous media: characterization under different boundary conditions. Frontiers in Physics, 7, 217.
- Nielsen, B. F., **Linga, G.**, Christensen, A., & **Mathiesen, J.** (2020). Substrate curvature governs texture orientation in thin films of smectic block copolymers. Soft Matter, 16(14), 3395–3406.
- Olsen, K. S.**, & **Campbell, J. M.** (2020). Diffusion entropy and the path dimension of frictional finger patterns. Frontiers in Physics, 8, 83.
- Olsen, K. S.**, **Angheluta, L.**, & **Flekkøy, E. G.** (2020). Active particles moving through disordered landscapes. Soft Matter.
- Olsen, K. S.**, **Angheluta, L.**, & **Flekkøy, E. G.** (2020). The escape problem for active particles confined to a disc. Physical Review Research 2 (4), 043314
- Papa, S., Pennacchioni, G., **Menegon, L.**, & Thielmann, M. (2020). High-stress creep preceding coseismic rupturing in amphibolite-facies ultramylonites. Earth and Planetary Science Letters, 541, 116260.
- Passelègue, F. X., Almakari, M., Dublanchet, P., **Barras, F.**, Fortin, J., & Violay, M. (2020). Initial effective stress controls the nature of earthquakes. Nature communications, 11(1), 1–8.
- 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.

