NJORD

Annual report 2018

UiO : University of Oslo

N J O R D

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

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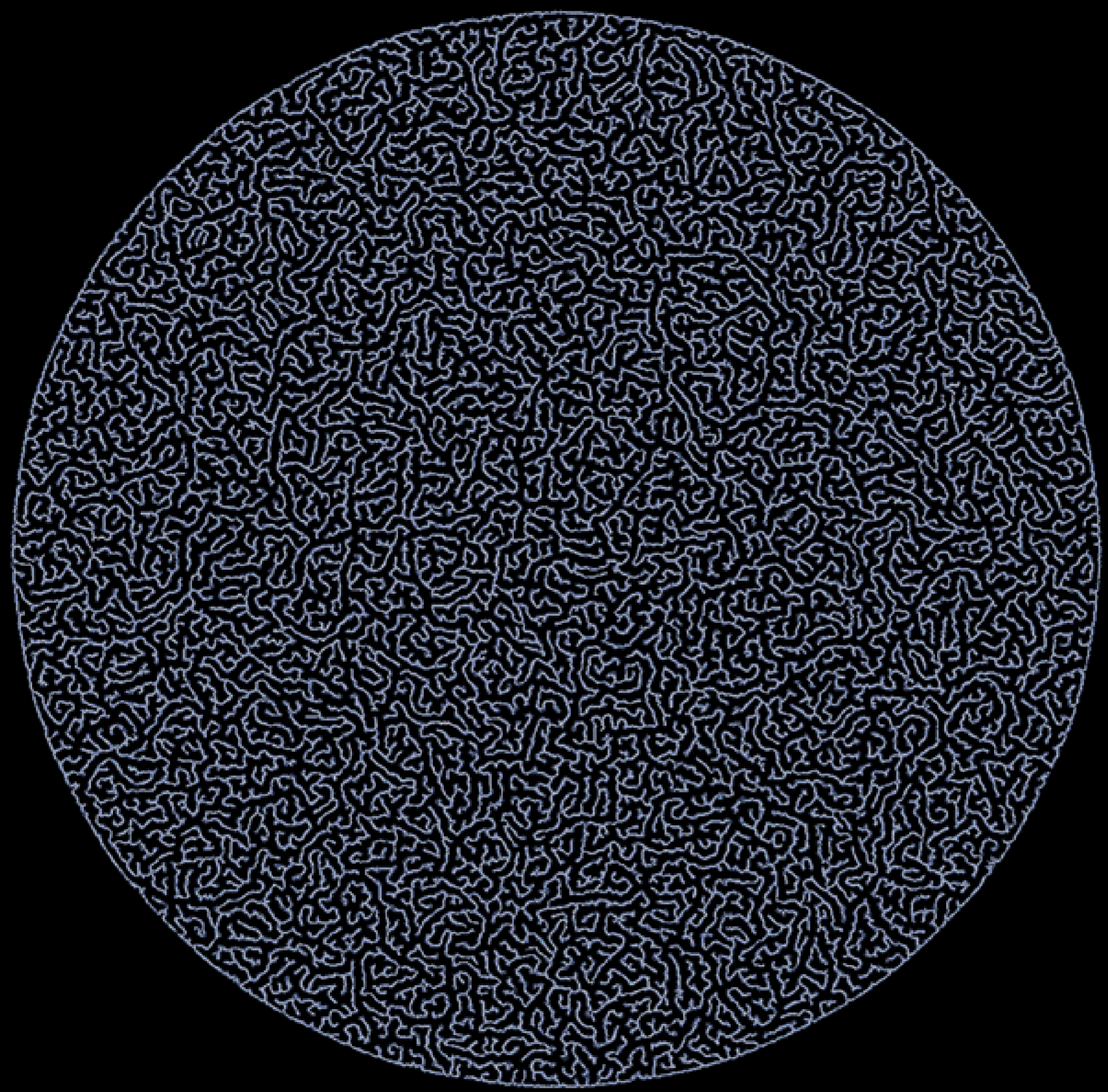
Contents



01

Preface

Preface

All experts are experts for things that did happen. There are no experts for things that may happen.

– David Ben Gurion

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', starting in August 2017). Through curiosity-driven research near the interface between physics and geoscience, we hope to advance the frontier of knowledge about the behavior of Earth-like systems at far-from equilibrium conditions. To achieve these aims, we build on our diversity in an open environment with a high level of technical skills.

During it's first year in operation *Njord* staff produced 66 papers in international journals, including three in Nature journals (*Nature, Nature Communications, Scientific Reports*), two in *Physical Review Letters*, and one in *Environmental Science and Technology*. For a research centre with 10 senior staff members, this is already a remarkable production.

Three out of five PhD students who graduated in 2018 continued as postdocs, Frank Guldstrand stayed within *Njord*, whereas Tobias Schmiedel moved to Uppsala University in Sweden, and Audun Skaugen to University of Tampere in Finland.

Four new *Njord* projects were funded from 2019 onwards. The Strategic Research Initiative Earthflows funded by UiO got extended into *'Earthflows II'* headed by Luiza Angheluta. Equinor's Academia program is funding the new project *'MODIFLOW'* headed by François Renard, and Anders Malthe-Sørenssen received funding from the Norwegian Research Council's (NRC) FRIPRO program for the project *'History dependent friction'*. Finally, Joanna Dziadkowiec who graduated from *Njord* in January 2019, received a 3 year 'Mobility grant' from NRC for her project *'Solid-solid interfaces as critical regions in rocks and materials'*.

Njord staff received generous media coverage in 2018. First and foremost, Anja Røyne received the prestigious 'Brageprisen' for her book 'Mennesket's grunnstoffer'. Anja also participated in a number of popular science programs on radio, including 5 appearances in the NRK P2 program 'Ekko'. In addition, Marcel Moura, Eirik Flekkøy and collaborators received considerable media attention for their paper on the 'flying chain', and Eirik was also called in as a science expert on the infotainment TV-show "Brille" on NRK. Finally, in November Karen Mair along with composer Natasha Barrett launched the Listening Lab *'Rock music - Exploring Geology using sound'* at the National Museum in Edinburgh.

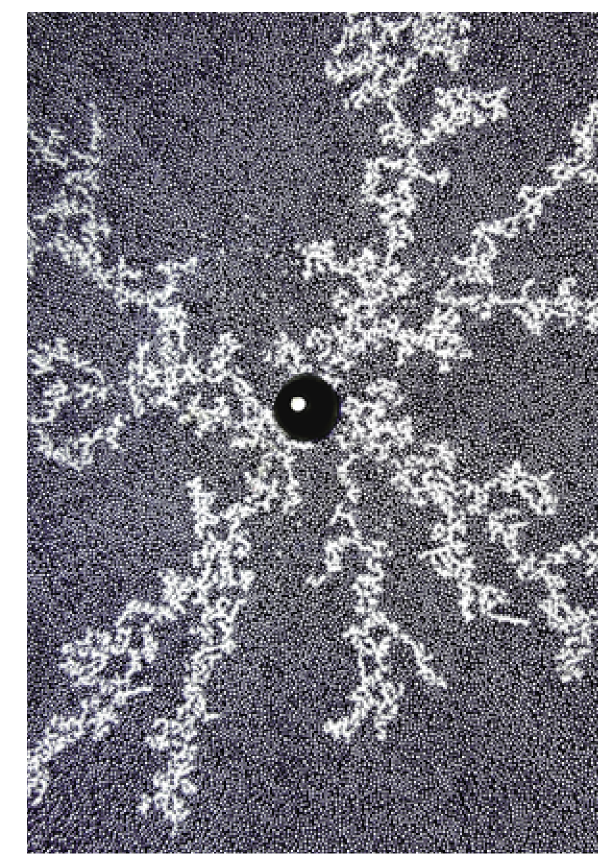
Njord members received several awards for their research and teaching in 2018. Anja Røyne shared the first Else-Ragnhild Neumann award for women in geosciences in December; Marcel Moura won the 'Inter-Pore Rosette Award' in recognition of sustained and valuable services to The International Society for Porous Media at the InterPore Conference on Porous Media in New Orleans in May; Lisa de Ruiter received an 'Outstanding student poster and PICO award' at EGU in Vienna in April, and Bjørn Jamtveit shared the 'Teacher of the year award' from the students at the Department of Geosciences in December.

During 2019, we will work to increase synergy and interactions between our 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.

Bjørn Jamtveit
Director, Njord

Mylonitized pseudotachylyte (below) and fragmented wall rock (above) from the Bergen Arcs, Western Norway. Picture by Arianne Petley-Ragan.

Mg-rich hyper alkaline water pool in Wadi Khafifa in Oman where aragonite and calcite precipitate to form travertines. Picture by Claire Aupart.



A number of interesting patterns arise when air invades a porous network saturated with a viscous wetting fluid. Picture by Marcel Moura.

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About Njord

About Njord

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

Valle de la Luna, Chile. Picture by Olivier Galland.

At Njord we conduct research on systems that range in scale from atoms to continents and apply methods where fieldwork, numerical modelling, experiments and theory act in concert. The prime products of our center is high quality basic research and education. However, 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 transport of water, pollutants and hydrocarbons in porous and fractured rocks, carbon sequestration and storage, avalanche dynamics, earthquakes and other geohazards.

Who are we?

The Njord center accommodates researchers from the former Center 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 Centre of Excellence (CoE) running in the period 2003-2013 and has roots back to the mid-90s as a Strategic University Program. A PGP precursor project lead by B. Jamtveit ('Dynamics of fluid-rock interfaces') also spent year at the Centre of Advanced Studies at the Norwegian Academy of Science and Letters in 2000-2001. At the end of the CoE period, PGP was 'phased-into' the host departments as one small section in the Department of Geosciences (named PGP), whereas the physics part of PGP became part of the Condensed Matter section of the Department of Physics.

Porous Media Laboratory (PoreLab) is a fourth generation CoE and will run in the period 2017-2027. It is directed by professor Alex Hansen at NTNU, but a major component of the staff and activities is located at UiO and coordinated by 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, nonequilibrium thermodynamics and statistical mechanics. The goals and methods of PoreLab is highly cross-disciplinary and show considerable overlap with ongoing PGP activities.

We believe there is an obvious and considerable potential for increased synergies between physics and geoscience at UiO by merging PGP and PoreLab CoE UiO onto a joint organizational platform.

We aim to:

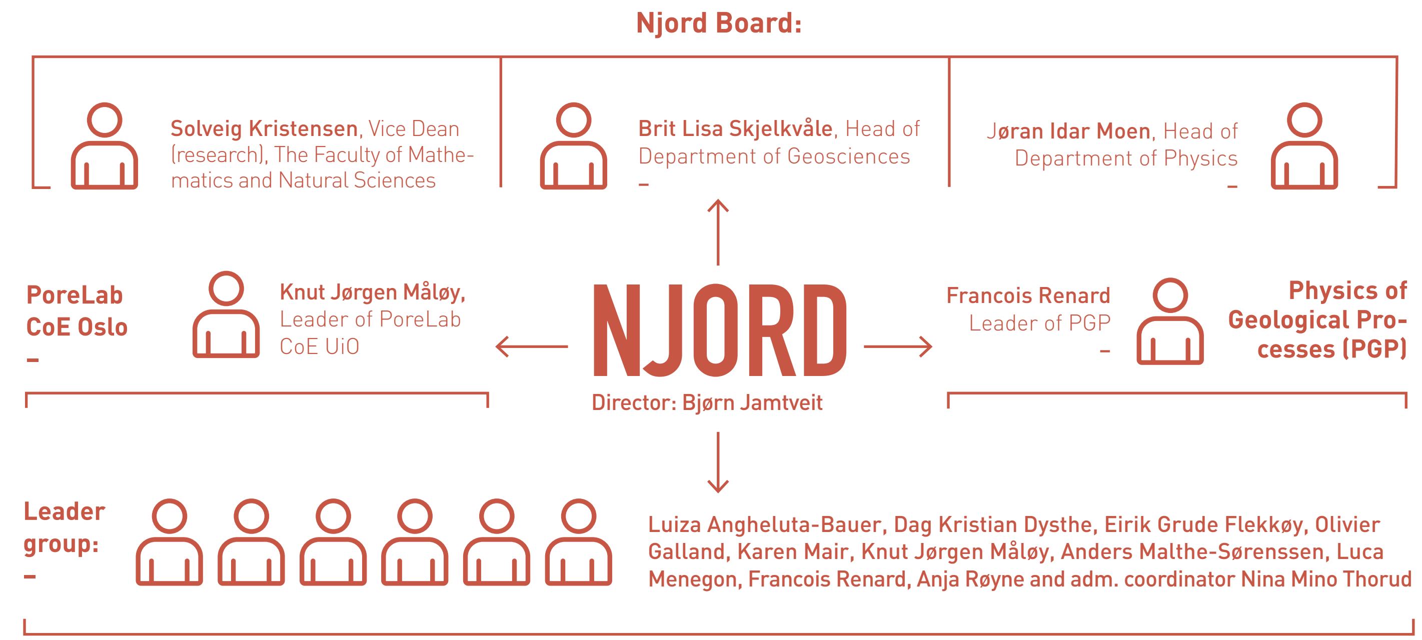
- Maintain and develop a world leading cross-disciplinary research center in physical sciences at UiO with focus on a fundamental understanding of the dynamics of fluid-solid systems with Earth-like complexity.
- Build the next generation of computational competences and experimental laboratory facilities 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 geo-systems, avalanches, landslides, and other geohazards.
- Generate an outstanding environment for research-based education at the Masters and PhD levels.
- Make complex Earth-like systems 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) and be a user of large-scale national and international facilities where Norway is a partner (ESRF, ESS, IFE, IOR).

Our philosophy for education is research based: 'Learning by doing'. We are doing this in close collaboration with the Center for Computing in Science Education (CCSE), a CoE in education directed by Njord's Anders Malthe-Sørenssen.

Organization



Staff

Geographical origin of Njord employees

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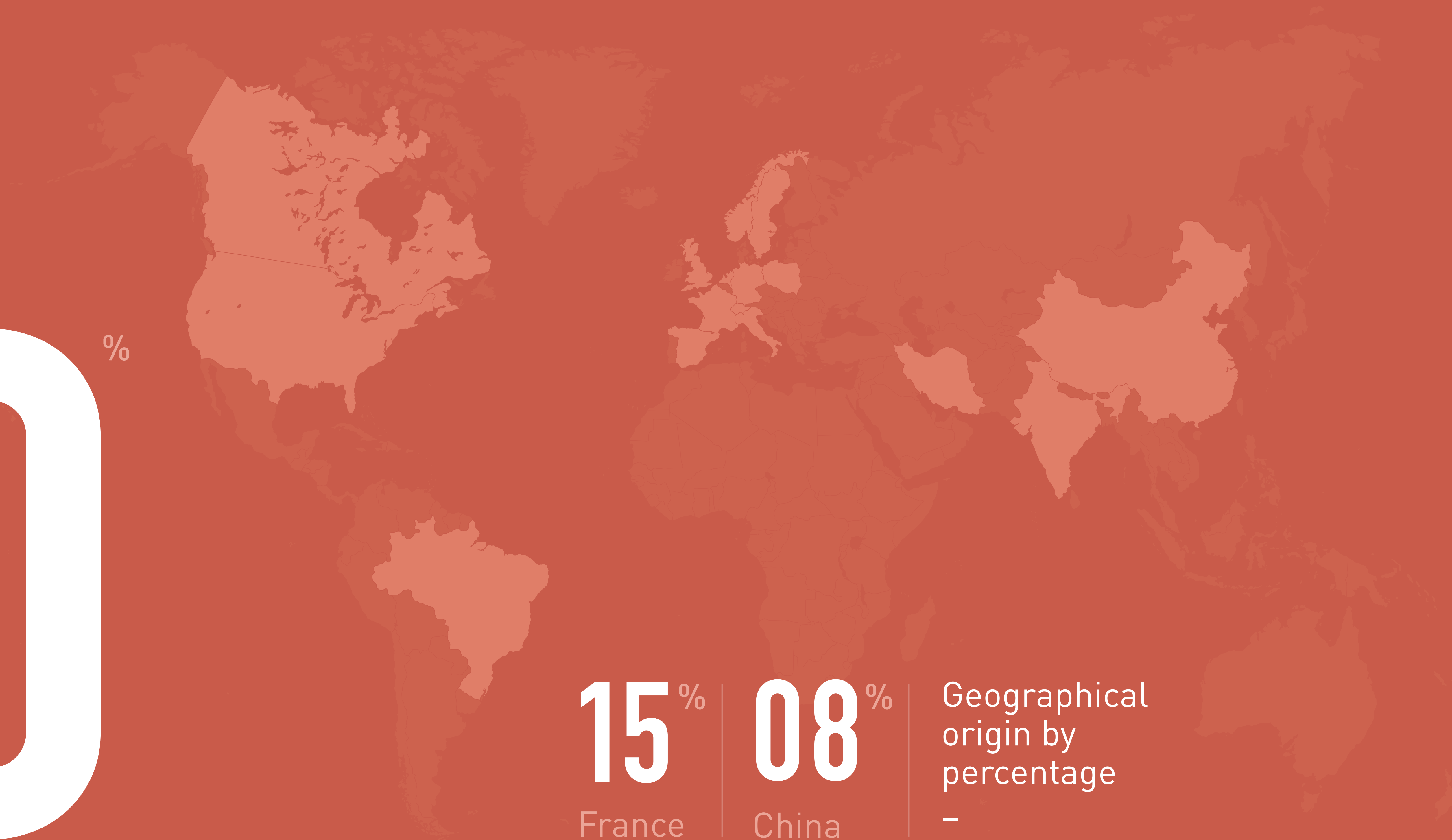

40 %
Norway

15 %
France

08 %
China

Geographical origin by percentage

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05 % Germany

05 % Italy

03 % Canada

03 % USA

03 % Poland

03 % UK

03 % Iran

03 % Iran

02 % Brazil

02 % Spain

02 % India

02 % Sweden

02 % Switzer-land

02 % Nether-lands

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Activity at Njord

Finances and Funding

48 MNOK

Funding in total in 2018

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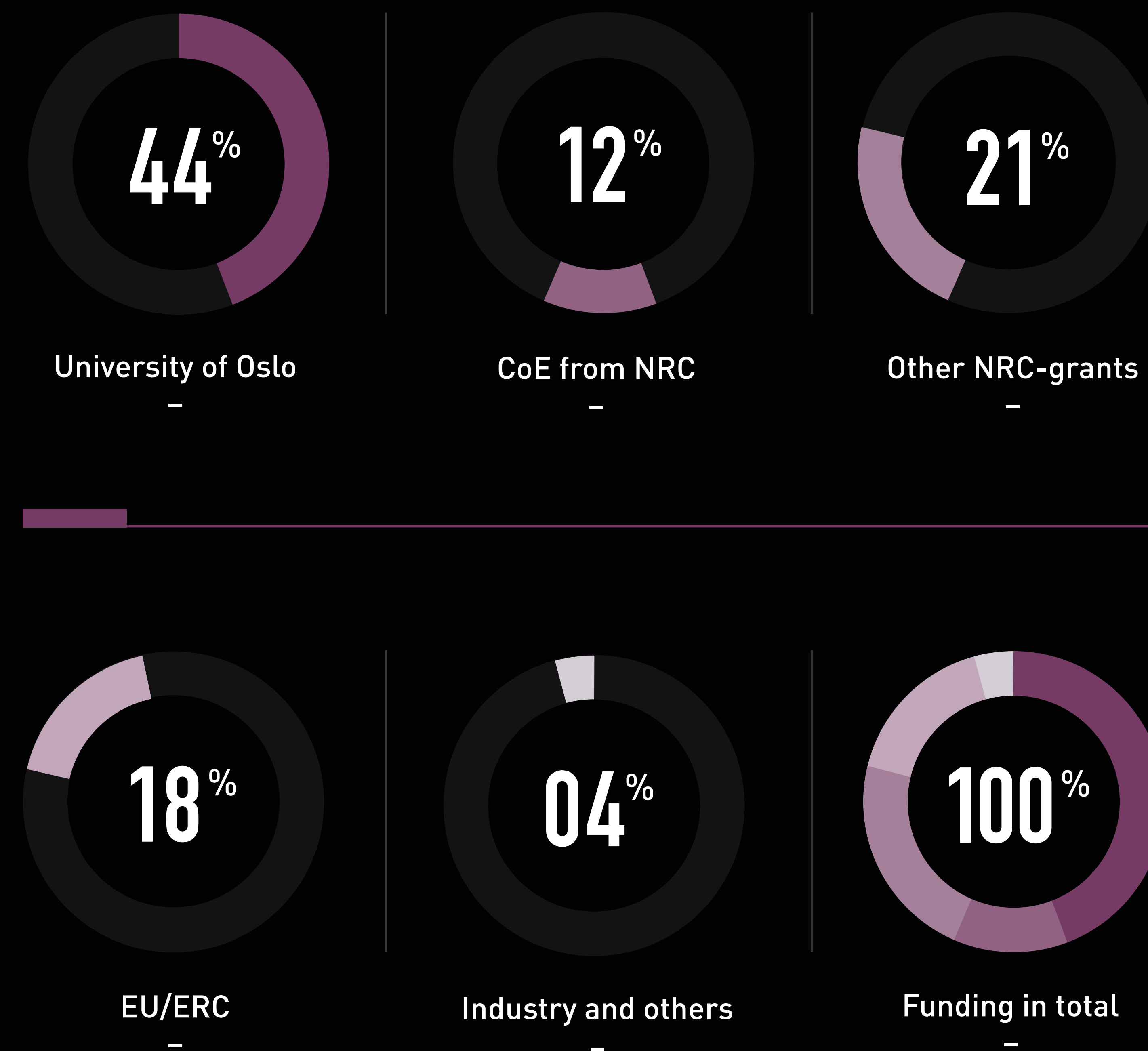
The Njord center is financed by the Department of Physics and the Department of Geosciences at the University of Oslo. The center receives contribution from both departments to cover the costs of running the center. Overhead from projects at Njord is split between Njord and the host department. The ambition is that with time the contributions from the departments will be replaced with overhead from projects at Njord, making the center self-sufficient. The staff at Njord is employed by either one of the departments or at Njord. Projects lead by staff at Njord, but started before the center was established, is formally at the host department. Since the activity is at the center, we do consider it Njord-projects as well.When including all of this factors we say that the center and the activity at the center is funded by the University of Oslo, the Norwegian Research Council, the European Research Council and other sources of funding.