57. Pierdominici, S., Millett, J. M., Kück, J. K., Thomas, D., Jerram, D. A., Planke, S., **Galland, O.** et al (2020). Stress Field Interactions Between Overlapping Shield Volcanoes: Borehole Breakout Evidence From the Island of Hawai'i, USA. *Journal of Geophysical Research: Solid Earth*, 125(8), e2020JB019768.
58. Poppe, S., **Galland, O.**, de Winter, N. J., Goderis, S., Claeys, P., Debaille, V., ... & Kervyn, M. (2020). Structural and geochemical interactions between magma and sedimentary host rock: the Hovedøya case, Oslo Rift, Norway. *Geochemistry, Geophysics, Geosystems*, 21(3), e2019GC008685.
59. Prando, F., **Menegon, L.**, Anderson, M., Marchesini, B., Mattila, J., & Viola, G. (2020). Fluid-mediated, brittle-ductile deformation at seismogenic depth—Part 2: Stress history and fluid pressure variations in a shear zone in a nuclear waste repository (Olkiluoto Island, Finland). *Solid Earth*, 11(2), 489–511.
60. **Rabbel, O., Mair, K., Galland, O.,** Grünher, C., & Meier, T. (2020). Numerical modeling of fracture network evolution in organic-rich shale with rapid internal fluid generation. *Journal of Geophysical Research: Solid Earth*, 125(7), e2020JB019445.
61. **Renard, F., Kandula, N., McBeck, J., & Cordonnier, B.** (2020). Creep Burst Coincident With Faulting in Marble Observed in 4-D Synchrotron X-Ray Imaging Triaxial Compression Experiments. *Journal of Geophysical Research: Solid Earth*, 125(9), e2020JB020354.
62. **Renard, F., McBeck, J., & Cordonnier, B.** (2020). Competition between slow slip and damage on and off faults revealed in 4D synchrotron imaging experiments. *Tectonophysics*, 782–783, 228437, <https://doi.org/10.1016/j.tecto.2020.228437>.
63. Rezakhani, R., **Barras, F.**, Brun, M., & Molinari, J. F. (2020). Finite element modeling of dynamic frictional rupture with rate and state friction. *Journal of the Mechanics and Physics of Solids*, 103967.
64. Roberts, A. J., Druckenmiller, P. S., **Cordonnier, B.**, Delsett, L. L., & Hurum, J. H. (2020). A new plesiosaurian from the Jurassic-Cretaceous transitional interval of the Slottsmøya Member (Volgian), with insights into the cranial anatomy of cryptoclidids using computed tomography. *PeerJ*, 8, e8652.
65. Rodríguez-Sánchez, J., Liberto, T., Barentin, C., & **Dysthe, D. K.** (2020). Mechanisms of phase transformation and creating mechanical strength in a sustainable calcium carbonate cement. *Materials*, 13(16), 3582.
66. **Rønning, J.**, Skaugen, A., Hernández-García, E., López, C., & **Angheluta, L.** (2020). Classical analogies for the force acting on an impurity in a Bose-Einstein condensate. *New Journal of Physics*, 22, 073018.
67. Salvalaglio, M., **Angheluta, L.**, Huang, Z. F., Voigt, A., Elder, K. R., & Viñals, J. (2020). A coarse-grained phase-field crystal model of plastic motion. *Journal of the Mechanics and Physics of Solids*, 137, 103856.
68. Sauermoser, M., Kjelstrup, S., Kizilova, N., Pollet, B. G., & **Flekkøy, E. G.** (2020). Seeking minimum entropy production for a tree-like flow-field in a fuel cell. *Physical Chemistry Chemical Physics*, 22(13), 6993–7003.
69. Senger, K., Betlem, P., Birchall, T., Buckley, S. J., Coakley, B., Eide, C. H., **Galland, O., Mair, K., Rabbel, O.,** ... & Jensen, M. (2020). Using digital outcrops to make the high Arctic more accessible through the Svalbox database. *Journal of Geoscience Education*, 1–15.
70. Sleveland, A. R. N., Midtkandal, I., **Galland, O.**, & Leanza, H. A. (2020). Sedimentary architecture of storm-influenced tidal flat deposits of the upper Mulichinco Formation, Neuquén Basin, Argentina. *Frontiers in Earth Science*, 8, 219.
71. Spacapan, J. B., D'Odorico, A., Palma, O., **Galland, O.**, Vera, E. R., Ruiz, R., ... & Manceda, R. (2020). Igneous petroleum systems in the Malargüe fold and thrust belt, Río Grande Valley area, Neuquén Basin, Argentina. *Marine and Petroleum Geology*, 111, 309–331.
72. Spacapan, J. B., Palma, O., **Galland, O.**, Senger, K., Ruiz, R., Manceda, R., & Leanza, H. A. (2020). Low resistivity zones at contacts of igneous intrusions emplaced in organic-rich formations and their implications on fluid flow and petroleum systems: A case study in the northern Neuquén Basin, Argentina. *Basin Research*, 32(1), 3–24.
73. Spacapan, J.B., Ruiz, R., Manceda, R., D'Odorico, A., Roxha, E., Rojas Vera, E., Medialdea, A., Cattaneo, D., Palma, O., Leanza, H.A., **Galland, O.** (2020). Chapter 20 – An Igneous Petroleum System within the Vaca Muerta Formation. Minisini, D., Fantin, M., Lanusse, I., and Leanza, H.A., eds., Integrated geology of unconventional: The case of the Vaca Muerta play, Argentina: AAPG Memoir 120.
74. **Sveinsson, H. A.**, Hafreager, A., Kalia, R. K., Nakano, A., Vashishta, P., & **Malthe-Sørensen, A.** (2020). Direct atomic simulations of facet formation and equilibrium shapes of SiC nanoparticles. *Crystal Growth & Design*, 20(4), 2147–2152.
75. **Vincent-Dospital, T., Toussaint, R.,** Cochard, A., **Måløy, K. J., & Flekkøy, E. G.** (2020). Thermal weakening of cracks and brittle-ductile transition of matter: A phase model. *Physical Review Materials*, 4(2), 023604.
76. **Vincent-Dospital, T., Toussaint, R.,** Santucci, S., Vanel, L., Bonamy, D., Hattali, L., ... & **Måløy, K. J.** (2020). How heat controls fracture: the thermodynamics of creeping and avalanching cracks. *Soft Matter*, 16(41), 9590–9602.
77. Vollestad, P., **Angheluta, L.**, & Jensen, A. (2020). Experimental study of secondary flows above rough and flat interfaces in horizontal gas-liquid pipe flow. *International Journal of Multiphase Flow*, 125, 103235.
78. Xu, L., Szymczak, P., **Toussaint, R., Flekkøy, E. G., & Måløy, K. J.** (2020). Dissolution Phase Diagram in Radial Geometry. *Frontiers in Physics*, 8, 369.
79. Zehner, J., **Røyne, A.**, Wentzel, A., & Sikorski, P. (2020). Microbial-induced calcium carbonate precipitation: an experimental toolbox for in situ and real time investigation of micro-scale pH evolution. *RSC Advances*, 10(35), 20485–20493.
80. **Zhong, X.**, Dabrowski, M., & **Jamtveit, B.** (2020). The effect of thermo-elastic anisotropy on quartz-in-garnet barometry. *American Mineralogist*, 105, 1585–1586.
81. **Zhong, X.**, Dabrowski, M., Powell, R., & **Jamtveit, B.** (2020). “EosFit-Pinc: A simple GUI for host-inclusion elastic thermobarometry” –Discussion. *American Mineralogist*, 105(10), 1585–1586.
82. **Zhong, X.**, Moulas, E., & Tajčmanová, L. (2020). Post-entrapment modification of residual inclusion pressure and its implications for Raman elastic thermobarometry. *Solid Earth*, 11(1), 223–240.
83. **Cheng, H-W., Dziadkowiec, J.,** Wieser, V., Imre, A., & Valtiner, M. Real-time visualization of metastable charge regulation pathways in molecularly confined slit geometries. Submitted.
84. **De Ruiter, L.,** Gunnæs, A.E., **Dysthe, D.K., & Austrheim, H.** (2021). Quartz dissolution associated with magnesium silicate hydrate cement precipitation. *Solid Earth*, in press.
85. **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.
86. Gessner, K., Zibra, I., Liu, J., Xiao, X., Pearce, M.A., Markwitz, V., **Menegon, L.,** Fielding, I., Korhonen, F., & Paesold, M. Earth's oldest seismic rupture: Archean continents stabilized as faults ran dry. *Nature Geoscience*, in review.
87. Gurfinkel, A. J., & **Rikvold, P. A.** (2020) A Current-flow Centrality with Adjustable Reach. Preprint: arXiv:2005.14356 [physics.soc-ph]. *Phys. Rev. E*, submitted.
88. **Jamtveit, B., Dunkel, K.G.,** Petley-Ragan, A., Austrheim, H., Corfu, F., & **Schmid, D.W.** Rapid fluid-driven transformation of lower continental crust associated with thrust-induced shear heating. *Lithos*, in review.
89. **Linga, G., Angheluta, L., & Mathiesen, J.** (2020). Onset of turbulence in channel flows with scale-invariant roughness. arXiv preprint arXiv:2006.16169.
90. **McBeck, J.,** Ben-Zion, Y., & **Renard, F.** How the force and fracture architectures develop within and around healed fault zones during biaxial loading toward macroscopic failure. *Journal of Structural Geology*, in review.
91. **McBeck, J.,** Mair, K., & **Renard, F.** (2021). Decrypting healed fault zones: How gouge production reduces the influence of fault roughness. *Geophysical Journal International*, in press.
92. **McBeck, J.,** Zhu, W., & **Renard, F.** The competition between fracture nucleation, propagation and coalescence in the crystalline continental upper crust. *Solid Earth*, in review.
93. Meghraoui, M., **Toussaint, R.,** & Aksoy, E. The slip deficit on the North Anatolian Fault (Turkey) in the Marmara Sea: Insights from paleoseismicity, seismicity and geodetic data. *Mediterranean Geoscience Review*, submitted.
94. **Menegon, L.,** Campbell, L.R., Mancktelow, N.S., Camacho, A., Papa, S., Toffol, G., & Pennacchioni, G. (2021). Brittle-viscous deformation cycles and earthquake nucleation in the lower crust. Invited contribution to Philosophical Transactions of the Royal Society A, in press.
95. **Olsen, K. S.** (2020) Perturbative effective diffusivity of microswimmers in the presence of oscillating torques. arXiv preprint arXiv:2012.05415
96. **Petley-Ragan, A.,** Plümper, O., Ildefonse, B., & **Jamtveit, B.** Nano-scale earthquake records preserved in plagioclase microfractures from the lower continental crust. *Solid Earth*, in review.
97. Putnis, C. V., Wang, L., Ruiz-Agudo, E., Ruiz-Agudo, C., & **Renard, F.** (2021). Crystallization via non-classical pathways: Nanoscale imaging of mineral surfaces. Book chapter in American Chemical Society, in press.
98. **Rabbel O.,** Palma O., **Galland O.,** Spacapan J.B., Senger, K., & **Mair K.** Fracture networks in shale-hosted igneous intrusions: Processes, distribution and implications for igneous petroleum systems. *Journal of Structural Geology*, in review.
99. **Renard, F.** (2021). Reaction-induced fracturing: when chemistry breaks rocks. *Journal of Geophysical Research*, in press.
100. **Skogvoll, V.,** Skaugen, A., **Angheluta, L.,** & Viñals, J. (2020). Dislocation nucleation in the phase field crystal model. arXiv preprint arXiv:2009.07524.
101. **Thorens L., Måløy K. J.,** Bourgoïn M., & **Santucci S.** Magnetic Janssen Effect. *Nature Communications*, in review.
102. **Thorens L., Måløy, K. J.,** Bourgoïn, M., & **Santucci, S.** Taming the Janssen Effect. *Powders and Grains 2021*, in review.
103. **Thorens L., Viallet, M., Måløy, K. J.,** Bourgoïn, M., & **Santucci S.** Discharge of a 2D magnetic silo. *Powders and Grains 2021*, under review
104. **Thøgersen, K.,** Aharonov, E., **Barras, F., & Renard, F.** A minimal model for the onset of slip pulses in frictional rupture. *Physical Review Letters*, submitted.
105. Van Stappen, J. F., **McBeck, J. A., Cordonnier, B.,** Pijenburg, R.P.J., **Renard, F.,** Spiers, C.J., & Hangx, S.J.T. In-situ observation of compaction and failure processes in Groningen sandstone through 4D synchrotron X-ray imaging. *Journal of the Mechanics and Physics of Solids*, submitted.