Distribution of funding



Education

Our approach to education is research based: 'Learning by doing'. The educational activities by Njord staff include teaching, supervising and contributing to teaching activities at the Department of Physics and the Department of Geosciences. 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 contributes substantial activities to the master level courses GEO4131 and GEO4151, as well as master-thesis project work. We are working in close collaboration with the CoE Center for Computation in Science Education, led by Njord's Anders Malthe-Sørenssen.

In 2018, Njord staff was either responsible for or guest lectures in the following courses:

Geomechanics
GEO4131
This course focused 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 focused 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 was split into three parts focusing on the most common geohazards in Norway: floods, landslides and avalanches. The course included 1 day field trips to selected sites and a 3 days excursion.

Introduction to Natural Hazards
GEO4181
This course introduced natural hazards, both globally and related to Scandinavian conditions.

Hydrogeology
GEO4190
This course teached the physical processes that control the flow of water below the ground, surface-water groundwater interactions, transport of solutes, and well hydraulics

Advanced Petrology
GEO4860
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.

Electromagnetism
FYS1120
The course described basic electrical and magnetic phenomena, as well as laws for electrical circuits, both at direct current and alternating current.

Thermodynamics and statistical physics
FYS2160
The course introduced the student to statistical mechanics and thermodynamics. Statistical mechanics is the microscopic foundation of thermodynamics.

Experimental techniques in condensed matter physics
FYS4420
The course contained four projects that gave students introduction to important experimental techniques in the field of condensed matter physics. The course was adapted to CoE PoreLab with a special focus on porous media physics.

Outreach and societal impact

Communication of our research and findings is an important mission for Njord. We communicate both to the international academic world, and to the public, both in Norway and abroad. We aim to convey our knowledge and to increase the appreciation and understanding of science through our outreach projects. To achieve this goal, we collaborate with media, renowned artists and industry partners.

Our 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. Even though our research is driven by curiosity, the scientific results can contribute to societal impact.

An important part of our outreach work is making science available for everyone and to inspire to curiousity. In 2018, Anja Røyne published her first book "Menneskets grunnstoffer" for which she was honored with the prestigious Brage-award from The Norwegian Book Prize Foundation. Anja got compliments for her precis language and for lifting the book to an existential level while combining advanced physics with the reader's everyday life. The first edition sold out quickly.

To increase the appreciation and understanding of science and the conduct of doing research, we made short videos documenting our work with the Hades Rock Deformation Rig at the European Synchrotron Radiation Facility in Grenoble. The videos have been made available on YouTube.

In 2018, Njord staff made several media appearances. Anja Røyne was part of the panel in NRK P2's radio programs *'Abels tårn'* and *'Ekko'*, and Eirik Grude Flekkøy had the role of 'expert' in the infotainment TV-program *'Brille'* on NRK. Røyne also wrote an article for the popular science magazine *'Aftenposten Viten'*.

To both challenge and inspire ourselves and the public Njord also collaborates with artists. In September 2018, Bjørn Jamtveit participated in the opening of the exhibit 'Soft Ice' focused on the Artic nature by graphical artist and long-time PGP collaborator Ellen Karen Mæhlum at Gallery Kunstverket in Oslo.

Then, in November 2018, Karen Mair ran a 'Listening Lab' during the Science Saturday public outreach event at the National Museum of Scotland in Edinburgh. The Listening Lab was entitled 'Rock music – Exploring Geology using sound' and featured a selection of geoscience data sonifications (where digital data is transformed into sound) created during a collaboration between composer Natasha Barrett and Mair over recent years. The hands-on audio display consisted of 6 headphone stations where members of the public could listen to spatial soundscapes of our different 'hits' including: QUAKES (UK earthquakes in the last 100 days); LOADED (what do rocks sound like when they break), CRUSH (inside an earthquake), and AFTERSHOCK. The listeners navigated between different 'hits' was via a Virtual Geology Jukebox which was intuitive and playful. The Listening Lab proved to be extremely popular, attracting ca 500 users during the 5 hour event.

Highlights of 2018

1. January

The Njord center is established
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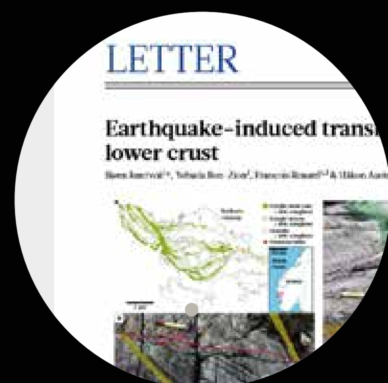
1.–15. February

Njord is in Oman for the multinational project "The Oman Drilling Project"

18. April



Article published in Nature "Earthquake-induced transformation of the lower crust."

1. June

PoreLab CoE arranges opening seminar in Oslo
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14.–15. June

Earthflows-seminar and Njord Summer Party
–

18.–22. June

Beijing Computational Research Science Center visits PoreLab CoE

15.–30. August

Njord is on board the research ship Chikyu for phase 2 of the "The Oman Drilling Project"

24. September

The first Njord-board meeting is held
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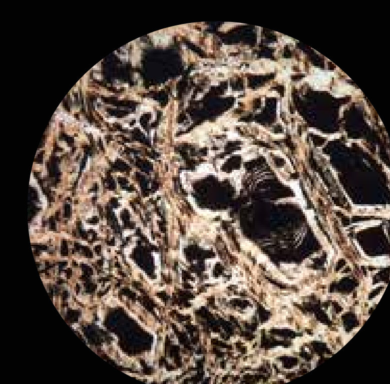
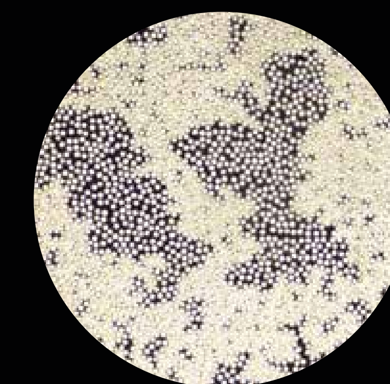


9. November



PoreLab CoE arranges 2nd National Interpore Workshop on Porous Media

22. November

Anja Røyne is awarded with "Brageprisen" for her book "Menneskets grunnstoffer"

1. December

The refurbishing of the laboratories for PoreLab CoE starts

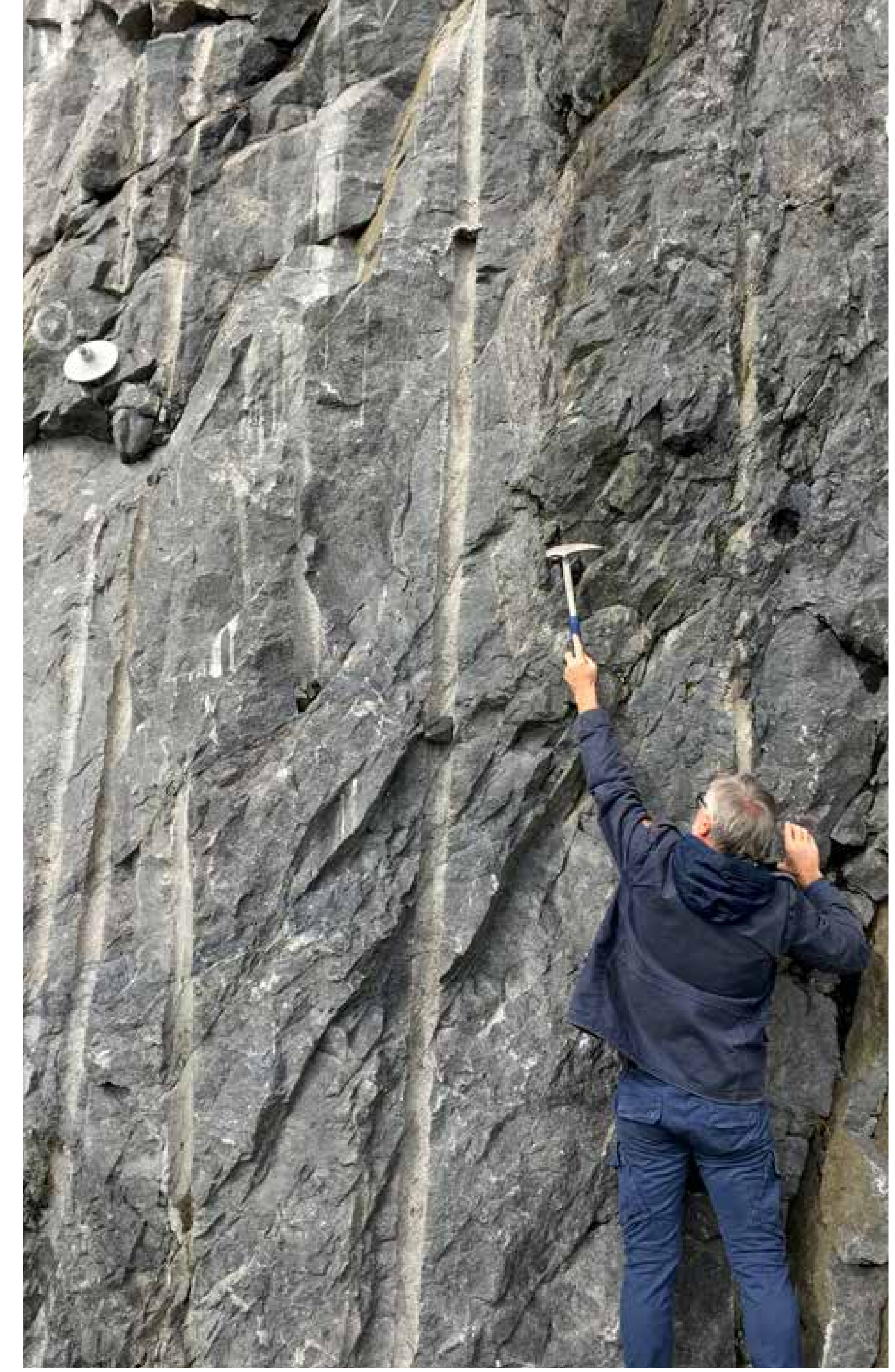
13. December

Bjørn Jamtveit is awarded "Teacher of the Year" by the Geoscience-students

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 and serves both to constrain and inspire experimental and modelling approaches to our studies of geological processes. In 2018, field studies were carried out in several areas across the globe, including Argentina, Oman, Svalbard, Bergen Arcs, and Lofoten in Northern Norway.

Bjørn Jamtveit providing a hammer for scale during a photo session of seismic faults in the lower crust along a roadcut near Reine, Lofoten. Picture by Francois Renard.



Early winter 2018 Claire Aupart, Ole Ivar Ulven, Bjørn Jamtveit and Benoît Cordonnier travelled to Oman to take part in the Oman Drilling Project, a multi-national collaboration to explore ancient seafloor in the deserts *of Oman*. The aim was to collect drill cores and then to curate, take pictures, scans, draw and give an overall description of the cores before they were sent to Japan for the next phase of the project. In August, the same group from Njord travelled to Japan for the second phase, which took place on the research vessel Chikyu. Onboard the ship, the aim was to precisely describe the cores which had been sampled during the winter. In January 2019, we received samples for further analysis. The goal is to study the timing and interaction between faulting and fracturing events and hydration of rocks from the oceanic mantle.

In May, Bjørn Jamtveit, Francois Renard, Sarah Incel, Arianne Petley-Ragan, Kristina Dunkel, and collaborator Yehuda Ben-Zion from the University of Southern California travelled to Lofoten for field work as part of the ERC/'DIME'-project. One of the main purposes of this trip was to explore different outcrops of seismic faults and ductile shear zones. The Lofoten archipelago provides a wide range of deformation features in different host rocks, including earthquake-produced frictional melts (now present as the rock 'pseudotachylyte') formed both in the absence and presence of fluids.

Jamtveit, Petley-Ragan and Dunkel also travelled to the Bergen Arcs in June along with Håkon Austrheim to collect pegmatites in an attempt to date deep crustal seismic faulting during the Caledonian orogeny. The samples were used for U-Pb geochronology, and for bulk rock geochemical analyses.

View from the Eastern part of the Al Hajar mountains in Oman. Picture by Claire Aupart.

The Japanese scientific drilling vessel, the Chikyu in the harbor of Shimizu in Japan. Picture by Claire Aupart.

Transport via Billefjorden to field location in Svenskehuset, Svalbard to sample and characterise excellently exposed volcanic sill.

Picture by Karen Mair.

In August, Ole Rabbel, Tobias Schmeidel and Karen Mair travelled to Svalbard to study the fracture networks of igneous intrusions and their host rocks in Isfjorden, Svalbard. The trip was funded by NRC through an Artic Field Grant to Ole Rabbel. Since fieldwork in Svalbard carries with it a range of risks that are distinctive for artic areas, they underwent a training program by UNIS for fieldwork in these areas before embarking on their fieldwork expedition.

With 2019 comes new opportunities for field work – and trips are already planned to California, Argentina, Lofoten, Bergen Arcs and elsewhere across the globe.

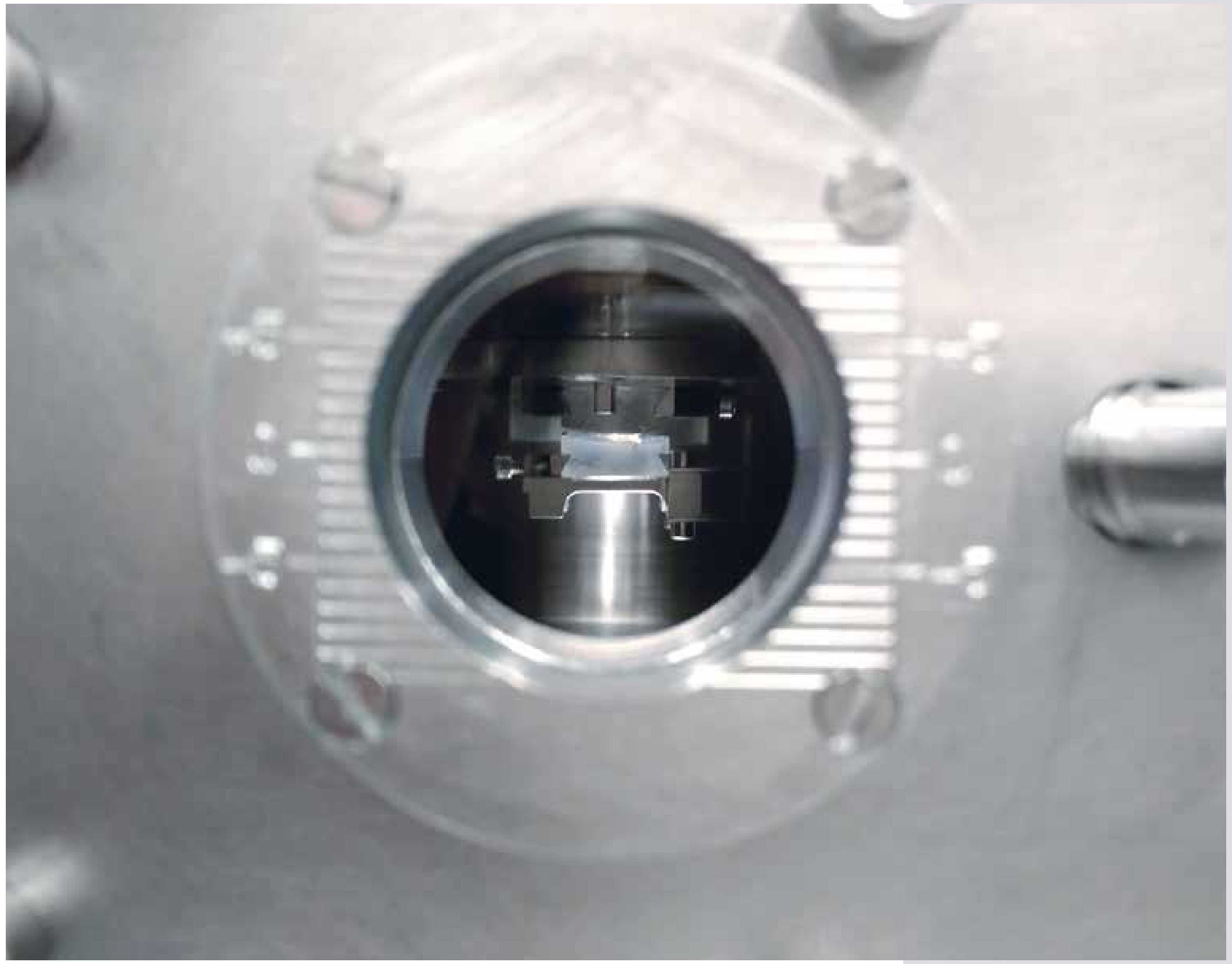
Laboratories

PGP: Within the Njord centre, researchers from both Department of Physics and Department of Geosciences use several laboratories facilities. PGP's three specialized laboratories (Frication lab, Volcanoe lab, and Flow lab) are equipped with several state-of-art techniques and apparatuses.

Flow Lab: At Flow lab, we have a Surface Forces Apparatuses (SFA 2000) equipped with a Spectrometer IsoPlane SCT320 that enables directly measurements of the static and dynamic forces between surfaces. We have a whole set of photolithographic equipment that can fabricate microfluidic channels, the size of channels ranges from million meter to Nano meter. 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, and Olympus PMG 3.

Frication Lab: At Frication lab we have two white light interferometer microscopes from Bruker (ContourGT and NT1100), which provide the highest performing non-contact surface measurements for experimental samples. We also have one atomic force microscope (Nanowizard 4 from JPK). To measure how the properties of materials and composites change under different loading conditions, we have a CT5000 in-situ testing stage from Deben, that can be mounted on the X-ray microtomograph at the National Science Museum in Oslo for imaging samples during deformation. We have developed a triaxial rock deformation apparatus, the HADES rig (Renard et al., 2016), which is installed at the beamline ID19 at the European Synchrotron Radiation Facility in Grenoble. This rig can allow imaging rocks during deformation, at conditions of pressure and temperature up to 10 km depth, using dynamic X-ray microtomography. We have also developed a rock core holder, ARGUS, that can reach up to 10 MPa confining pressure. This core holder is used on neutron sources (ILL in Grenoble and PSI in Villigen) for neutron tomography imaging of fluid flows in rocks.

Volcanoe Lab: This laboratory focuses on the physical processes that govern magma transport through, and emplacement within, the Earth's crust on various scales. Newly designed, high-resolution/precision monitoring tools and cutting-edge laboratory materials of variable and controlled rheology help us to achieve this ambitious goal. The result is a new generation of (quantitative) laboratory models for the emplacement of dykes, sills, laccoliths and plugs in the Earth's crust. Additionally, the Volcanoe Lab's equipment applies to geological systems beyond volcanic processes, including simulations of glacier, lava flow, fault behaviour and caldera collapse.



Preparation of a 2-D flow experiment.

By concentrating both standard and state-of-art techniques in the same physical space, our laboratory benefits from a relatively high degree of independence.

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PoreLab: PoreLab's 4 specialized laboratories at UiO are equipped with a wide set of state-of-art techniques to study the dynamics and structure of flow in 2D and 3D porous media. We have a full range of high-resolution and high-speed imaging techniques, including 2 ultrafast Photron Ultima (SA5 and APX) cameras with 7000 fps. at a spatial resolution of 1024x1024 pixels and up to 1 million fps. at a reduced resolution.

We have also a high-resolution FLIR SC300 infrared camera used for real-time measurements of heat dissipation in fractures, hydrofractures and porous media flows 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 stereo microscope which couples to our high-speed and high-resolution cameras and is in process of being upgraded for enhanced magnification. Flicker-free illumination sources tailored for the different applications (including high-speed microscopy) are also available. PoreLab have recently bought a *Krüss DSA25* drop shape analyzer to perform direct measurements of surface tension, wetting properties and surface free energy. Additionally, our laboratories include a large set of different optical equipment, such as lasers with different intensities and wavelengths, lenses and other optical components, cameras and microscopes for Particle Image Velocimetry. We are well-equipped to perform homodyne correlation spectroscopy for the measurement of particle velocity fluctuations in fluids, diffusion constants and viscosities. We further have a modern optical tweezer setup, fully equipped for particle manipulation and fluctuation studies at microscopic scales.

In addition to this wide variety of state-of-art techniques, our laboratories are also fully equipped with standard fluid mechanics labware, such as capillary viscometers, high-precision scales, pressure and temperature sensors, surface treatment chemicals for the control of wetting properties and general laboratorial glassware. By concentrating both standard and state-of-art techniques in the same physical space, our laboratory benefits from a relatively high degree of independence.

04

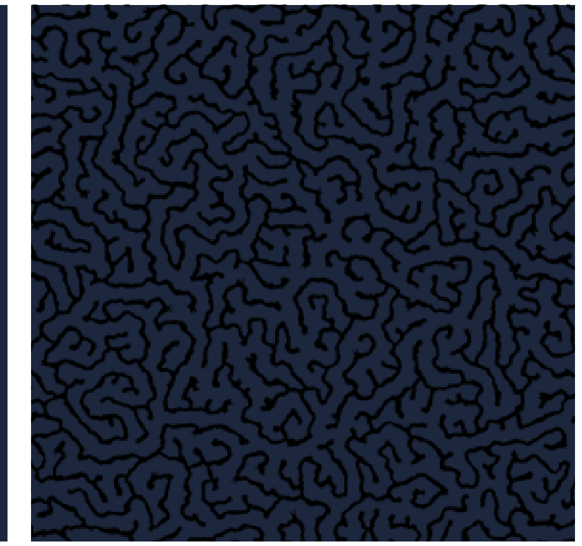
Research Projects

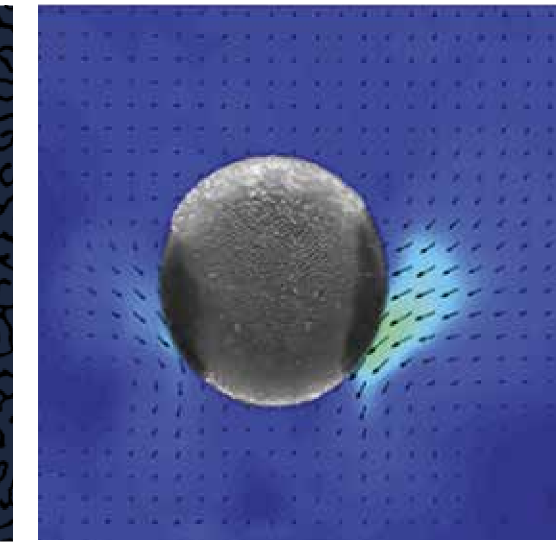
Much of the research at the Njord Centre is focused on the dynamics of fluid migration through porous materials and geological media. Some of it is focused on single or multi-phase fluid dynamics in the confinement of a complex pore space where fluid-solid interactions vary along the interfaces. In other 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.

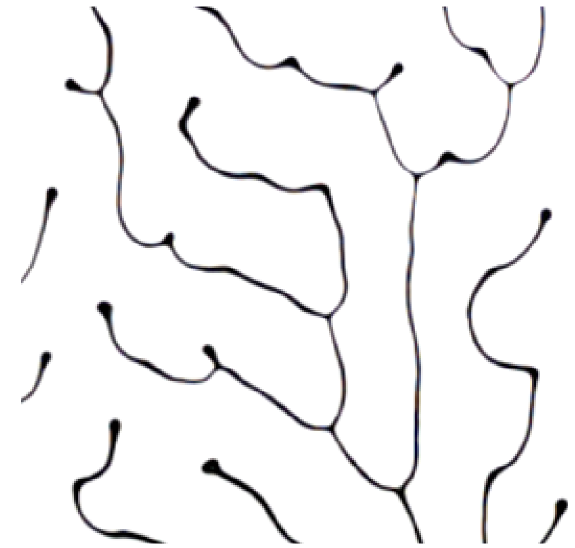
About Chapter 4

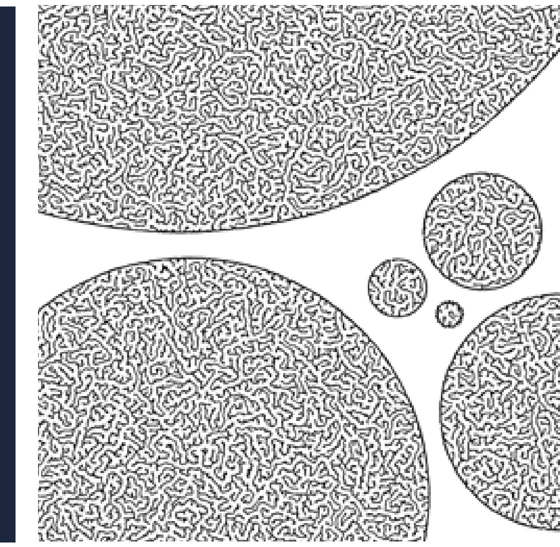
Part 1 Fluid Flows in Complex Media
Part 2 Pattern Formation and Dynamical Systems
Part 3 Fracture and Friction in Rocks and Materials
Part 4 Coupled Chemical Processes from the Nanoscale to the Scale of Continents

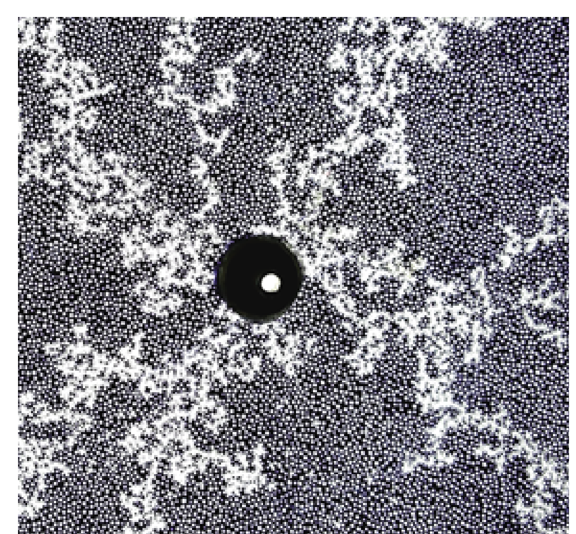
Fluids are often entering the solids through fractures. Hence, the physics of fracturing is a central Njord activity. In natural systems, fracturing is often associated with displacement along the fracture surface and the frictional properties of fractured surfaces are important. This situation applies 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 in 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 actin concert. Pattern-formation is perhaps the common denominator for all senior researchers currently working in Njord. The description of our research activity is divided into four overlapping sections: Fluid Flow in Complex Media, Pattern Formation and Dynamical Systems, Fracture and Friction in Rocks and Materials, Coupled Chemical and Mechanical Processes from the Nanoscale to the Scale of Continents











Chapter 4 | Part 1

Fluid Flows in Complex Media

1) Anomalous diffusion and the geometry of frictional fingers, *2) Connectivity enhancement due to thin film flow in porous media*, 3) Fluid driven deformation and channel formation in confined granular media, *4) Dynamics and structure of interfacial crack*, 5) Frictional Fluid Dynamics and Plug Formation in Multiphase Millifluidic Flow, *6) The relative probability of pore invasion events during the slow drainage of a porous medium*, 7) Particle-covered drops in electric fields: drop deformation and surface particle organization, *8) Realization and scanning of 2 phase flow experiments in 3D*, 9) Dispersive Transport in Porous Media *10) Rheology of High-Capillary Number Flow in Porous* 11) Steady state two-phase flow in porous media: Linking experiments, simulations and a thermodynamic description, *12) Physics of Volcanic Plumbing Systems*, 13) EarthFlows

Funding:
Norwegian Research Council,
CoE-program

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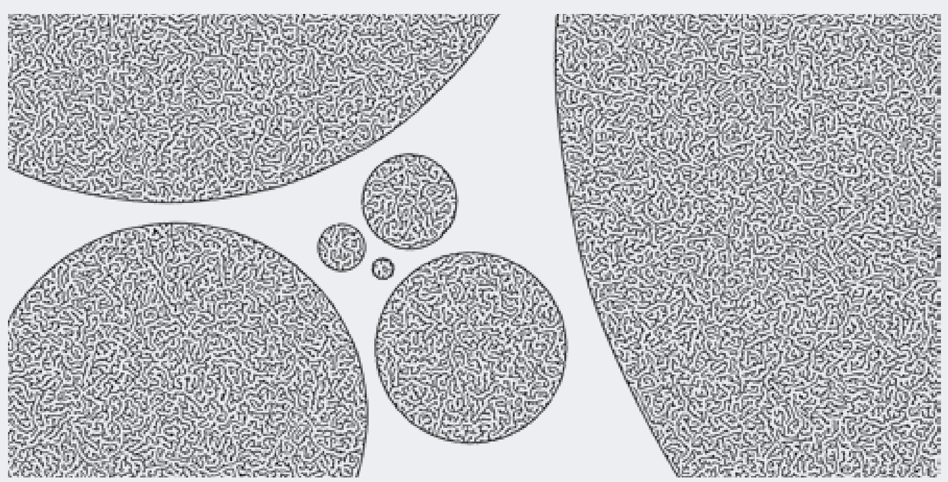
Anomalous diffusion and the geometry of frictional fingers

Introduction

Deformable porous media is a source of a myriad of complex patterns. Frictional fingers appear due to flow instabilities in quasi-2D systems dominated by frictional and capillary forces. These are complex branching structures that are space-filling in the sense that their standard Euclidean fractal dimension is very close to 2. It may be argued that a more natural choses of distance measure is the geodesic distance along the branches. This allows for a study of the geometry of the patterns without reference to its orientation or distribution in the Euclidean plane, and is in a sense a topological study.

Main results

When a random walker explored such a geometry, its dynamical properties reflect many geometric and topological properties. We can therefore think of a random walker not only as a way to study transport in complex systems, but also as a probe of the geometry. In particular, we have studied the relation between the anomalous diffusion exponent and geometry of the frictional finger patterns. Several analytical results are known for random walkers in tree-like geometries. In particular, the Alexander-Orbach relation and a version of the fluctuation-dissipation theorem predicts that the diffusion exponent for space-filling trees depend only on the average fractal dimension of the shortest paths in the tree. In this way, the random walker as a probe of geometry contains two essential fact about the frictional fingers: its space-filling nature and the fractal properties of the branches. We have numerically tested this prediction, with a positive outcome. Another fractal dimension, based on Horton-Strahler ordering, is also estimated using both analytical and numerical results.



Frictional finger patterns of different sizes generated numerically.

Publications:

B. Sandnes, H. A. Knudsen, K. J. Måløy, and E. G. Flekkøy, *Physical Review Letters 99, 1* (2007).

H. A. Knudsen, B. Sandnes, E. G. Flekkøy, and K. J. M° aløy, *Physical Review E 77, 1* (2008).

J. A. Eriksen, R. Toussaint, K. J. Måløy, E. G. Flekkøy, and B. Sandnes, *Physical Review E 92* (2015).

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CoE-program

Participants
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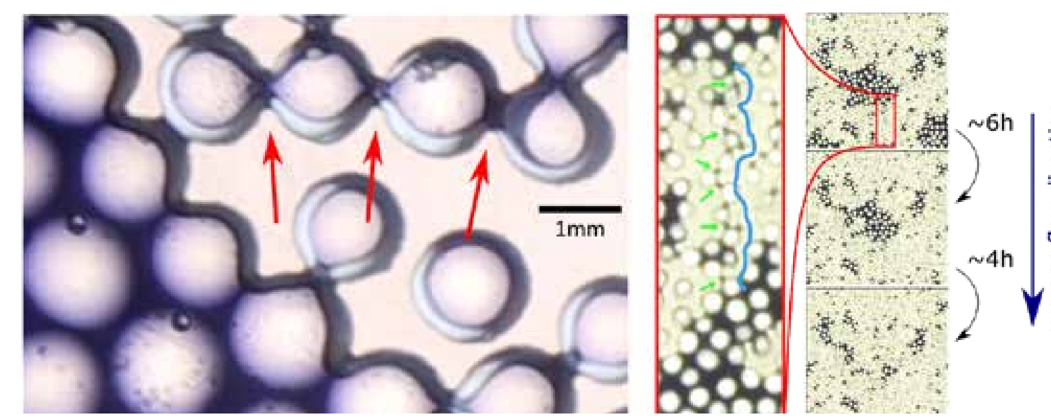
Connectivity enhancement due to thin film flow in porous media

The standard fluid transport processes in porous media happen through the usual network of interconnected pore bodies and pore throats (here called the *primary network*). When air displaces water from a porous rock, thin films of water are left behind, covering the rock grains. In general, when a non-wetting phase displaces a wetting phase from a porous sample (drainage), thin films of the wetting phase are bound to be left on the surface of the constituting grains. Under certain conditions, isolated liquid films can eventually merge, forming a *secondary network* of interconnected films and capillary bridges that can effectively enhance the overall connectivity of the medium and act as a new pathway for fluid transport.

Experiments in transparent networks have shown the existence of an *active zone* behind the main invasion front where the probability of drainage (via the secondary network) of seemingly trapped clusters is maximized. Fig. 2 shows an experiment in which a monolayer of glass beads, initially saturated with a viscous liquid (wetting phase, dark color), is slowly invaded by air (non-wetting phase, light color). After the usual drainage process, a set of trapped liquid clusters remains in the sample, but we observe that a small portion of them can (surprisingly!) still be drained. The three frames in the rightmost panel in Fig. 2 show the drainage of a cluster that would otherwise be trapped if transport happened only through the primary network. This kind of drainage event can only be possible due to the enhanced connectivity introduced by the secondary network of thin films and capillary bridges (red and green arrows in the figure).



Thin liquid films and capillary bridges (red arrows in the left panel and green arrows in the central panel) can enhance the connectivity of a porous medium leading to the drainage of seemingly trapped liquid clusters (as seen on the right part of the figure). The central panel shows an enlarged view of the red rectangle, indicating that the capillary bridges help to form a connected pathway (schematically shown by the blue line) between the cluster being drained and the outlet of the system.

Publications:

M. Moura, K. J. Måløy, E. G. Flekkøy, Gerhard Schäfer and R. Toussaint, *"Connectivity enhancement due to film flow processes in porous media,"* in preparation.

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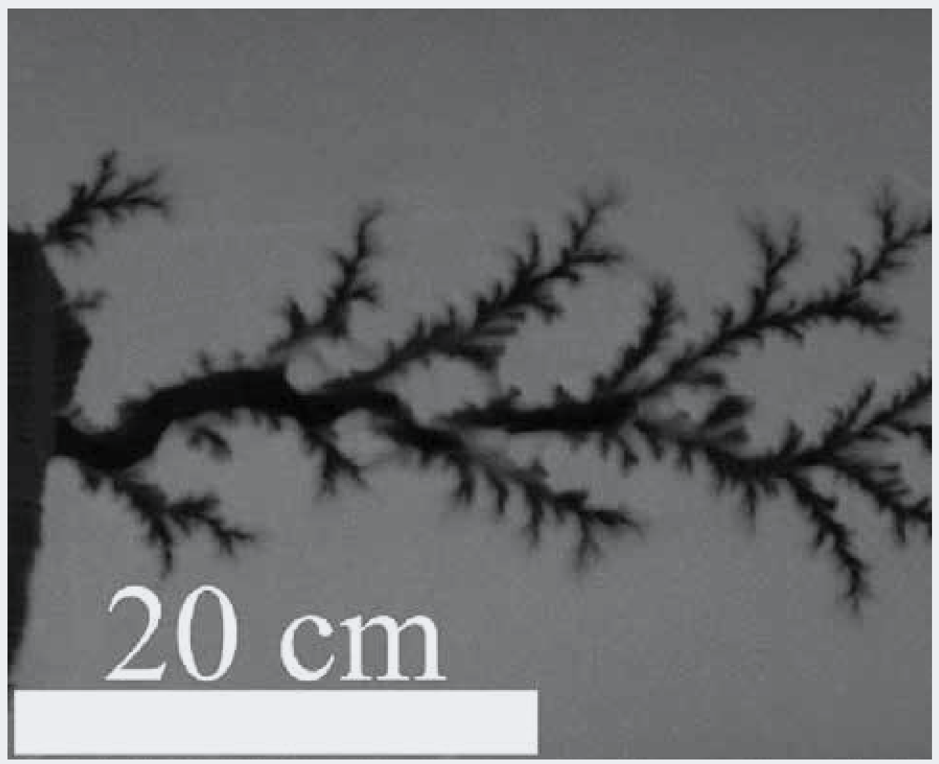
Fluid driven deformation and channel formation in confined granular media

When a fluid is injected into a porous or granular medium at a sufficient overpressure or flow rate, it will deform the medium and open up flow channels or fractures as shown in the figure below. The formation of these channels increases the permeability of the medium, which can be an advantage. Processes like this often occur in industry, for example to enhance oil & gas recovery, CO_2 storage, water well- and thermal energy production. As an adverse effect, such fluid injections also lead to changes in the stress state of the reservoir rock surrounding the channels, which may de-stabilize the region.

Industrial fluid injections and deposits have sometimes led to deformation and pressure changes in the earth's crust resulting in unwanted damage, even earthquakes far away from tectonic plate boundaries. In this project, we study and characterize the phenomena of fluid driven deformation and channel formation in a fine grained medium (80 ffim beads) confined between two horizontal glass plates (separated by 1 mm).

In experiments, we inject air with overpressures in the range 50 – 250 kPa while filming from above with a high-speed camera. We obtain channel structures and deformation over time from the images, and evaluate the pore pressure evolution numerically. We present fundamental observations and theoretical models from the results.



A top-down image of the invasion channels (black) formed in a granular medium between two glass plates (gray) when air is injected from the left side at a constant pressure of 200 kPa. The long sides of the cell are completely sealed, while the right side has a filter that stops beads but allows air to escape. In this experiment, pressurized air forces its way through the medium to reach the atmosphere, leading to the formation of these branched channels.

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Publications:

F.K. Eriksen, R. Toussaint, A.L. Turquet, K.J. Måløy and E.G. Flekkøy. *Pneumatic fractures in confined granular media. Phys. Rev. E 95, 062901* (2017)

F.K. Eriksen, R. Toussaint, A.L. Turquet, K.J. Måløy and E.G. Flekkøy. *Pressure evolution and deformation of confined granular media during pneumatic fracturing. Phys. Rev. E 97, 012908* (2018)

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Dynamics and structure of interfacial crack

This project concerns the avalanche and extreme statistics of the global velocity of a crack front, propagating slowly along a weak heterogeneous interface of a transparent polymethyl methacrylate block. The different loading conditions used (imposed constant velocity or creep relaxation) lead to a broad range of average crack front velocities. Our high-resolution and large dataset allows to characterize in detail the observed intermittent crackling dynamics. Those quantities characterizing the crackling dynamics follow robust power-law distributions, with scaling exponents in agreement with the values predicted and obtained in numerical simulations of the critical depinning of a long-range elastic string, slowly driven in a random medium We further use state-of-the-art fast microscopy techniques to dynamically analyze the nucleation and propagation of fractures. Real-time dynamic measurements of the nucleation of micro-fractures are challenging to perform and mostly absent in the scientific literature. Our experimental setup provides the means to perform those measurements in a controlled manner.

This project concerns the avalanche and extreme statistics of the global velocity of a crack front, propagating slowly along a weak heterogeneous interface of a transparent polymethyl methacrylate block.
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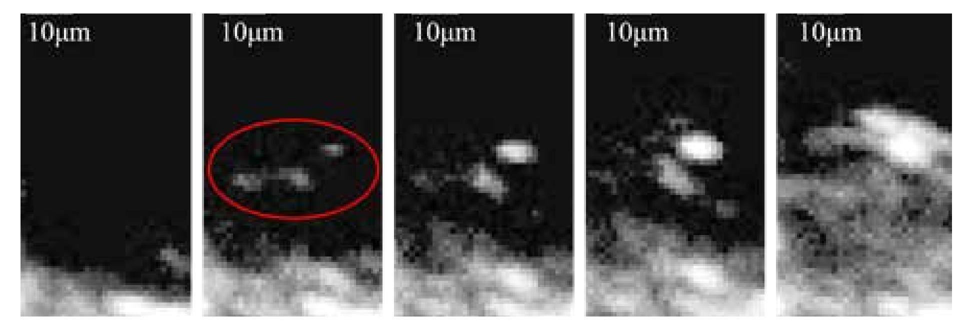

The figures show the nucleation and growth of micro-fractures, indicated by the red ellipse. The micro-fractures grow with time and finally merge with the main fracture interface.