32. **Vincent-Dospital, T. & Toussaint, R.** (2020). *Thermo-mechanical pain : the signaling role of heat dissipation in biological tissues*. ArXiv preprint arXiv:2005.04991

33. **Vincent-Dospital, T., Cochard, A., Måløy, K. J., & Toussaint, R.** (2020). *Thermally activated intermittent dynamics of creeping crack fronts along disordered interfaces*. Scientific reports, submitted. ArXiv preprint arXiv:2010.06865

34. **Vincent-Dospital, T., Steyer, A., Renard, F., & Toussaint, R.** (2021). *Frictional anisotropy of 3D-printed fault surfaces*. Frontiers in Earth Sciences, in press. ArXiv preprint arXiv :2011.05012

35. **Vincent-Dospital, T., Toussaint, R., Cochard, A., Flekkøy, E. G., & Måløy, K. J.** (2020). *Is breaking through matter a hot matter? A material failure prediction by monitoring creep*. Soft Matter, in review. ArXiv preprint arXiv:2010.06865

36. **Zehner, J., Røyne, A., & Sikorski, P.** *Calcite seed-assisted microbial induced carbonate precipitation (MICP) and its potential in biocementation*. PLOS One, in review.

37. **Zehner, J., Røyne, A., & Sikorski, P.** *Experimental study of microbial induced carbonate precipitation (MICP) in the presence of CaCO₃ seeds*. Sustainable Chemistry & Engineering, in review.

38. **Zhong, X., Dabrowski, M., & Jamtveit, B.** (2021) *The effect of thermo-elastic anisotropy on quartz-in-garnet barometry*. American Mineralogist, in press.

39. **Zhong, X., Dabrowski, M., & Jamtveit, B.** *Analytical solution for residual stress and strain preserved in anisotropic inclusion entrapped in isotropic host*. Solid Earth, in review.

40. **Zhong, X., Petley-Ragan, A., Incel, S., Anderson, N.H., & Jamtveit, B.** *Deep crustal earthquakes facilitated by high pressure frictional melts*. Nature Geoscience, in review.

Invited talks

1. **Dunkel, K.G.,** *Microstructural records of earthquakes in the dry lower crust*. The Royal Society of London Discussion Meeting on "Understanding earthquakes using the geological record", London, GB, February 17–18.

2. **Brodin J. F.** *Visualizing 3D multiphase flows in porous media*. Porous Media Tea Time Talks, June 30.

3. **Dziadkowiec, J.** *Interactions between mineral surfaces studied with the surface forces apparatus*. Seminar at Geochemistry Department of the Lawrence Berkeley National Laboratory, Earth and Environmental Sciences Area Berkeley, California. December 4 (2019).

4. **Galland, O.,** *Structure, emplacement mechanism and magma-flow significance of igneous fingers – Implications for sill emplacement in sedimentary basins*. Keynote, Nordic Geological Winter Meeting, Oslo, January 9.

5. **Jamtveit, B.** *Earthquakes, fluids and the metamorphic transformation of the lower continental crust*. Johannes Gutenberg University Mainz, December 8.

6. **Jamtveit, B.** *Earthquakes, fluids and the metamorphic transformation of the lower continental crust*. Lawrence Berkeley Laboratory, November 20.

7. **Jamtveit, B.** *Earthquakes, fluids and the metamorphic transformation of the lower continental crust*. Univ. College London, June 12.

8. **Korkolis, E.** *Are earthquakes predictable? A laboratory perspective*. ISTerre, June 18.

9. **McBeck, J. A.** *Predicting the proximity of failure using fracture networks*. EGU General Assembly, April 21.

10. **McBeck, J.A.** *Decrypting healed fault zones: How gouge production weakens the impact of fault roughness*. Fall meeting American Geophysical Union, December 15.