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Publications:

S.Santucci, K.T. Tallakstad, L. Angheluta, L. Laurson, R. Toussaint, K.J. Måløy (2018) *Avalanches and extreme value statistics in interfacial crackling dynamics. Phil. Trans. R. Soc.* A20170394, http://dx.org/10.1098/rsta.20170394

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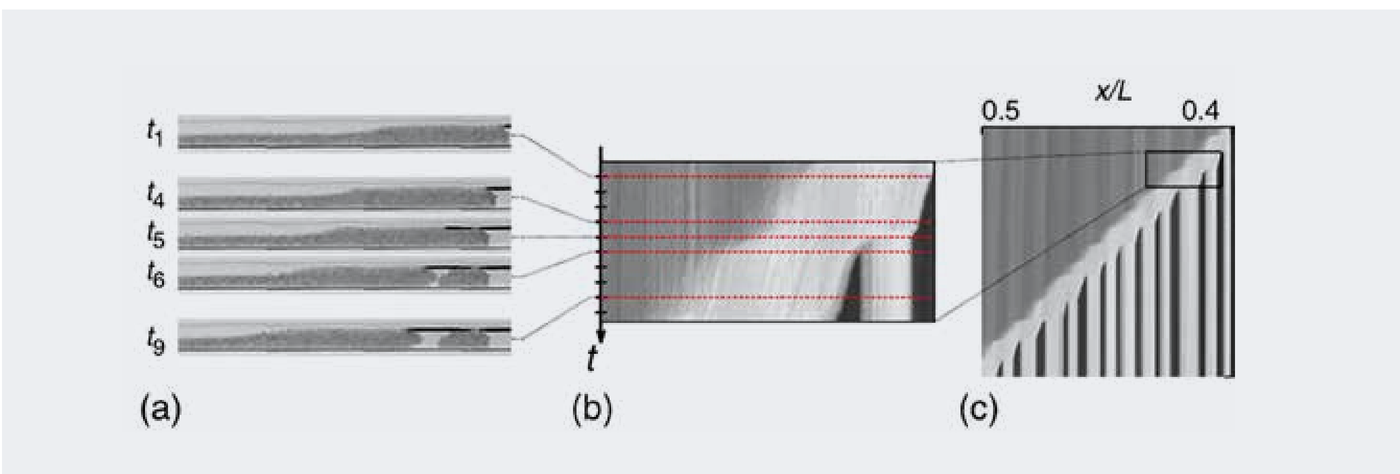
Frictional Fluid Dynamics and Plug Formation in Multiphase Millifluidic Flow

This project is motivated by the need to understand the way labyrints are formed, in particular the transition from granular displacement to drainage of a defending fluid by an invading one.

The progress of a capillary interface across a deformable granular material in a simple cylindrical tube shows the complex interplay between viscous forces, solid friction and capillary forces. There is a transition from a state of granular displacement to a state where the displacing fluid starts to invade the pore space between the grains. This transition causes plugs of a characteristic size to form, as is shown in the figure.

(a) Consecutive images of plug formation (a), a spatiotemporal diagram (c) and a close-up of that (b). It may be seen that the viscous displacement regime is characterized by a fluidization of the immersed granular material which is draged by the flow driving the displacement of the capillary interface.



This project is motivated by the need to understand the way labyrints are formed, in particular the transition from granular displacement to drainage of a defending fluid by an invading one.
–

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Publications:

Guillaume Dumazer, Bjørnar Sandnes, Monem Ayaz, Knut Jørgen Måløy, and Eirik Grude Flekkøy, *Phys. Rev. Lett. 117, 028002* (2016)

Funding:
Norwegian Research Council,
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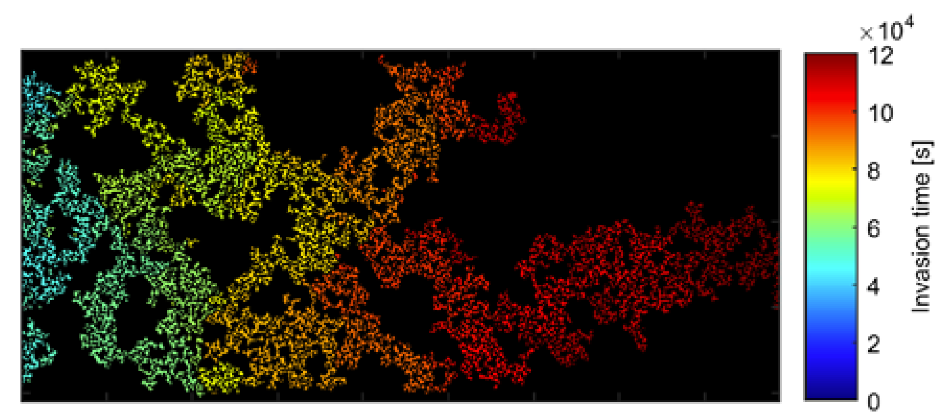
The relative probability of pore invasion events during the slow drainage of a porous medium

The process of drying of a porous or fibrous network is probably one of the most common examples of two-phase flow in porous media. Water evaporates from the soil when the Sun shines after a rainy day, and wet clothes hanging on a string are not too wet anymore after a couple of hours. Although extremely common, upon close inspection one quickly realizes that this process is in fact a lot more interesting than it might seem: the apparently continuous motion of the drying front actually happens as a rich succession of pore invasion events, one following the other in an intermittent manner. This is something that would be hard to guess if one looked only at the macroscopic perspective. In each invasion event, air penetrates into one or several pores, removing the liquid that previously filled the pore-space.

The intermittent dynamics of slow drainage flows has been extensively studied by the scientific community. In the late 80s, Furuberg et al. employed a numerical scheme called invasion percolation to analyze this system. They posed the following question: if a given pore is invaded at some specific time, what is the probability that another pore, located at some given distance from the first one will be invaded after a certain time? Their numerical work revealed the existence of an interesting dynamic scaling for the relative probability map (pair correlation function). Nearly 3 decades later we have been able to give experimental grounding to this important observation by employing artificial transparent porous networks, which allowed us to directly image the full invasion dynamics, see Fig. 1. We have also given a full theoretical explanation for the observed scaling regimes that complemented the ideas presented by Furuberg et al.



Spatiotemporal map of a slow drainage experiment in a porous network. Air invades the system from left to right, displacing a liquid from the initially saturated medium. The color map indicates the time at which a given pore is invaded by air.

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Publications:

M. Moura, K. J. Måløy, E. G. Flekkøy and R. Toussaint, *"Verification of a dynamic scaling for the pair correlation function during the slow drainage of a porous medium," Phys. Rev. Lett. 119, 154503* (2017), https://doi.org/10.1103/PhysRevLett.119.154503.

L. Furuberg, J. Feder, A. Aharony, and T Jøssang, *"Dynamics of Invasion Percolation" Phys. Rev. Lett. 61, 2117* (1988), https://doi.org/10.1103/PhysRevLett.61.2117.

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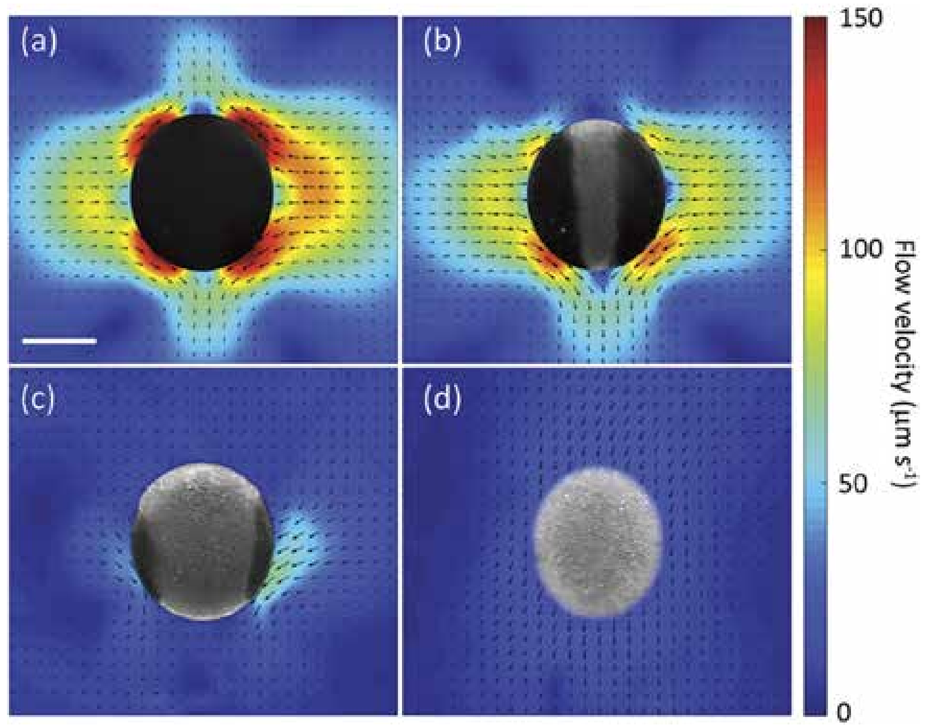
Particle-covered drops in electric fields: drop deformation and surface particle organization

Drops covered by adsorbed particles are a prominent research topic because they hold promise for a variety of practical applications. Unlocking the enormous potential of particle-laden drops in new material fabrication, for instance, requires understanding how surface particles affect the electrical and deformation properties of drops, as well as developing new routes for particle manipulation at the interface of drops.

In this study, we utilized electric fields to experimentally investigate the mechanics of particle-covered silicone oil drops suspended in castor oil, as well as particle assembly at drop surfaces. We used particles with electrical conductivities ranging from insulating polystyrene to highly conductive silver. When subjected to electric fields, drops can change shape, rotate, or break apart. We demonstrate how the deformation magnitude and shape of drops, as well as their electrical properties, are affected by electric field strength, particle size, conductivity, and coverage. We discuss the role of fluid flow induced by electric fields on drop deformation.

We also study the electric field-directed assembly and organization of particles at drop surfaces. In this regard, we studied various parameters in detail, including electric field strength, particle size, coverage, and electrical conductivity. Finally, we present a novel method for controlling the local particle coverage and packing of particles on drop surfaces by simply tuning the frequency of the applied electric field. This approach is expected to find uses in optical materials and applications. Our findings on drop deformation (or interface deformation) by various electric fields could introduce a method to control immiscible two-phase flow in porous media.

Image processing of experimental videos is done to characterize the flow field in the oil surrounding the drop. The flow field (color map) comes from following tracer particles in the surrounding oil. Here, we see that increasing the amount of particles (gray) on the drop reduces the flow induced by the electric field. The particle coverage is a) 0 %, b) 20 % c) 50% and d) 80 % (max.)



Publications:

A. Mikkelsen, K. Khobaib, F.K. Eriksen, K.J. Måløy, Z. Rozynek, *Particle-covered drops in electric fields: drop deformation and surface particle organization. Soft Matter, 14, 5442* (2018)

Funding:
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CoE-program

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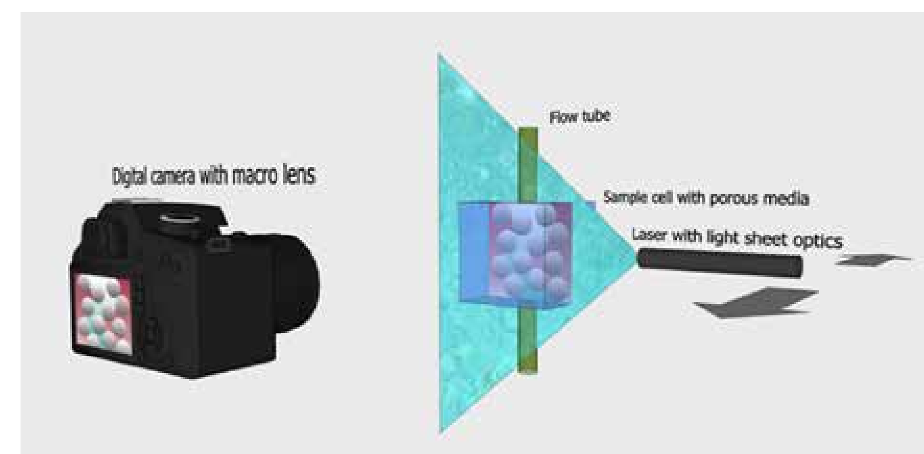
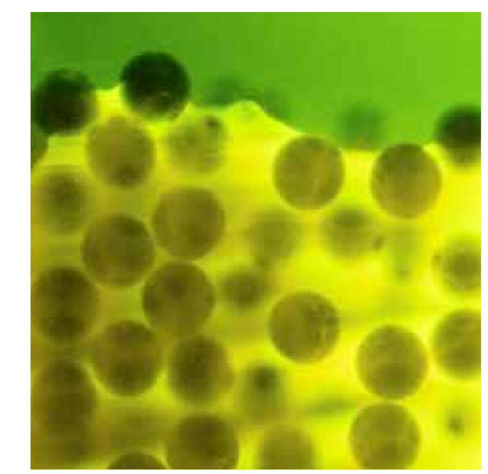
Realization and scanning of 2 phase flow experiments in 3D

We wish to scale these experiments up to 3D. Since the process of imaging a 3D sample is more complicated than in 2D (where we could benefit from the camera-friendly Hele-Shaw geometry), we need to take a different approach here. The basic idea is to make the porous media and the liquids used in the experiments transparent by matching the respective refractive indices. A sample is prepared with glass beads of uniform size, fully immersed in an index-matched liquid with fluorescent particles. The illumination coming from a laser sheet reveals a 2D slice of the sample that can be recorded with a high-resolution camera. By putting the camera and the laser on motorized stages a synchronized recording of the full sample can be realized (see Fig. 2).

A second liquid with fluorescent particles that emits at a different wavelength is then flowed through the porous network. The data from several parallel 2D sheets within the sample can then be processed using image analysis codes and a full 3D map of both liquid phases and the porous network can be obtained. Pressure sensors will be mounted at the inlet and outlet of the flow and we will use the setup to extend to 3D systems the characterization of steady-state flows previously done in 2D. It's worth mentioning that once the imaging technique is fully established, its applicability extends to a much wider array of possible studies in 3D two-phase flows, including not only the steady state case but also transient regimes.





Schematics of the 3D scanner being developed to study two-phase flows. On the left we show the main parts of the setup. A laser with light sheet optics is mounted on a moving stage to scan through the sample. A digital camera with appropriate lenses and filters is mounted on another stage. Flow control devices such as syringe pumps and pressure reservoirs can be directly connected to the setup. On the right we show an example of a typical 2D image, where one can identify the two liquid phases and the porous matrix (glass beads).

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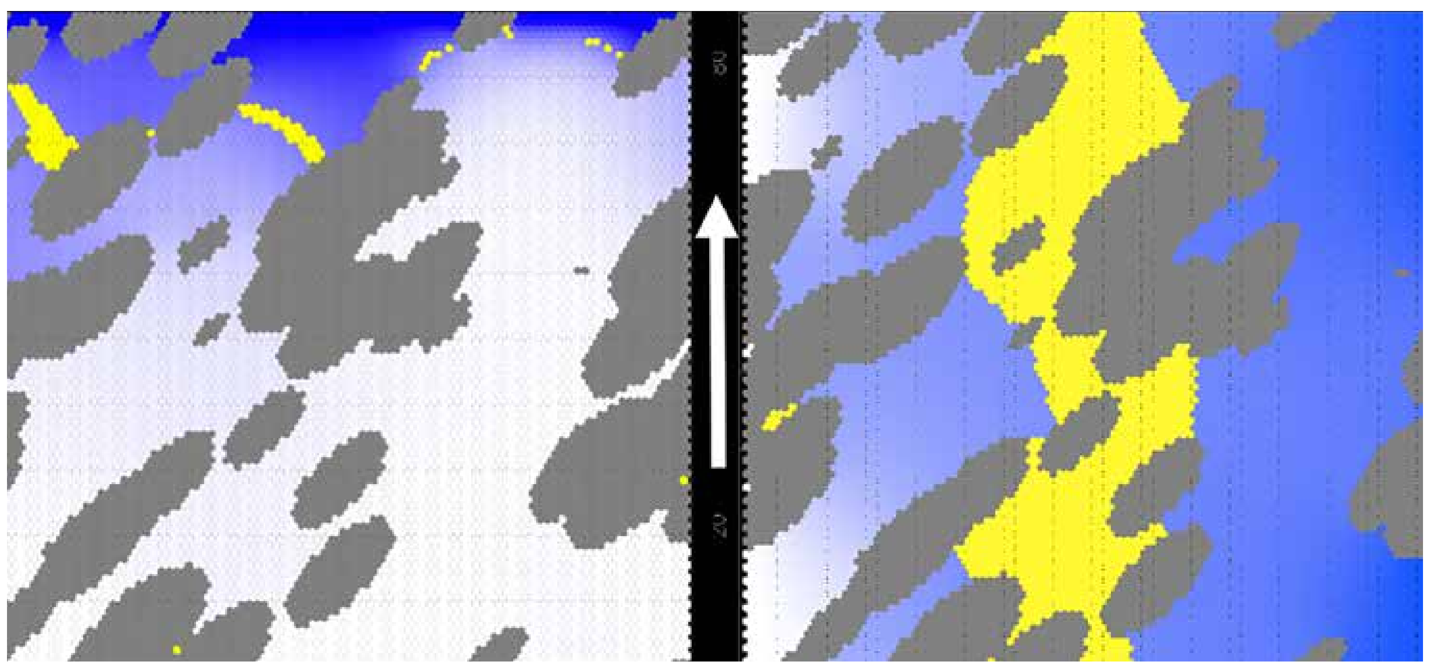
Dispersive Transport in Porous Media

It has long been assumed that the dispersion tensor controlling solute transport in a porous material is symmetric. The basis for this assumption has been to cite the Onsager reciprocity theorem. We show here that, in general, the dispersion tensor is not symmetric when advection of solute is important. On the contrary, it only becomes symmetric when the background flow field is reversed, that is, the transport in the x-direction due to gradients in the y-direction is the same as the transport in the y-direction due to gradients in the x-direction, provided the flow field is reversed everywhere. This symmetry is demonstrated analytically and investigated by lattice-Boltzmann simulations, as is illustrated in the figure.



Lattice Boltzmann simulations of dispersion in a porous media (gray). High concentrationsare shown by white, low concentrations by blue and intermediate values by yellow. The background flow is in the diagonal direction in both figures, but the concentration gradient is vertical in the first- and horizontal in the second figure.

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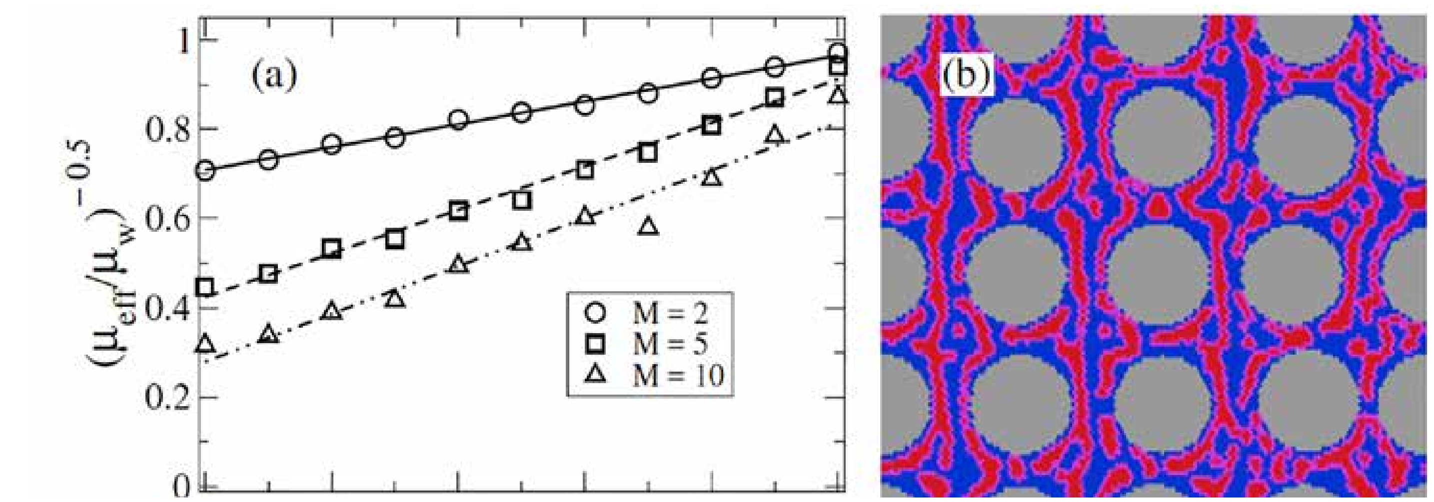
[3] PoreLab, Department of Physics, University of Oslo, Porelab, The Njord Center

Rheology of High-Capillary Number Flow in Porous



Flow of immiscible fluids in porous media at high capillary numbers may be characterized by an effective viscosity. We demonstrate that the effective viscosity is well described by the Lichtenecker-Rother equation

(a) Plot of the effective viscosity as a function of saturation.
(b) The corresponding lattice Boltzmann simulations with a less viscous wetting fluid (blue)

$$\mu^{\alpha}_{\text{eff}} = \mu^{\alpha}_{w} S_w + \mu^{\alpha}_{n} S_n \ ,$$

Here the exponent ranges from -1 to 1 and S_w and S^n are the saturations of wetting and non-wetting fluids respectively. Depending on the pore geometry, wettability and viscosity of the fluids, the exponent in this equation can have different values. We get the value 1 when fuids are well mixed with small bubbles, the values 0.5 and 0.6 in three-dimensional systems when there is less mixing with the appearance of big bubbles, and -0.5 when lubrication layers are formed along the pore walls, as is illustrated in the figure.