11. **Menegon, L.,** *Brittle-viscous deformation cycles and earthquake nucleation in the lower crust*. Royal Society Discussion Meeting “Understanding Earthquakes from the Geological Record”, London, February 17–18.

12. **Rabbel, O.** *Fracturing of igneous intrusions emplaced in shale: processes, distribution and implications for igneous petroleum systems*. Uppsala University, June.

13. **Renard, F.** *4D imaging of laboratory earthquakes*. SOLID seminar, DTU, Denmark, December 10.

14. **Renard, F.** *Imaging fault nucleation in laboratory experiments*. The Deformation & Tectonics Talk Series, April 24.

15. **Renard, F.** *Quantifying the precursors to brittle failure in rocks using synchrotron imaging and machine learning*. EGU General Assembly, April 21.

16. **Renard, F.** *System size failure in laboratory experiments*. Southern California Earthquake Centre, April.

17. **Rikvold, P. A.** *Centrality Reach and Grasp: Attenuation of Influence Flows in Parametrized Centrality Measures on Complex Networks*. International Webinar in Statistical Physics, Department of Physics, Presidency University, Kolkata, India, August 23.

18. **Thorens L.** *(Ferromagnetic) Frictional Fluids*. Lavrentyev Institute of Hydrodynamics Laboratory Seminar, Novosibirsk, Russia, November 13.

Other talks

1. **Aupart, C., Morales, L., Godard, M., Jamtveit, B.,** and the Oman DP science team. *Early faulting and cataclasis in the Samail peridotites*. International Conference on Ophiolites and the Oceanic Lithosphere, in Muscat, Sultanate of Oman, January 14.

2. **Barras, F.** *Fluid-induced reactivation of faults: a tale of pressure and rupture*. EarthFlow Seminar, Oslo, June 12.

3. **Barras, F.** *On the energy balance behind frictional ruptures*. EGU General Assembly, May 4–8.

4. **Barras, F.** *There is a crack in everything, that’s how the light gets in; But what about fluid?* PoreLab Lecture Series, May 13.

5. **Bouchayer, C.** *Why do glaciers surge? Understanding the controlling parameters using machine learning and simulations*. EarthFlows December meeting, Oslo, December 3.

6. **Brodin, J. F. Måløy K. J. & Moura M. Rikvold P. A.** *An experimental study of the interplay between viscous, capillary and gravitational forces in two-phase flow in a three-dimensional porous medium*. Interpore 2020, online conference, August 31–September 3.

7. **Brodin, J. F. Måløy K. J., Moura M. & Rikvold P. A.** *3D experiments on flow in porous media, with an optical 3D scanner*. PoreLab lecture series, April 30.

8. **Demurtas, M.** *Faulting and surface propagation of seismic ruptures within unconsolidated gravels*. EarthFlow Seminar, Oslo, June 12.

9. **Dziadkowiec, J., Cheng, H., Røyne, A., Valtiner, M.** *Interactions between reactive mineral surfaces studied with the surface forces apparatus*. 3S20 Symposium on Surface Science, St. Christoph am Arlberg, Austria, March.

10. **Galland, O.** *Introduction: Workshop motivations and background*. Magmatic Flows workshop, Oslo, Norway, September 22.

11. **Galland, O.** *Numerical modelling of plastic deformation accommodating magma emplacement*. Magmatic Flows workshop, Oslo, Norway, September 22.

12. **Galland, O.** *To blow or not to blow? What controls whether a volcano erupts or not*. GeoExtreme Seminar, Oslo, April 21.

13. **Kobchenko, M., Pluymakers, A., Cordonnier, B., & Renard, F.** *Time-lapse X-ray imaging of deformation modes in organic-rich Green River Shale heated under confinement*. EGU General Assembly, April 21.

14. **Le Borgne, T.** *Irreversible signatures of chaotic mixing*. EarthFlows Seminar, Oslo, June 11.

15. **Linga, G.** *Stretching and mixing in two-phase flow in porous media*. EarthFlows seminar, Oslo, June 11.

16. **Linga, G., & Barras, F.** *Near-tip dynamics of a fluid-driven fracture*. Magmatic Flows workshop, September 22.

17. **Linga, G., Mathiesen, J., Renard, F., & Le Borgne, T.** *Stretching and Folding in Intermittent Two-Phase Porous Media Flows*. American Physical Society conference, November.

18. **McBeck, J.** *Predicting the proximity to system-scale rupture using fracture networks*. EarthFlow Seminar, Oslo, June 12.

19. **McBeck, J., Aiken, J., Mathiesen, J., Ben-Zion, Y., Renard, F.** *Predicting the proximity to system-scale rupture using fracture networks*. EGU General Assembly, April 21.

20. **Menegon, L.** *Earthquake nucleation in the lower crust by local stress amplifications*. EarthFlow Seminar, Oslo, June 12.

21. **Menegon, L., & Fagereng, A.** *Viscous creep drives brittle failure at the base of the seismogenic zone*. Geophysical Research, January.

22. **Menegon, L., Campbell, L., Mancktelow, N., Camacho, A., Papa, S., Toffol, G., & Pennacchioni, G.** *The geological record of the earthquake cycle in the lower crust: insights from field studies in the Musgrave Ranges (Central Australia) and in Lofoten (northern Norway)*. Geological Society of America Meeting, GSA 2020 Connects Online, October 26–30.

23. **Moura, M., Måløy, K. J., Flekkøy, E. G., Schäfer, G., & Toussaint, R.** *Thin film flow: fluid transport via thin liquid films in slow porous media flows*. Interpore 2020 Online conference, August 31–September 4.

24. **Måløy, K. J.** *Drainage in porous media under influence of a gravitational field*. EarthFlows Seminar, Oslo, June 11.

25. **Petley-Ragan, A., Ben-Zion, Y., Austrheim, H., Ildefonse, B., & Renard, F.** *Direct observations of a dynamic earthquake rupture in the lower crust*. EGU General Assembly, April 21.

26. **Petley-Ragan, A., Ben-Zion, Y., Austrheim, H., Ildefonse, B., & Renard, F.** *Direct observations of a dynamic earthquake rupture in the lower crust*. EGU General Assembly, April.

27. **Rabbel, O., Spacapan, J. B., & Betlem, P.** *Integrated Rock Physics and Seismic Modeling of Igneous Reservoirs*. Fifth EAGE Workshop on Rock Physics. Vol. 2020. No. 1. European Association of Geoscientists & Engineers, February 11.

28. **Rikvold, P. A., Brodin, J. F., Moura, M., & Måløy, K. J.** *Visualization of Two-phase Flow in a Threedimensional Porous Medium*. Talk at 33th Workshop on New Developemnts in Condensed Matter Physics, University of Georgia, Athens, GA. February 18.

29. **Skogvoll, V.** *A minimal model for crystal plasticity*. EarthFlows December meeting, Oslo, December 3.

30. **Skogvoll, V.** *Phase field crystal modelling of dislocation nucleation*. EarthFlow Seminar, Oslo, June 11.

31. **Sveinsson, H.A., Thøgersen, K., & Mälthe-Sørenssen, A.** *Grain boundary behavior of hydrate–hydrate and ice–ice bicrystals: Molecular dynamics insights*. Gordon Research Seminar on Natural Gas Hydrate Systems; February 22–23.

32. **Teuling, F., Guren, M. G., Renard, F., Drury, M. R., Hangx, S. J. T., King, H. E., Plümper, O., & Sveinsson, H. A.** *Molecular dynamics simulations of diffusive properties of stressed water films in quartz and clay grain contacts*. EGU General Assembly, April 21.

33. **Thorens, L.** *Impact of pair interactions on frictional fluid dynamics*. InterPore 2020 online conference, August 31–September 3.

34. **Thorens, L.** *Tunable interactions during the discharge of a 2D silo*. Interpore 2020, online conference, August 31–September 3.

Posters

1. **Betlem, P., Rabbel, O., Lecomte, I., & Senger, K.** *Seismic Modelling of Virtual Outcrops: Application of Rock Physics Beyond the Borehole*. In Fifth EAGE Workshop on Rock Physics (Vol. 2020, No. 1, pp. 1–5). European Association of Geoscientists & Engineers, February. Poster

2. **Bouchayer, C., Schuler, T. V., Thørgersen, K., Renard, F., & Kääh, A.** *Modeling transient velocity variations in glaciers*. CHESS Annual Seminar, October 28. Poster.

3. **Dunkel, K. G., Zhong, X., Morales, L. F., & Jamtveit, B.** *Highly stressed lower crust: Evidence from dry pseudotachylytes in granulites, Lofoten, Norway*. EGU General Assembly Conference Abstracts (p. 2890), May. Poster.

4. **Dziadkowiec, J., Cheng, H.-W., Røyne, A., Valtiner, M.** *Interfacial processes at dissimilarly charged mineral surfaces in contact – a surface forces apparatus study*. EGU2020: European Geosciences Union General Assembly 2020, April 21. Poster.