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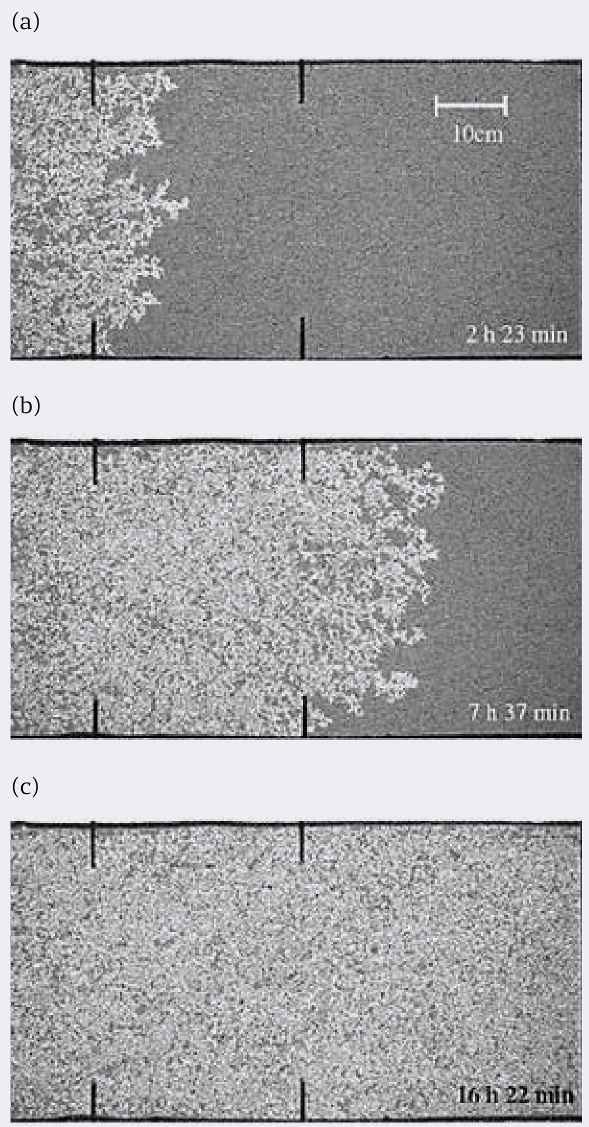
Steady state two-phase flow in porous media: Linking experiments, simulations and a thermodynamic description

During the previous decade, much attention was focused on understanding the flow instability that occurs when one fluid invades a porous medium saturated with an other fluid at rest. On the other hand, the simultaneous flow of both such fluids in a porous medium also occurs in many situations, but has been paid much less attention. Earlier experimental work has been done on simultaneous two-phase flow in porous media, however mainly in horizontal Hele-Shaw cells.

An important observation in these experiments is that a steady state configuration is eventually reached for the fluids. This experimental project aims to further explore steady state two-phase flow in porous media, where we will have the possibility to tilt the cell at any angle to play with the influence of gravity on the flow. In addition, we will perform measurements dedicated to aid the development of a new thermodynamic model for steady state two-phase flow in porous media.

We have been working on the preparation of this experimental setup, it is now complete, and we are ready to begin. In the experiments, 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 will capture high resolution images in time-lapse series during the experiments, record the pressure at several locations in the cell, and systematically vary the influence of gravity.



The system is shown at three different times. Both fluids are injected at left hand side; the outlet is at the right. The left panel a) shows a sample in the early transient regime, where air is invading the initially liquid saturated sample. The water-glycerol mixture is of dark color and the air is white. The middle panel b) shows a later stage in the transient regime with a local steady state behind the invasion front, and the right panel c) shows the fully developed steady state where the system is in a statistical equilibrium. In this state, both fluids are flowing through the system while the distribution of the air and liquid phases remain more or less constant over time.

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Physics of Volcanic Plumbing Systems

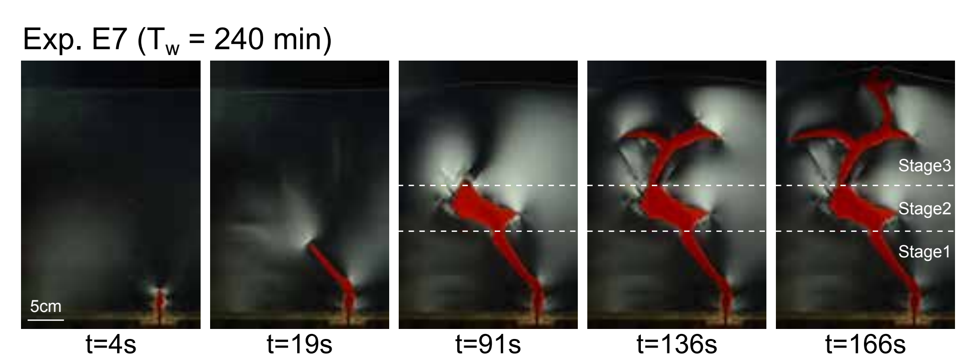
In this project, we designed multi-disciplinary research that integrates quantitative field observations, geological and geophysical subsurface data, and laboratory modelling, numerical and theoretical modelling to reveal the dynamics of volcanic plumbing systems.

Mechanics of dyke emplacement
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. We designed 2D quantitative laboratory modeling of a viscous golden syrup intruding into fine-grained cohesive flour of varying cohesion in a 2D Hele-Shaw cell (Guldstrand et al., in preparation). We performed strain analyses in the host rock of the propagating intrusions and we show that sheet intrusions are associated with uplift and shear bands extending from the intrusion tip. Our results are in very good agreement with field observations (Magee et al., 2018), results from 3D laboratory experiments (Guldstrand et al., 2017; Poppe et al., in revision) and numerical models (Souche et al., in revision), but contradict established theories of dyke emplacement.

Emplacement of tabular intrusions
Tabular intrusions are common features in the Earth's brittle crust (Galland et al., 2018). Field and seismic observations show that numerous sills exhibit lobate morphologies. In order to understand the emplacement of igneous fingers, we performed detailed structural mapping on an exceptional, easily accessible 1-km long outcrop in the Neuquén Basin, Argentina, which exhibits a sill, its contacts and the structures in the finely layered sedimentary host rock (Galland et al., submitted)(Figure 1). We also demonstrate that the fingers were emplaced according to the viscoelastic fingering or viscous indenter models, not as tensile elastic fractures as commonly assumed in mechanical models of sill emplacement.

Field observations show that tabular intrusions exhibit a broad variety of shapes, ranging from thin sheet intrusions (sills, saucer-shaped sills, cone sheets), to more massive intrusions (domed and punched laccoliths, stocks). We investigate the effects of the host rock's Coulomb properties on magma emplacement by integrating (1) laboratory models using dry Coulomb granular model hosts of variable strength (cohesion) and (2) limit analysis numerical models (Haug et al., 2018; Schmiedel et al., accepted). Our results show that both sheet and massive tabular intrusions initiate as a sill, which triggers shear failure of its overburden along an inclined shear damage zone at a critical sill radius R, which depends on the emplacement depth and the overburden's cohesion. Our study suggests that the emplacement of sheet and massive tabular intrusions are parts of the same mechanical regime, in which the Coulomb behavior of the Earth's brittle crust plays an essential role.

Magma emplacement in visco-elasto-plastic crust
The mechanics of magma emplacement in the Earth's crust corresponds to the flow of a viscous fluid into a deforming solid. The Earth's crust through which magma is emplaced is visco-elasto-plastic, and field observations show that most intrusions are likely to be accommodated by combined brittle and ductile deformation of their host. We designed a series of 2D experiments where a viscous fluid (oil) was injected into a host matrix (laponite gel), the visco-elasto-plastic rheology of which is varied from dominantly viscous to dominantly elastic (Bertelsen et al., 2018) (Figure 2). Our experiments show a strong correlation between intrusion shapes and host matrix deformation modes: (1) thin intrusions dominantly propagate by tensile failure and elastic deformation of the host, (2) rounded "diapiric" intrusions dominantly propagate by viscous flow of



Time series photographs of characteristic laboratory experiment of oil intrusion in visco-elasto-plastic laponite gel (Bertelsen et al., 2018).

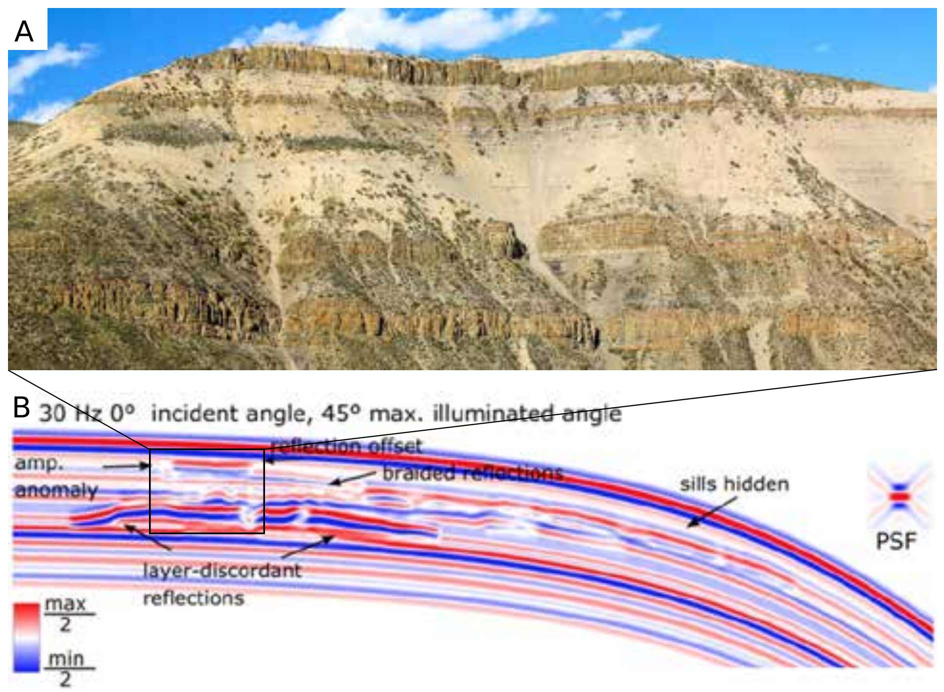
the host, and (3) irregular "hybrid" intrusions propagate by coeval brittle (tensile and shear) and ductile deformation of the host. Our novel experiments are the first able to produce the natural diversity of intrusion shapes and host deformation mechanisms.

Petroleum implications of igneous intrusions

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 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 (Spacapan et al., 2018a;b), (2) the igneous sills are fractured reservoirs for the hydrocarbons (Spacapan et al., revised; accepted), (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., submitted).

In addition, we integrate seismic-scale outcrop structural mapping of exceptionally well exposed sill complexes with state-of-the-art seismic modelling to assess the challenges inherent to seismic imaging of igneous sill complexes (Rabbel et al., 2018) (Figure 3).

Field photograph of well-exposed andesitic sills emplaced in organic-rich shale. This outcrop is an exceptional field analogue of nearby hydrocarbon fields hosted in igneous sills (Spacapan et al., 2018a; b; revised; accepted; submitted). B. Synthetic seismic model calculated from the entire outcrop of A (Rabbel et al., 2018). The box locates the extent of photograph A, which is a close-up of a 4-km long exposed geological section.



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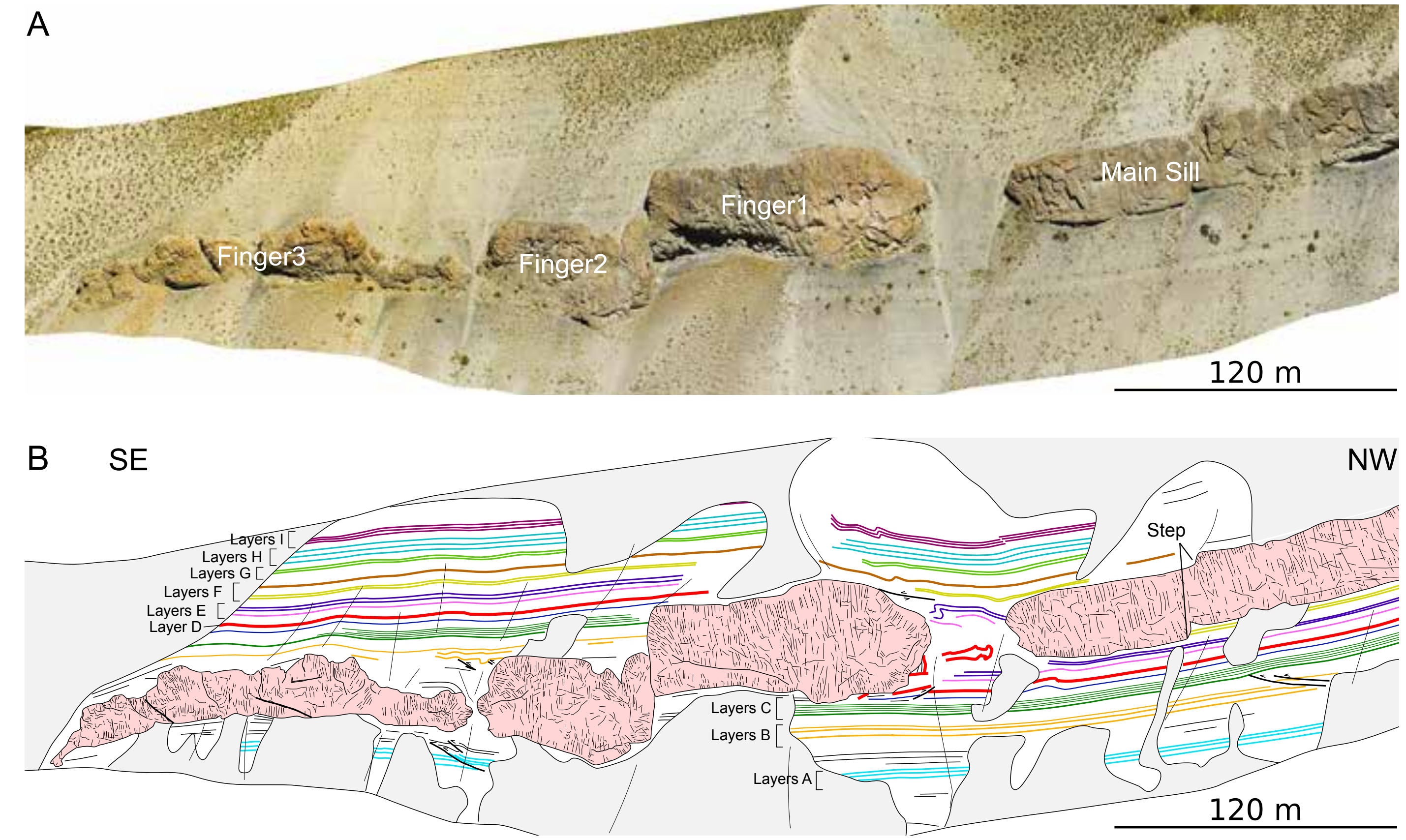

Orthorectified image of exceptional outcrop of igneous sill and fingers emplaced in organic-rich shale. B. Structural map of the orthorectified image in A. The structures in the host rock reveal the emplacement mechanisms of the igneous intrusions. After Galland et al. (submitted).

Publications:

Rabbel, O., Galland, O., Mair, K., Lecomte, I., Senger, K., Spacapan, J.B., Manceda, R.E., 2018, *From field analogues to realistic seismic modelling: A case study of an oil-producing igneous sill complex in the Neuquén Basin, Argentina*. Journal of the Geological Society, doi: https://doi.org/10.1144/jgs2017-116.

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Funding:
University of Oslo, Strategic Research Initiative

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EarthFlows

Geophysical flow processes provide first order controls on the evolution of the Earth's crust and near-surface environments, including the hydrosphere, the atmosphere, the cryosphere and even the biosphere. The flow may include magmas, water and air, or chemically and physically more complex fluids such as hydrocarbons, CO_2-water mixtures, and fluid-solid mixtures. Moreover, several rocks as well as ice, can behave both as solids or fluids, depending on the relevant time scales. The solid Earth provides the boundary conditions for a variety of flow processes on all scales. These boundaries, the interfaces between the Earth and the Flows, can be highly complex and evolve in time as a result of interactions between the flows and the solid Earth. Despite the variety of such interfaces in natural systems, their dynamics can be adequately described with a very limited set of mathematical concepts and equations, enabling a focused approach to a large number of geophysical processes. The Earth-Flow boundary also represents a rarely crossed scientific frontier between specialists in fluid dynamics and fluid flow processes and researchers focused on the solid materials of the Earth. The dynamics of the solid-fluid boundary is rarely studied in detail as this requires an interdisciplinary group of researchers, with expertise both in the dynamics of the fluid and the solid Earth, and with theoretical, numerical, observational and experimental expertise.

Lacking insights into the dynamics of the solid-fluid boundaries seriously limits the understanding of a large range of geophysical flow processes. The goal of the EarthFlows project is to provide fundamentally new understanding of the dynamics of fluid-solid interfaces for a number of important geophysical systems, including: Magma and hydrocarbon movements in a deforming crust; Glacier flow; Reactive fluid migration in stressed rocks; and Granular flow in a fault. EarthFlows also study interfacial dynamics in air-water pipe flow.

Project example:

Our incomplete understanding of glacier dynamics is a major source of uncertainty in assessments of sea-level rise from land-based ice. Through increased ice discharge into the oceans, fast glacier flow has the potential to considerably accelerate expected sea level change, well ahead of scenarios considered by the IPCC. At the heart of this problem lies our inability to accurately predict the friction at the ice/bedrock interface, which remains a long-standing problem in glaciology. We have introduced, for the first time, a rate-and-state type friction law that applies for glaciers. This framework allows for direct modeling of both transient glacier dynamics and glacier-flow instabilities through the introduction of unstable velocity-weakening branches.

We have demonstrated the potential of this new concept by modeling the perhaps most striking class of glacier-flow instabilities: Glacier surges. After a long period of quiescence, some glaciers suddenly accelerate, sometimes by orders of magnitude for a period of time before returning to quiescence. The mechanism responsible for glacier surges has been discussed for decades, but still no consensus on a unifying surge mechanism exists. We identify a transition from velocity-strengthening to velocity-weakening friction including a characteristic length scale for the evolution of frictional strength as a sufficient criterion to explain the onset of glacier surges, observed features of surge propagation, as well as the time-dependent evolution of frictional strength found in previous inversions of friction at glacier beds during a surge. A direct consequence of the rate-and-state framework is the emergence of an instability criterion for the onset of rapid glacier motion. The criterion can be reached locally leading to a fast flowing region that propagates up and down-glacier possibly affecting the entire glacier. The instability criterion can be reached in numerous ways; e.g. geometrical changes of the glacier or increased water pressure.