5. **Dziadkowiec, J., Zareeipolgardani, B., Dysthe, D. K., Røyne, A.** *Confined Nucleation of Calcium Carbonate Studied in the Surface Forces Apparatus*. Goldschmidt 2020 Virtual Conference, June. Poster.



6. Kobchenko, M., Pluymakers, A., Cordonnier, B., & Renard, F. Time-lapse X-ray imaging of deformation modes in organic-rich Green River Shale heated under confinement. EGU General Assembly, April.

7. Sveinsson, H.A., Thøgersen, K., Malthe-Sørenssen, A. Poster. Grain boundary behavior of hydrate-hydrate and ice-ice bicrystals: Molecular dynamics insights. Gordon Research Seminar on Natural Gas Hydrate Systems; February 22–23.

8. Teuling, F., Guren, M. G., Renard, F., Drury, M. R., Hangx, S. J. T., King, H. E., Plümper, O., & Sveinsson, H. A. Molecular dynamics simulations of diffusive properties of stressed water films in quartz and clay grain contacts. EGU General Assembly, April. Poster.

In media

1. Brodin, J., & Måløy, K. J. Splitter ny 3D-skanner følger væsker fra hulrom til hulrom. Teknisk Ukeblad, May 14. [Magazine]

2. Brodin, J., & Måløy, K. J. Splitter ny 3D-skanner følger væsker fra hulrom til hulrom. Titan, May 8. [News]

3. Galland, O. Supervulkaner. NRK, June 24. [News]

4. Galland, O., Mescua, J., Palma, O., Marín, G., & Albino, J. A Fresh Perspective on Intricate Volcanic Plumbing Systems. EOS, December 16. [Magazine]

5. Jamtveit, B. – En ny generasjon forskere som kan forandre verden. Titan, June 24. [News]

6. Moura, M. Especial Caruaru 163 anos. AO VIVO, May 18. [TV]

7. Moura, M. Ta en kopp te og tenk på jord-skjelv. Titan, April 23. [News]

8. Olsen, K. S., Brodin, J., Dop, A., Eriksen, F. K., Flekkøy, E. G., Thorens, L., Xu, L., Moura, M., Vincent-Dospital, T., Cochard, A., & Toussaint, R. Se skjønnheten i fysikernes eksperimenter. Titan [News], September 25.

9. Røyne, A. – Vi må ta oss råd til karbonlagring. Å la være, blir dyrere på sikt. Morgenbladet, October 28. [News paper]

10. Røyne, A. Bokanmeldelse: Liste over ting å gjøre for å redde verden. NRK, December 8. [News]

11. Røyne, A. Ekko. Løsninger på klimakrisen. NRK P2, October 12. [Radio]

12. Røyne, A. Ekko: Abels Tårn. NRK P2, May 29. [Radio]

13. Røyne, A. Ekko: Abels tårn. NRK P2, September 25. [Radio]

14. Røyne, A. Kan en CO2-støvsuger redde verden? D2, October 22. [News magazine]

15. Røyne, A. Lahlum og Lysbakken koker kloden. Lahlum og Lysbakken, November 22. [Podcast]

16. Røyne, A. Om løsninger på klimakrisen – med Anja Røyne – #33. Vett og Vitenskap, December 27. [Podcast]

17. Røyne, A. Ryddesjau på kloden. Dag og tid, November 6. [News paper]

18. Røyne, A., Seehusen, J. Lager betong med bakterier – gir store reduksjoner i CO-utslipp. Teknisk Ukeblad, March 19. [Magazine]

Outreach

1. Bouchayer, C. Un an en Antarctique. APECS France Polar Week for targetted audience: classes from 7 to 12 years old, November 13. [Talk]

2. Dunkel, K. G. The Grid – A serpentine pseudomorph after carbonate. EGU Blogs, June 1. [Blog post]

3. Galland, O. En vulkan våkner på Island. Er vi beredt? Aftenposten Viten, April 28. [Magazine article]

4. Galland, O. Slik kan Island passe på vulkanen. Aftenposten Junior, July. [News article]

5. Haffner, F., Couturier, M., & Dziadkowiec, J. Crystals: From rock candy to rock(et) science. Espurlette, June. [Magazine article]