Publications:

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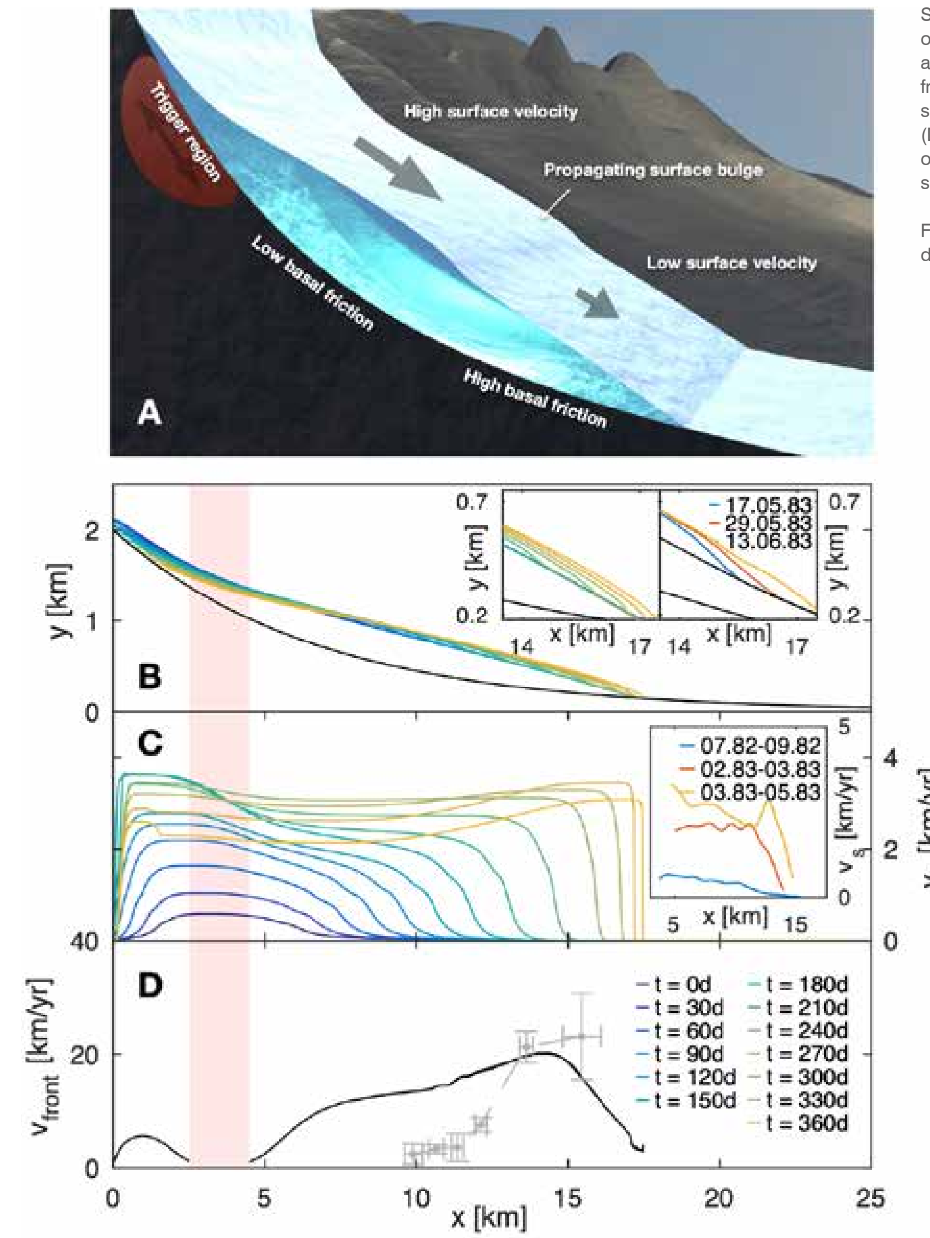

Summary of our main findings: (A) a sketch of the propagation of glacier surges. (B): Modeled surface elevation during a glacier surge, with a zoom in the left inset and observations from the Variegated glacier in the right inset. (C): Modeled surface velocity with observed surface velocity in the inset. (D) modeled surge propagation speed with crosses showing observations from the Variegated glacier. The red rectangle shows the trigger region.

From 2019, EarthFLows I will continue as EarthFLows II, directed by Luiza Angheluta (PI) and Francois Renard (co-PI).

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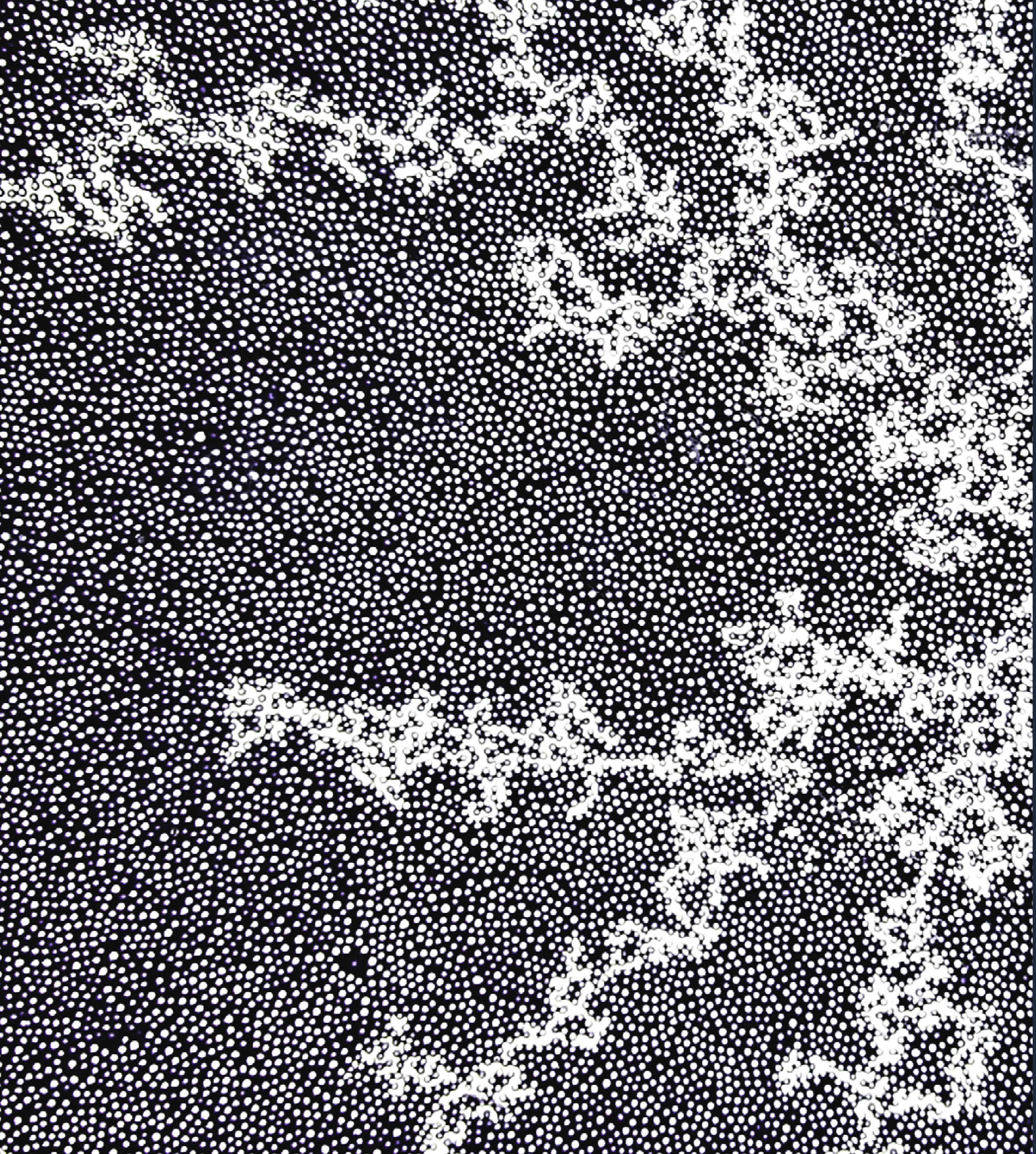

Pattern Formation and Dynamical Systems

1) Complex free-energy landscapes for spin-crossover materials, *2) The fabulous flying chain*, 3) Pattern formation of frictional fingers in a gravitational potential, *4) Dynamics of network evolution*

Funding:
Norwegian Research Council, CoE-program

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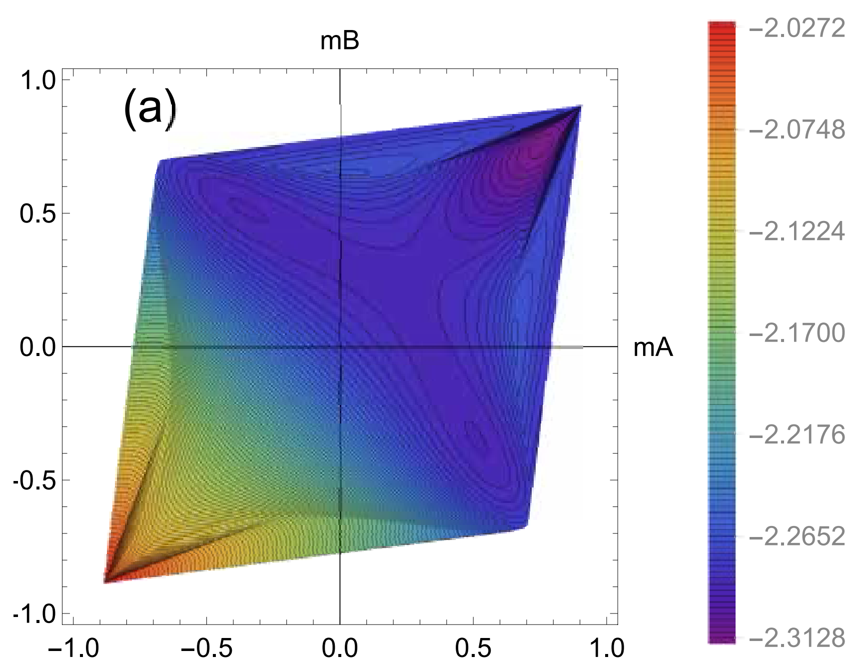
Complex free-energy landscapes for spin-crossover materials

Background

In this collaboration with researchers in Japan, we study the effects of competing short-range attractive and long-range repulsive interactions on the complex phase diagrams and dynamics of spin-crossover (SC) materials. These are organic molecular crystals, in which the molecules contain transition-metal ions that can exist in two different spin states: a low-spin ground state (LS) and a high-spin excited state (HS). The HS molecules have higher degeneracy and larger volume than the LS ones. Due to the higher degeneracy of the HS state, SC crystals can be brought into a HS phase by changing temperature, pressure, or magnetic field, or by exposure to light. The resulting phase diagrams contain multiple stable and metastable phases that make SC materials suited for technological applications, including memories, switches, and actuators.



Contour maps of an example free-energy landscape for a model SC material [1]. The color changes from orange to purple as the free energy decreases.

Recent results

The latest result of this project is a paper [1], in which we obtain free-energy landscapes (FEL) of a model SC material by a novel cluster mean-field approximation. An example FEL is shown in the Figure. Under the particular conditions of pressure, temperature, and model parameters used here, the stable phase is uniform, with equal, high concentrations of HS molecules on two interpenetrating sublattices of the model (mA = mB fj 0.7), represented by the global free-energy minimum (FEM) in the first quadrant of (a). Metastable phases with equal concentrations of HS and LS molecules on the two sublattices, respectively, are represented by local FEM in the second and fourth quadrants of (a). A secondary, metastable phase is represented by the very shallow, local FEM near mA = mB = 0.2, near the center of the enlarged detail figure (b). It is a disordered phase, consisting of equal concentrations of HS and LS, randomly distributed on the two sublattices.

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Publications:

[1] P. A. Rikvold, M. Nishino, C. Omand, and S. Miyashita. *Multistability in an unusual phase diagram induced by the competition between antiferromagnetic-like short-range and ferromagnetic-like long-range interactions*. Phys. Rev. B 98, 144402 (2018).

Funding:
Norwegian Research Council, CoE-program

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The fabulous flying chain

Quantum mechanics and general relativity are the usual buckets to which the everyday scientist goes to whenever in the mood for a daily dose of strangeness. However (and perhaps even more strangely) sometimes very classical systems can behave in ways that seem to contradict our entire notion of what regular objects moving at regular speeds are supposed to do.

A remarkably unusual phenomenon occurs when one puts a long chain of metallic beads inside a container (the same kind of chain that is sometimes used to open or close the curtains) and drops one of its ends from a given height. Instead of simply falling down toward the ground, the chain moves upwards first, developing a striking vertical loop which extends far beyond the edge of the container. This very curious gravity-defying behavior was the subject of a (now viral) YouTube video produced by science communicator Steve Mould in 2013. The cause behind the loop formation is a reaction force that the beads lying in the container exert against the immediate chain segment that is triggered into motion as this segment is dragged by the previously moving part of the chain. Using computer simulations, experiments and theoretical arguments, we have studied the nature of that force and how it depends on the parameters related to the chain geometry (its resistance to bending) and on the bumpy interaction between the moving chain and the underlying bead pack.

A remarkable self-sustained arch is formed when a long chain of metallic beads is dropped from a container (placed approximately 5m above the ground in this experiment). In the background we see the Physics Department at the University of Oslo.

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Publications:

E. G. Flekkøy, M. Moura and K. J. Måløy, *"Mechanisms of the flying chain fountain," Front. Phys. 6, 84* (2018).

Mould S., *"Self siphoning beads"*: https://www.youtube.com/watch?v=_dQJBBklpQQ

Funding:
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CoE-program

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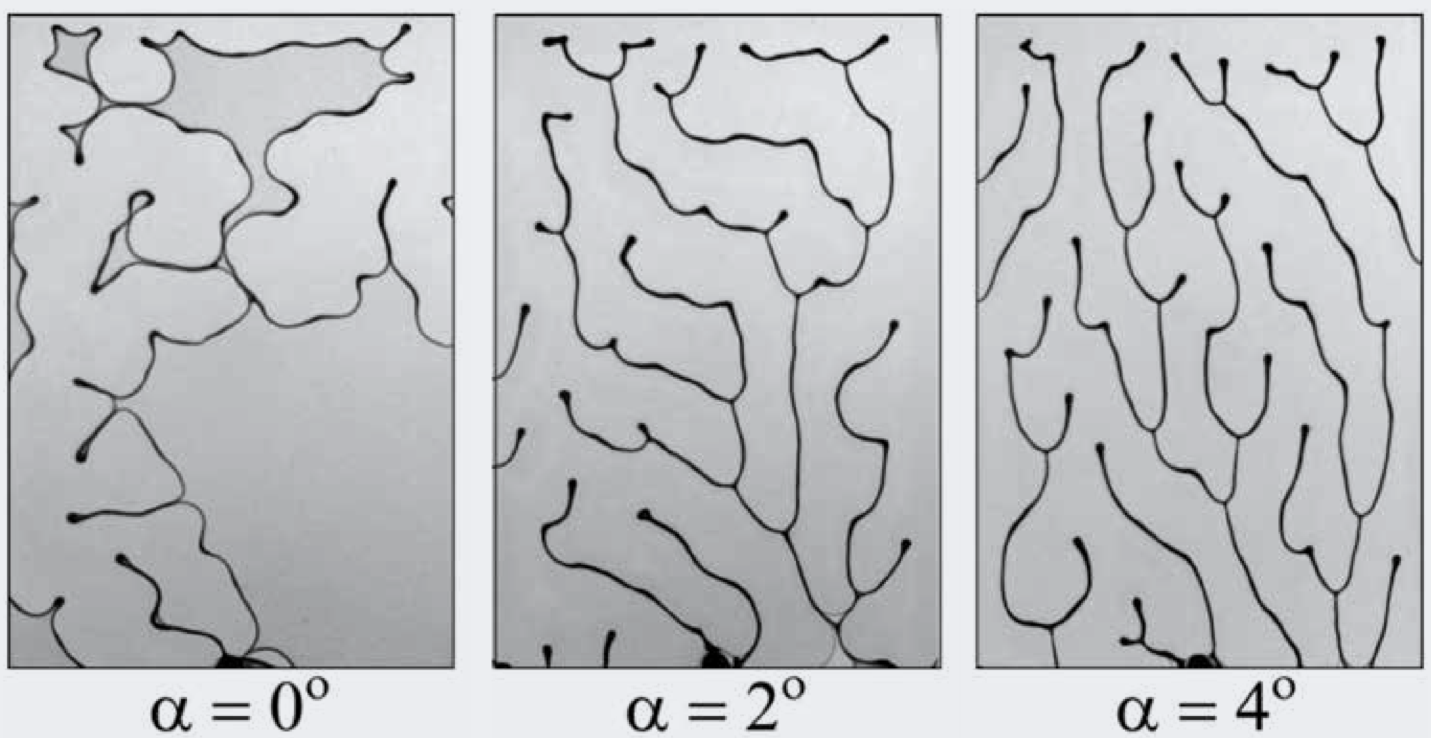
Pattern formation of frictional fingers in a gravitational potential

This project concerns experiments and simulations of slow drainage in a deformable quasi 2D porous media Hele Shaw. Here we introduce gravity as a new parameter in experiments where air displaces a liquid-granular mixture during drainage of a Hele-Shaw cell, by imposing shallow tilt angles. The receding interface accumulates a front of granular material, and an instability caused by a competition between surface tension and frictional forces results in an emerging pattern of frictional fingers, canals of air separated by branches of compacted grains, as also observed in horizontal systems. Aligned finger structures, with a characteristic width, emerge during the slow drainage. A transition from vertical to horizontal alignment of the finger structures is observed as the tilting angle and the granular density are varied. An analytical model is presented, demonstrating that the alignment properties are the result of the competition between fluctuating granular stresses and the hydrostatic pressure. The dynamics is reproduced in simulations. We also show how the system may explain patterns observed in nature, created during the early stages of a dike formation.

Examples of experimental patterns in a deformable porous medium at different tilt angles.



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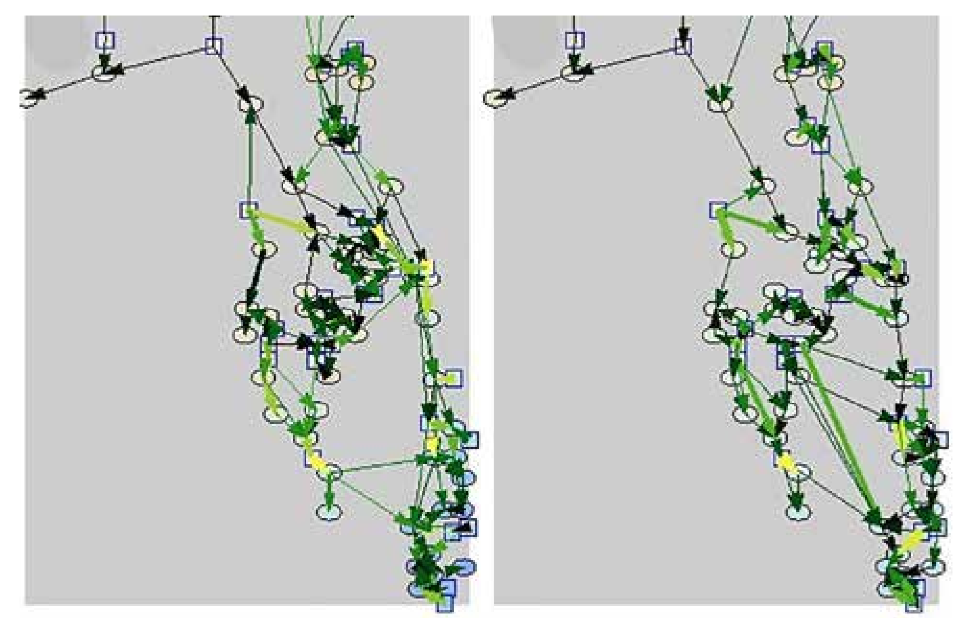
Dynamics of network evolution

Background

Network theory, first introduced by Leonhard Euler in 1735 as the famous problem of *The Seven Bridges of Königsberg*, has undergone a dramatic evolution over the last half century. Its many current applications in natural and social science and technology include such diverse examples as the Internet and the World Wide Web, power grids and transportation systems, ecological interaction and food networks, and channels in porous media.

Applications

In this project we consider the growth dynamics and resulting structures of various networks, including the wiring pattern of the power grid of the US state of Florida [1], and the web of interspecies interactions in a model ecological community subject to introduction of new species through immigration or evolution [2]. In the former example we added power lines one by one, each time minimizing the ratio of the increased line length to the reduction in energy dissipation. The growth was stopped by matching a parametrized centrality measure to the known generation capacities of the power plants. See the Figure. In the latter example we added new species to the interacting network, each time removing all existing species whose total interactions with the rest of the community became unfavorable, creating a cascade of extinctions. This study enabled us to show that the much discussed possibility of such a process leading to a self-organized critical (SOC) state requires conservation of the total number of species.



Left: The true Florida power grid of 200 high-voltage transmission lines, with squares representing power plants and circles representing loads.

Right: The best centrality-matched approximation to the true grid, containing 208 lines. From [1].

Publications:

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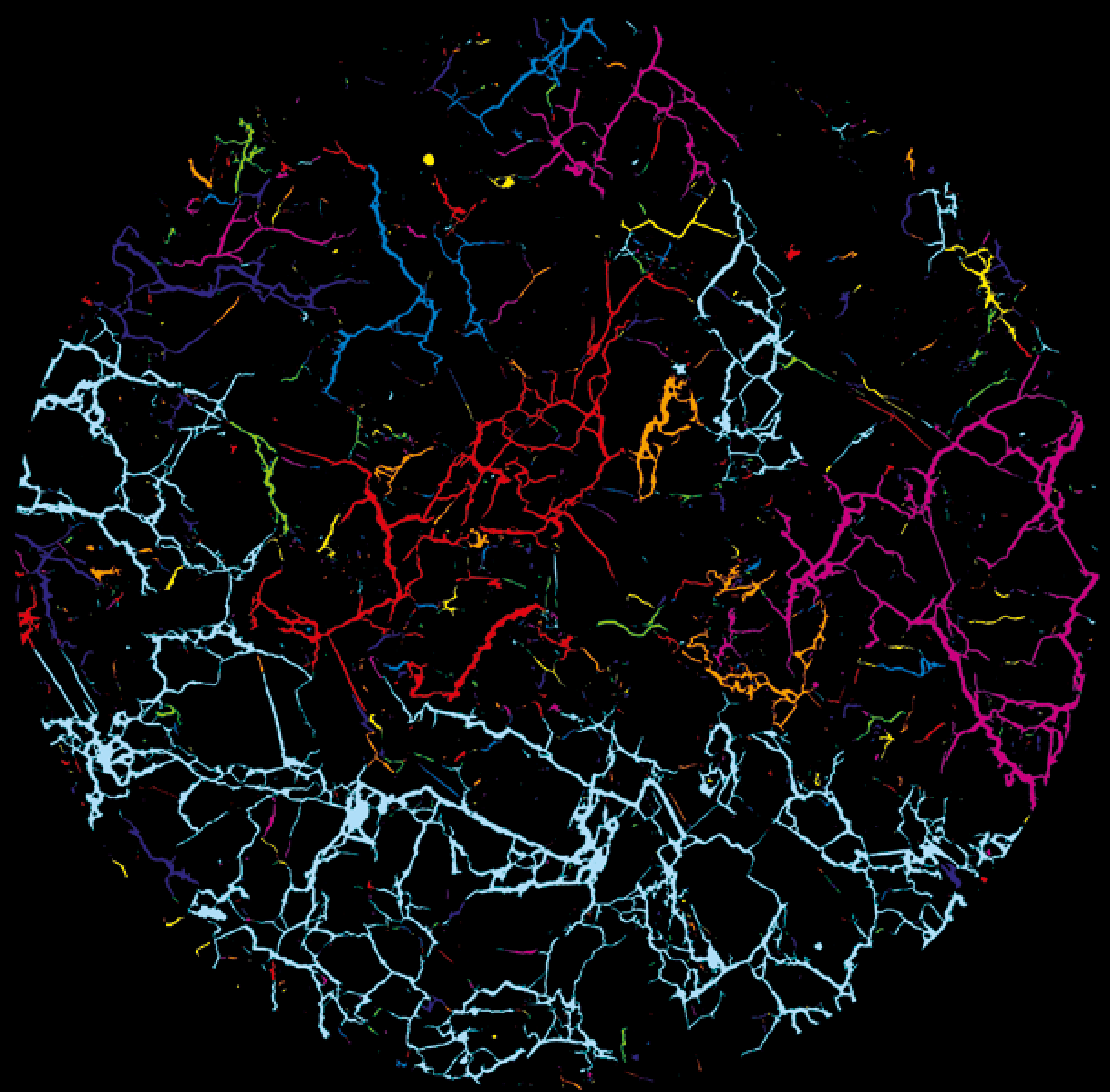

Chapter 4 | Part 3

Fracture and Friction in Rocks and Materials

1) How cracks are hot and cool, *2) Thermal weakening of cracks: a phase transition model*, 3) Microfractures in black shales and their transport properties (Prometheus), *4) Advanced X-ray and neutron imaging of fractured and porous rocks (ARGUS)*, 5) Unravelling the spatio-temporal nature of rock deformation using 4D X-ray tomography (Hades), *6) Role of grain scale heterogeneity on macroscopic deformation in granular systems (HADES)*

Funding:
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CoE-program

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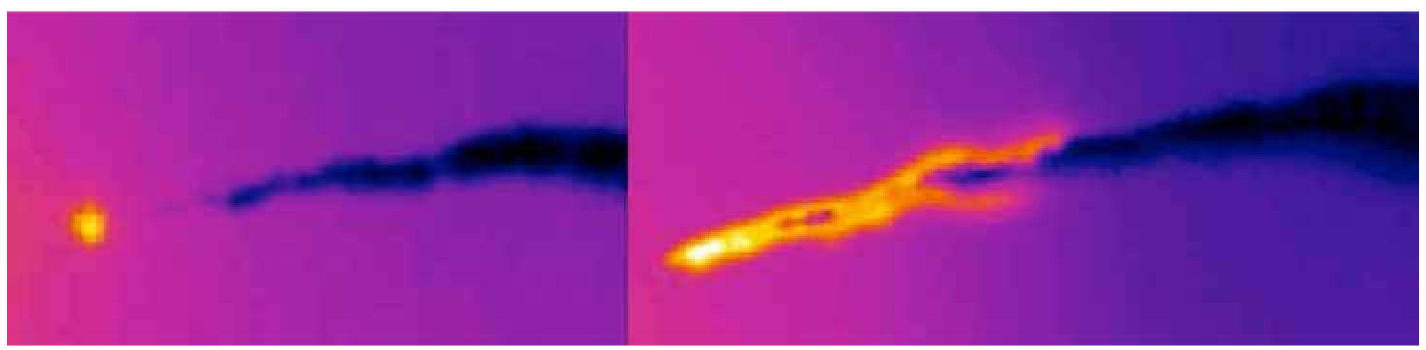
How cracks are hot and cool

Material failure is accompanied by very high local dissipation rates. Temperatures at the crack tip may reach thousands of degrees. Such temperatures may subsequently alter the mechanical properties of stressed solids, and finally facilitate their rupture. Thermal runaway weakening processes could explain stick-slip motion and even be responsible for deep earthquakes. Therefore, to better understand catastrophic rupture events, it appears crucial to establish an accurate energy budget of fracture propagation from a clear measure of various energy dissipation sources. In this project, we combine analytical calculations and numerical simulations, and we directly relate the temperature field around a moving crack tip to the part a of mechanical energy converted into heat. By monitoring the slow crack growth in paper sheets using an infrared camera, we measure a significant fraction of 12% heat dissipation. Besides, we show that (self-generated) heat accumulation could weaken our samples by microfiber combustion, and lead to a fast crack/dynamic failure/regime.



In this project, we combine analytical calculations and numerical simulations, and we directly relate the temperature field around a moving crack tip to the part a of mechanical energy converted into heat. By monitoring the slow crack growth in paper sheets using an infrared camera, we measure a significant fraction of 12% heat dissipation.
–

Heat dissipation of fracture growth in paper. The increase in temperature is observed in front of the initial notch just before the main crack starts to propagate, seen as a bright yellow spot just in front of the fracture tip. The temperature rise from blue to yellow corresponds to 6oC.

Publications:

R. Toussaint, O. Lengline , S. Santucci, T. Vincent-Dospital, Naert-Guillot, K.J. Måløy, *How cracks are hot and cool: a burning issue for paper*. Soft Matter, 12, 5563 (2016)

A.Cochard, O. Lengline, K.J. Måløy, R. Toussaint (2018). *Thermally activated cracks fronts propagating in pinning disorder: simultaneous brittle/creep behavior depending on scale*. Phil. Trans. R. Soc. A10170399, (2018)

Funding:
Norwegian Research Council,
CoE-program

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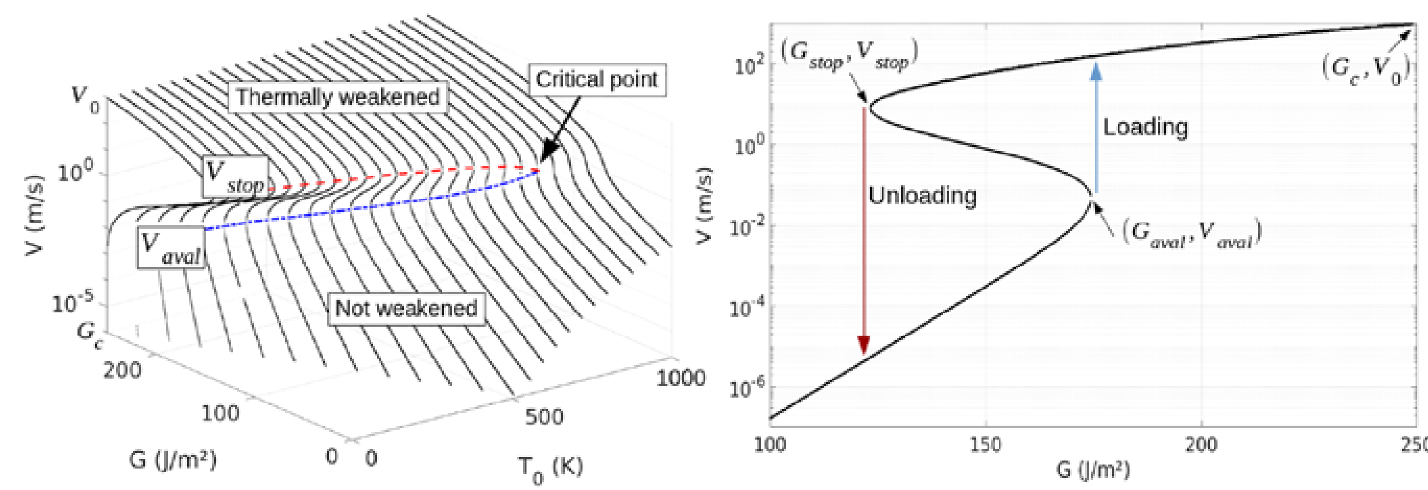
Thermal weakening of cracks: a phase transition model

The impact of temperature in fracturing processes can be sorted into two categories: background effects where the temperature is treated as an environmental constant affecting the rates at which the defects of a medium are propagating or healing and dynamic effects where the propagation of fractures induces a rise in temperature in the vicinity of the crack front. In the latter case, the rise in temperature may cause a coupling back that affects the crack propagation. This phenomenon will be here referred to as "thermal weakening." In this project we use a model which focuses on the statistical physics consideration of higher reactions rates (i.e., quicker fracture propagation) at higher temperatures, as implied by an Arrhenius law. We show that the propagation of a crack can then be described as a phase transition, where a crack can either be in a weakened or a non-weakened state. Such transitions, together with the toughness heterogeneities of a body, can potentially explain the common stick-slip behavior observed in fracturing processes. In addition, we predict a critical ambient temperature above which the weakened phase ceases to exist. This critical point could be directly related to the brittle-ductile transition of rocks at a higher geological depth.



(Left): Solutions for the crack velocity as a function of the fracture energy release rate G and the background temperature T_0. The dashed lines show the velocities ^{V}stop and ^{V}aval and converge to the critical point. All solutions in between Vstop and Vaval are unstable, any other point is a possible crack velocity. (Right): Same plot for T_0 = 293 K. The arrows represent how a crack avalanches of slows down at the phase transition thresholds.

Publications:

T. Vincent-Dospital, R. Toussaint, A. Cochard, K.J. Måløy. and E. Flekkøy, *Thermal weakening of cracks: a phase transition model*, submitted Nature

Funding:
Norwegian Research Council Petromaks and University of Oslo

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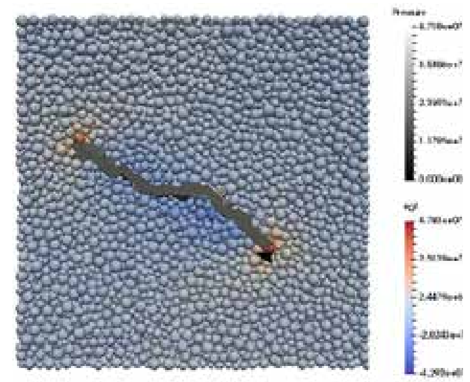
Microfractures in black shales and their transport properties (Prometheus)

During erosion of continents and deposition of sediments and organic matter in shallow seas, sedimentary layers form, creating the so-called sedimentary basins. With burial of these sediments, their organic and non-organic grains are compacted and heated, leading to their transformation into solid rocks. With temperature increase, the organic matter, initially present into what geologist call a "source rock" layer, will mature and evolve into oil and gas. However, these source rocks are known to be very resistant to fluid transmission; they are impermeable.

The question arises then on how oil and gas produced in such impermeable rocks can escape and migrate to reservoirs where they accumulate and can be exploited. This process is called primary migration of hydrocarbons. Here, we test the hypothesis that during maturation of organic matter in source rocks, microfractures will nucleate, grow, then merge, to finally create a flow path allowing hydrocarbons to escape. For this, we analyze rock samples collected at several kilometers depths in the Norwegian Continental Shelf. We also reproduce the process of organic matter maturation and rock fracturing in laboratory conditions.

Finally, we develop computer models of the coupling between organic matter maturation in source rocks, production of hydrocarbon, creation of microfractures, and escape of the produced oil and gas towards reservoirs. The research is performed in collaboration with the British Geological Survey, the University Grenoble Alpes, and Temple University (USA).



Numerical modelling of the overpressure and micro-fracture formation generated by the transformation of kerogen into hydrocarbon, using the discrete element method. Size of the domains 0.1 mm3. Simulations Thomas Chauve.

With temperature increase, the organic matter, initially present into what geologist call a "source rock" layer, will mature and evolve into oil and gas.
–

Publications:

McBeck, J., Kobchenko, M., Hall, S. A., Tudisco, E., Cordonnier, B., Meakin, P., Renard, F. (2018) *Investigating the onset of strain localization within anisotropic shale using digital volume correlation of time-resolved X-ray microtomography images*. Journal of Geophysical Research, https://doi.org/10.1029/2018JB015676.

Panahi, H., Kobchenko, M., Meakin, P., Dysthe, D., and Renard, F. (2019) *Fluid expulsion and microfracturing during the pyrolysis of an organic rich shale*, Fuel, https://doi.org/10.1016/j.fuel.2018.07.069.

Panahi, H., Kobchenko, M., Meakin, P., Dysthe, D., and Renard, F. (2019) *Fluid expulsion and microfracturing during the pyrolysis of an organic rich shale*, Fuel, https://doi.org/10.1016/j.fuel.2018.07.069.

Funding:
Norwegian Research Council Nano2021 and University of Oslo

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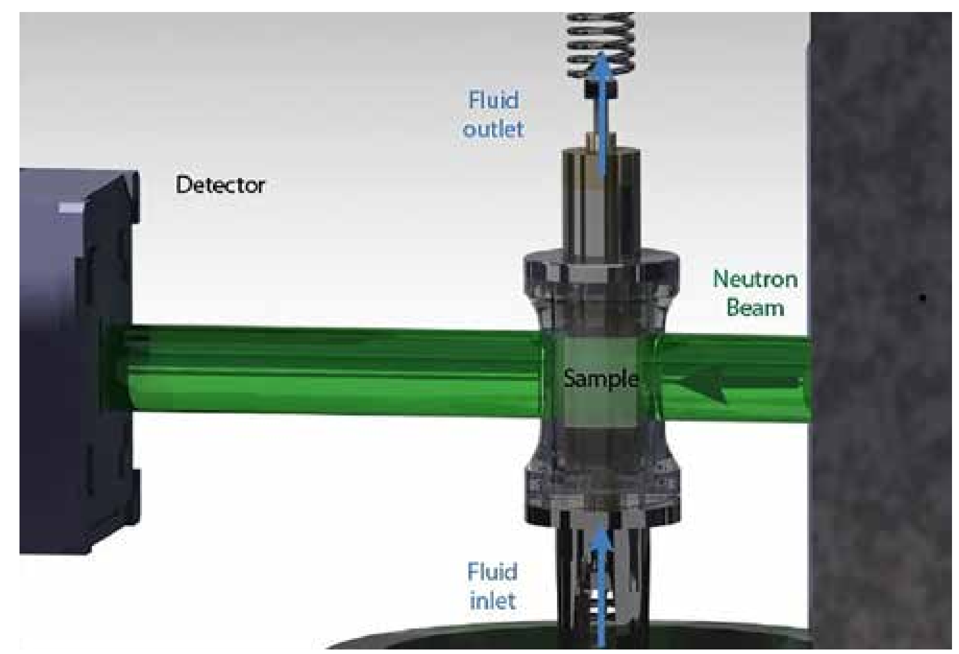
Advanced X-ray and neutron imaging of fractured and porous rocks (ARGUS)

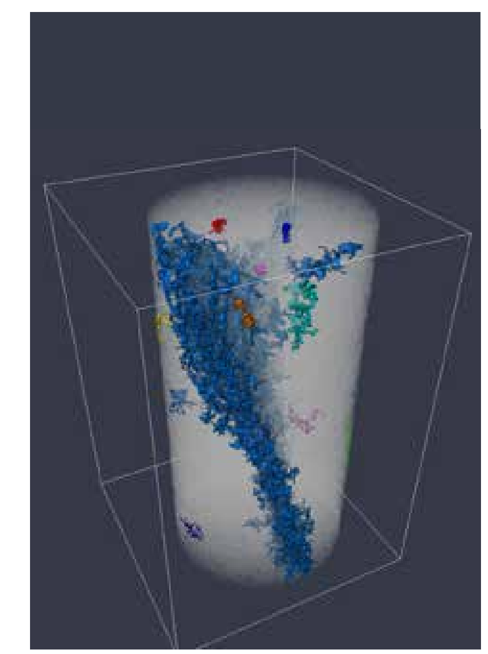
The primary goal is to combine advanced imaging using X-rays and neutrons, available at large facilities (European Synchrotron Radiation Facility, Institut Laue Langevin, European Spallation Source, Paul Scherrer Institute). We use time-lapse imaging of fractured rocks and fluid flow and characterize 2-D and 3-D dynamic processes. The secondary goals are:

- Identify, map and quantify the growth of a micro-crack network in rocks loaded in shear and in tension using the state-of-the-art triaxial HADES rig.
- Understand the effects of roughness and aperture on fluid flow and local permeability, through neutron imaging experiments and a novel X-ray micro-tomography flow-through experiment.
- Understand the coupling between flow and transport of contaminants through fractures and porous media. Using neutron imaging we will track water, heavy water and cadmium solution, the latter of which is also a soil pollutant.

The experimental program is performed in collaboration with the Universities of Edinburgh, the Paul Scherrer Institute and the University Grenoble Alpes.



Core holder installed at the Institut Laue Langevin neutron source (Grenoble, France) to study fluid flow in rocks and the transport of contaminants (design Benoit Cordonnier).



X-ray tomography imaging of a fault into a sandstone, using the HADES rig at the European Synchrotron Radiation Facility.

Publications:

Renard, F., McBeck, J., Cordonnier, B., Zheng, X., Kandula, N., Sanchez, J. R., Kobchenko, M., Noiriel, C., Zhu, W., Meakin, P., Fusseis, F., Dysthe, D. K. (2018) *Dynamic in situ three-dimensional imaging and digital volume correlation analysis quantify strain localization and fracture coalescence in sandstone*, Pure and Applied Geophysics, https://doi.org/10.1007/s00024-018-2003-x.

Funding:
Norwegian Research Council Frinatek/
FriPro and University of Oslo

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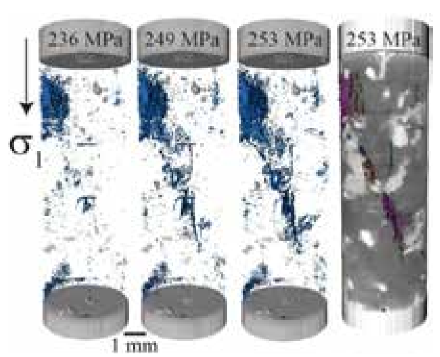
Unravelling the spatio-temporal nature of rock deformation using 4D X-ray tomography (Hades)

Rocks in the 30 kilometers thick upper layer of the Earth, called the crust, deform slowly, for example during the formation of geological reservoirs, or very fast, for example during earthquakes. Such deformations control how voids and fractures are created underground and how fluids may circulate in rocks and transport hydrocarbons, heat (geothermal energy), or minerals that later deposit as ores. Here, we reproduce rock deformation processes, coupled to fluid circulations, using a state-of-the-art deformation apparatus that reproduces conditions of pressure, temperature, and fluid flow in a rock sample similar to that at 5 to 10 kilometers depth. This rig is installed at the European Synchrotron Radiation Facility in Grenoble (France), where high-energy X-rays are used, for the first time, to image in real-time the evolution of the rocks. This project involves collaboration between the Njord Center at the University of Oslo, researchers at the universities of Maryland and Grenoble Alpes. A collaboration with a famous graphic artist from Norway makes it possible to develop new science-art interactions.



In-situ X-ray microtomography imaging of the nucleation of a fault into a crystalline rock.

Graphic art inspired from our experiments (© Ellen Karin Maelhum).

Publications:

McBeck, J., Kobchenko, M., Hall, S. A., Tudisco, E., Cordonnier, B., Meakin, P., Renard, F. (2018) *Investigating the onset of strain localization within anisotropic shale using digital volume correlation of time-resolved X-ray microtomography images*. Journal of Geophysical Research, https://doi.org/10.1029/2018JB015676.

Renard, F., Cordonnier, B., Kobchenko, M., Kandula, N., Weiss, J., Zhu, W. (2017). *Microscale characterization of rupture nucleation unravels precursors to faulting in rocks*. Earth Planet. Sci. Lett., 476, 69-78, doi: 10.1016/j.epsl.2017.08.002.

Renard, F., Weiss, J., Mathiesen, J., Ben Zion, Y., Kandula, N., Cordonnier, B. (2018) *Critical evolution of damage towards system-size failure in crystalline rock*, Journal of Geophysical Research, doi: 10.1002/2017JB014964. Editor Highlight in Eos.org.