6. Moura, M. Career Development Event. Inter-Pore 2020 Annual Meeting, September. [Initiative and Event Organization]

7. Moura, M. Porous Media Tea Time Talks. Zoom/YouTube, happening fortnightly from June 30. [Webinar series]

8. Nielsen, B. F., Linga, G., Olsen, K. S., Simonsen, L. Vejen til frihed. Weekend-avisen, May 7. [Newspaper article]

9. Røyne, A. Blir det tomt? Ressurser, forbruk og fremtiden. Fagdag for 10. klasse, January 24. [Talk]

10. Røyne, A. Fysikk – enkelt forklart. Universitetsforlaget 2020 (ISBN 9788215034454) 159 s. UiO. [Book]

11. Røyne, A. Menneskets grunnstoffer. February 6, June 6, September 21, September 23. [Talk]

12. Røyne, A. Menneskets grunnstoffer. School visits with "Den Kulturelle Skolesekken" in Hedmark, in total 14 talks. October 18–December 14. [Talk]

13. Røyne, A. Menneskets og økosystemets grunnstoffer i et evig kretsløp? Den beboelige planeten (NMBU), February 11. [Talk]

14. Røyne, A. Presentation of the book "Varm klode, kaldt hode" for Fremtiden i våre hender. November 24.

15. Røyne, A. Varm klode, kaldt hode. Løsninger på klimakrisen. Kagge Forlag AS 2020 (ISBN 9788248926344) 231 s. UiO. [Book]

16. Røyne, A., Samset, B. H., Sundal, A., Storelvmo, T., Jøner, E. Boklansering: Varm klode, kaldt hode. Løsninger på klimakrisen. Realfagsbiblioteket, October 8. [Event]

17. Sveinsson, H. A. Gasshydrater: fra laboratoriekuriositet til klimatrussel. Naturen, 144(01–02), 38–43. [Magazine article]

18. Sveinsson, H. A., & Thøgersen, K. Simulations for article: <https://www.aftenposten.no/amagasinet/i/QmIX9Q/minuttene-foer-katastrofen>. Based on this dataset: Sveinsson, H. A., Thøgersen, K. (2020). Simulering av karbonmonoksid under grottefesten i St.Hanshaugen august 2020 [Data set]. Zenodo. <http://doi.org/10.5281/zenodo.4045683>, September 25. [News article]

Project portfolio

Project leader	Project title	Host	Source	Account- ing in 2020 (NOK in 1000)	Project Start Date	Project End Date	Total External Financing (NOK in 1000)
Angheluta, Luiza; Renard, Francois	EarthFlows 2	The Njord Centre	UiO	34	01.01.2019	31.12.2023	
Dziadkowiec, Joanna	Solid-solid interfaces as critical regions in rocks and materilas: probing forces, electrochemical reactions, friction and reactivity.	The Njord Centre	RCN	829	01.04.2019	31.03.2022	3 234
Jamtveit, Bjørn	Disequilibrium metamorphism of stressed litosphere (DIME)	Dept. of Geosciences	ERC	3 132	01.09.2015	31.08.2021	21 200
Malthe-Sørenssen, Anders	History-dependent friction	The Njord Centre	RCN	3 031	01.07.2019	31.06.2023	9 229
McBeck, Jessica Ann	Emergent networks: Predicting strain localization and fracture network	The Njord Centre	RCN	425	01.09.2020	28.02.2025	6 852
Måløy, Knut Jørgen	Porous Media Laboratory	Dept. of Physics	RCN	7 192	01.07.2017	30.06.2027	66 400
Renard, Francois	Advanced X-ray and neutron imaging of fractures and porous rocks (ARGUS)	Dept. of Geosciences	RCN	1 379	01.01.2018	31.12.2020	3 093
Renard, Francois	Microfractures in black shales nd their transport properties (PROMETHEUS)	Dept. of Geosciences	RCN	2 108	01.04.2017	30.09.2021	11 201
Renard, Francois	Unravelling the spatio-temporal nature of rock deformation using 4D X-ray tomography (HADES)	Dept. of Geosciences	RCN	701	01.05.2016	30.09.2020	8 989
Renard, Francois	COLOSSAL: Collaboration on Flow Across Scales (Norway, Brazil, France, USA)	The Njord Centre	RCN	n/a	01.12.2020	31.05.2025	4 499
Renard, Francois	PoreFlow: Visualizing multiphase flow in porous media with neutron imaging	NTNU	RCN	n/a	01.12.2020	30.06.2024	900
Renard, Francois; Jamtveit, Bjørn	MODIFLOW: Modelling Flow Across Scales	The Njord Centre	Equinor	1 439	01.01.2019	31.12.2023	9 048
Røyne, Anja	Systems analysis & fundemental control of bacterial processes in the production of bio-concrete for construction purposes	Dept. of Physics	RCN	1 970	01.05.2017	30.09.2020	4 726

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