Zheng, X., Cordonnier, B., Zhu, W., Renard, F., & Jamtveit, B. (2018). *Effects of confinement on reaction-induced fracturing during hydration of periclase*. Geochemistry, Geophysics, Geosystems, 19. https://doi.org/10.1029/2017GC007322.

Funding:
Norwegian Research Council Frinatek/
FriPro

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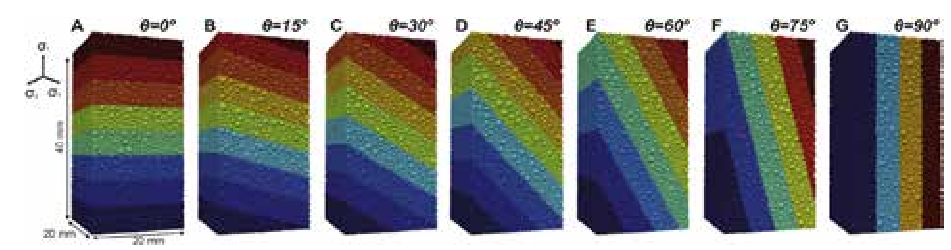
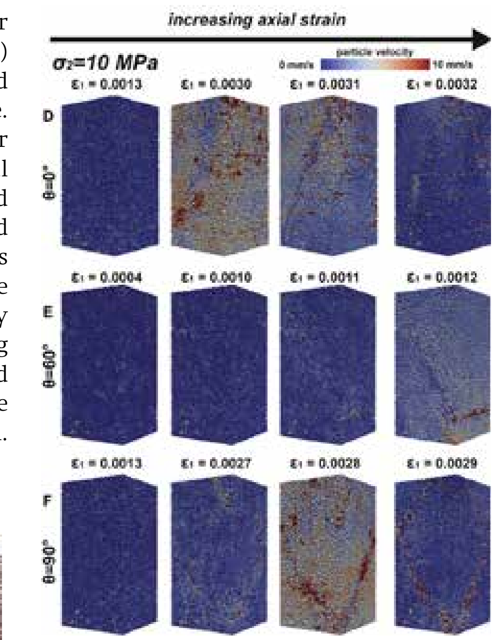
Role of grain scale heterogeneity on macroscopic deformation in granular systems (Hades)

Numerical simulations using 3D Discrete Element Modelling (DEM) are a powerful tool allowing us to 'look inside' evolving deformation zones and link grain scale processes with frictional sliding or deformation of granular materials. Here, we build geomaterials from aggregate grains (or layers) that can break, evolve or interact with their neighbours. Using novel methods, we tune roughness, porosity, and cement strength to simulate the effects of structural anisotropy (commonly ignored in numerical simulations) and isolate the main drivers responsible for macroscopic strength changes during deformation. Our investigation reveals the dominant role played by preexsiting weakness (rather than host rock strength or confinement) on spatial distribution of fracturing and subsequent localisation that leads to failure. In addition, porosity exerts a first order control on precursory micromechanical processes including developing force and fracture networks that are directly linked to macroscopic forcing parameters such as external work. New work will tackle the influence of crystallographic anisotropy (weak cleavage) on granular flows, tracking development of preferred orientation and revealing implications for developing force networks and macroscopic sliding friction.



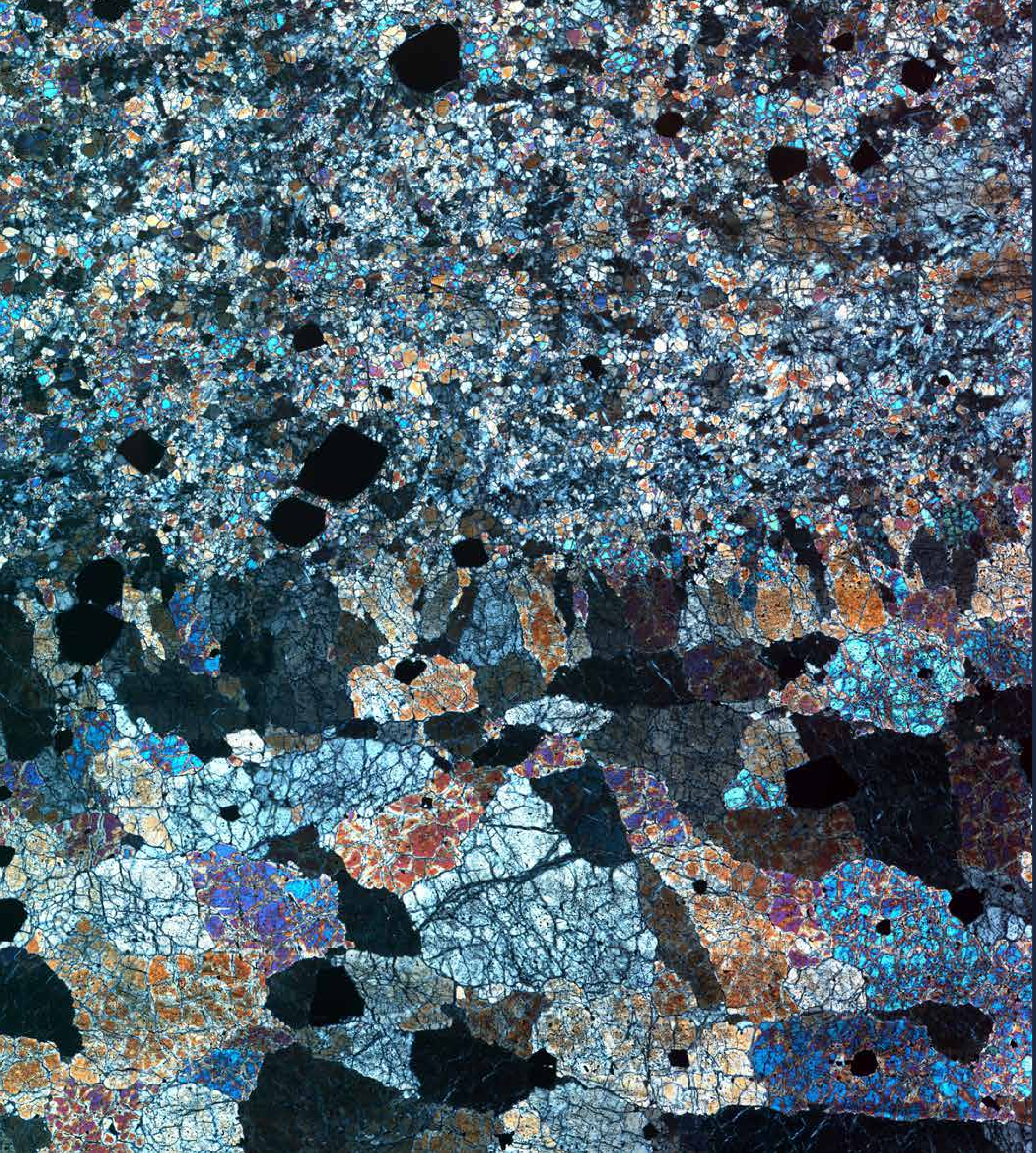
Models of blocks with all tested layer orientations, θ. (McBeck et al., 2018)



Influence of layer orientation on distribution of damage with increasing strain. (McBeck et al., 2018)

Publications:

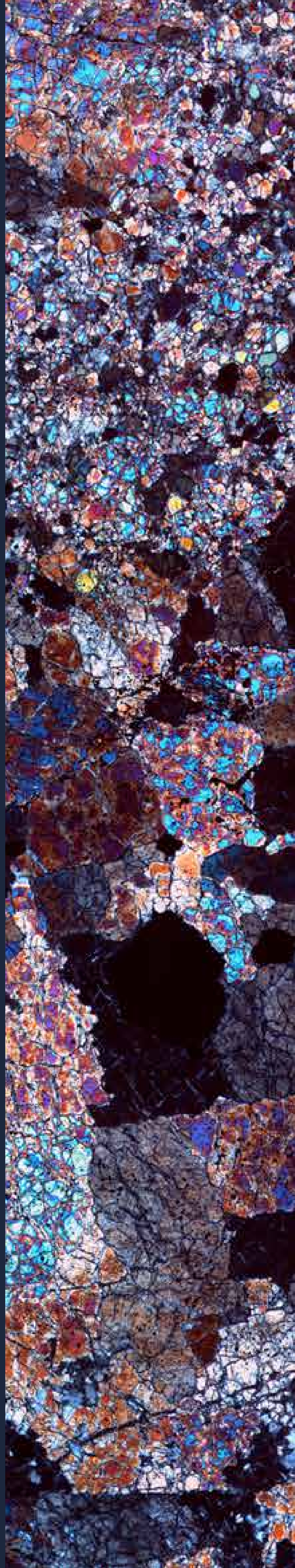
Jessica McBeck, Karen Mair, François Renard, 2018, *Linking macroscopic failure with micromechanical processes in layered rocks: How layer orientation and roughness control macroscopic behaviour*, Tectonophysics 750 (2019) 229–242, https://doi.org/10.1016/j.tecto.2018.11.016



Chapter 4 | Part 4

Coupled Chemical Processes from the Nanoscale to the Scale of Continents

1) BioZEment 2.0 – Systems analysis and fundamental control of bacterial processes in the production of bio-concrete for construction purposes, *2) Capture of toxic oxyanions in mineral nanoparticles by coupled dissolution-precipitation process (Cybele)*, 3) Disequilibirum metamorphism of stressed lithosphere (DIME), *4) NanoHeal*, 5) Molecular dynamics simulations of geological processes (Atomify)



Funding:
Norwegian Research Council IDELAB

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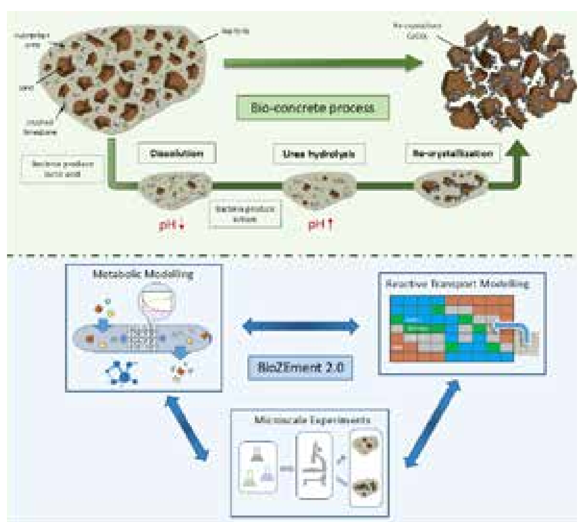
4) Oslo Metropolitan University, Norway
5) Pure Logic, Norway
6) NORCE, Norway
7) RISE, Sweden

BioZEment 2.0 – Systems analysis and fundamental control of bacterial processes in the production of bio-concrete for construction purposes

The production of concrete accounts for more than 5% of global anthropogenic CO_2 emissions. The BioZEment project aims to develop a more sustainable alternative to conventional concrete through the use of naturally occurring mineral-microbe interactions, by integrating efforts across multiple disciplines, including biotechnology, nanotechnology, geochemistry, techno-economics, and social sciences. The project is part of the Center for Digital Life Norway.

The BioZEment concept is based on the dissolution and precipitation of calcium carbonate, induced by selected, non-pathogenic bacterial strains. Our ambition is to combine systems biology metabolic modeling of bacterial strains, advanced microbiological techniques, material characterization, and geochemical reactive transport simulations, to gain in-depth understanding of the biogeochemical system in order to optimize it with respect to production time and material properties. We are also investigating the regulatory, environmental and consumer aspects that may influence the future use of the product.

> The BioZEment project aims to develop a more sustainable alternative to conventional concrete through the use of naturally occurring mineral-microbe interactions, by integrating efforts across multiple disciplines
> –



Publications:

Karlsen, Emil; Schulz, Christian; Almaas, Eivind. (2018) *Automated generation of genome-scale metabolic draft reconstructions based on KEGG*. BMC Bioinformatics 2018 ;Volum 19.(467)

Funding:
University of Oslo

Participants
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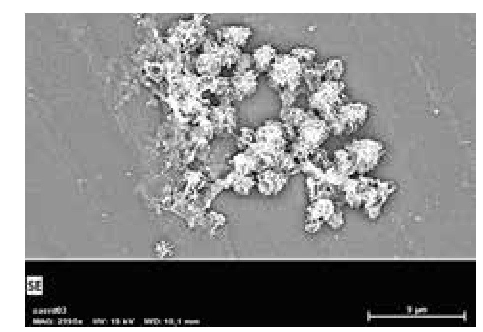
5) University of Utrecht, The Netherlands

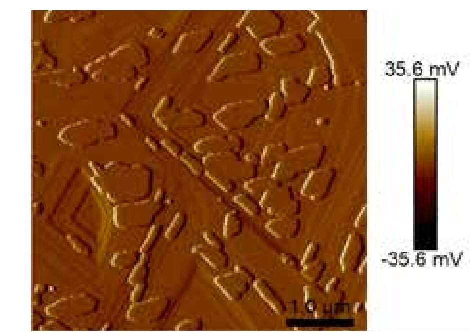
Capture of toxic oxyanions in mineral nanoparticles by coupled dissolution-precipitation process (Cybele)

The coupling between dissolution of minerals and formation of inorganic nanoparticles can trap toxic compounds to avoid their release in the environment. Our goal is to understand and mitigate the release of hazardous elements (arsenic, selenium, antimony, chromium) from these cements, fly ash and other inorganic waste products into the environment. We perform series of laboratory experiments (atomic force microscopy, flow-through reactors, synchrotron EXAFS and XANES spectroscopy) on carbonate minerals, gypsum, fly ash, and ettringite (a mineral constituent of concrete), where dissolution of the host mineral and precipitation of new nanoscale minerals will be imaged and followed over time.

We also perform atomic scale numerical simulations (molecular dynamics, phase field crystal model) to characterize the formation and growth of nanoparticles and their evolution from amorphous to crystalline structure. In the presence of various hazardous species in the reacting fluid, the cation released during mineral dissolution will bind with these species to form new minerals that sequester the hazardous substances in the form of stable solid nanoparticles.

As a consequence, the formation of nanoparticles allows trapping of toxic elements that were initially dissolved into the aqueous phase. This prevents elements to pollute water and soil and strengthens the possibilities for the recycling of concrete and other man-made geomaterials (i.e. fly ash). Experiments are performed in tight collaboration with the Universities of Münster and Grenoble Alpes.





Capture of chromium on calcite by a process of coupled dissolution-precipitation. Precipitates are imaged with scanning electron microscopy (a) or atomic force microscopy (b). © Marthe Guren.

Publications:

Renard, F., Røyne, A., Putnis, C. V. (2018) *Timescales of interface-coupled dissolution-precipitation reactions on carbonates*, Geoscience Frontiers, https://doi.org/10.1016/j.gsf.2018.02.013.

Renard, F., Putnis, C. V., Montes-Hernandez, G., King, H. E., Breedveld, G. D., Okkenhaug, G. (2018) *Sequestration of antimony on calcite observed by time-resolved nanoscale imaging*, Environmental Science & Technology, 52, 107-113.

Funding:
European Research Council, Advanced grant

Participants
Bjørn Jamtveit[1], Kristina Dunkel[1], Sarah Incel[1], Håkon Austrheim[1], Francois Renard[1], Claire Aupart[1], Arianne Petley-Ragan[1], Xin Zhong[1]

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Disequilibirum metamorphism of stressed lithosphere (DIME)

Most changes in mineralogy, density, and rheology of the Earth's lithosphere take place by *metamorphism*, whereby rocks evolve through interactions between minerals and fluids. These changes are coupled with a large range of geodynamic processes and they have first order effects on the global geochemical cycles of a large number of elements. In the presence of fluids, metamorphic reactions are fast compared to tectonically induced changes in pressure and temperature. Hence, during fluid-producing metamorphism, rocks evolve through near-equilibrium states. However, much of the Earth's lower and middle crust, and a significant fraction of the upper mantle do not contain free fluids. These parts of the lithosphere exist in a metastable state and are mechanically strong. When subject to changing temperature and pressure conditions at plate boundaries or elsewhere, these rocks do not react until exposed to externally derived fluids. Metamorphism of such rocks consumes fluids, and takes place far from equilibrium through a complex coupling between fluid migration, chemical reactions, and deformation processes. This *disequilibrium metamorphism* is characterized by fast reaction rates, release of large amounts of energy in the form of heat and work, and a strong coupling to far-field tectonic stress.

The overarching goal of DIME is to provide new fundamental understanding of fluid driven metamorphism that properly connects fluid-rock interactions at the micro and nano-meter scale to lithosphere scale stresses. The most significant discoveries include: A thorough documentation of the coupling between metamorphism and earthquake activity in the lower crust; Observational evidence that earthquakes in the lower crust are preceded by dynamic ruptures at confining pressures far beyond the traditional brittle-ductile transition; Statistical data showing that earthquakes in the lower crust may be triggered by stress pulses from large earthquakes in the shallower crust, and finally numerical modelling showing that local weakening of rocks in the lower crust during metamorphism following earthquake events will lead to significant local pressure perturbations.

DIME has made major progress in the understanding of how nanoscale porosity generated by far-from-equilibirum metamorphic reactions may accelerate reactions rates way beyond what is expected by 'normal' diffusion processes, and we have studied the effects of external stress on reaction driven fracturing *in situ* in 3D using our novel 'Hades' rig mounted at beamline 19 of the European Synchrotrone Facility in Grenoble. Finally, 'DIME' participated in the Continental Drilling Program in Oman which was conducted in Jan-Feb 2018 with 4 DIME people present in Oman and on board the research vessel Chikyu during core logging and sampling in August-September 2018.

Publications:

Aupart, C., Dunkel, K.G., Angheluta, L., Austrheim, H., Ildefonse, B., Malthe-Sørenssen, A.M., and Jamtveit, B., 2018, *Olivine grain size distributions in faults and shear zones: Evidence for non-steady state deformation*. Journal of Geophys. Research, 123, 7421-7443.

Austrheim, H., Dunkel, K.G., Plümper, O., Ildefonse, B., Liu, Y., and Jamtveit, B., 2017, C *Fragmentation of wall rock garnets during deep crustal earthquakes*. Science Advances, 3, e1602067

Clerc, A., Renard, F., Austrheim, H., and Jamtveit, B., 2018, *Spatial and size distribution of garnet grown in a pseudotachylyte generated during intermediate-depth earthquake*. Tectonophysics, 733, 159-170

Dunkel, K.G., Austrheim, H., Cordonnier, B., Renard, F., and Jamtveit, B., 2017, *Localized slip controlled by dehydration embrittlement of partly serpentinised dunites*, Leka Ophiolite Complex, Norway. Earth and Planetary Science Letters, 463, 277-285

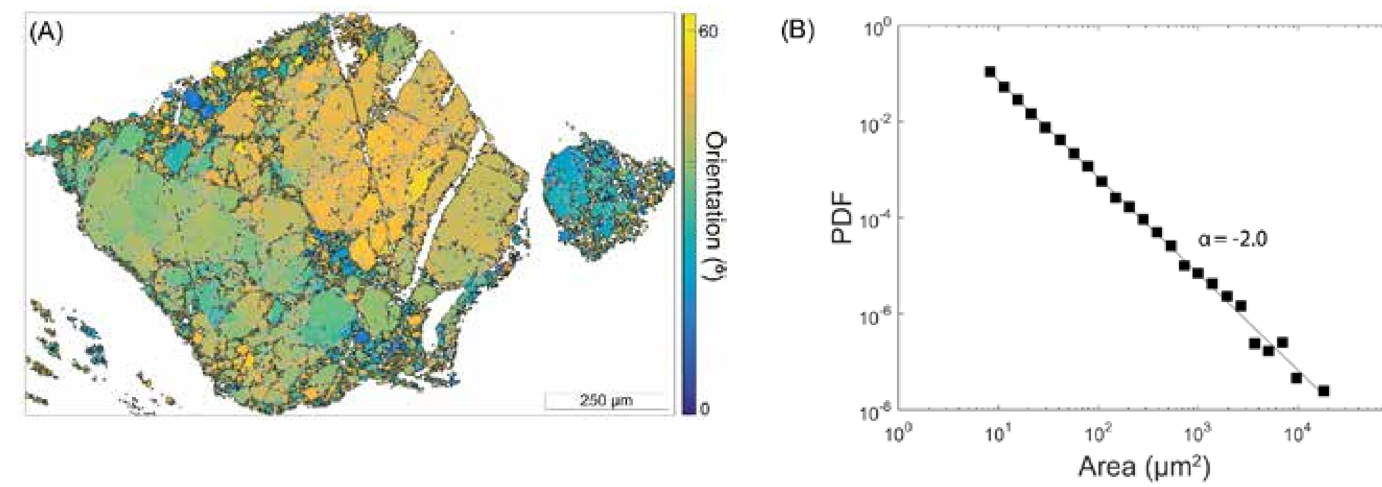
Dunkel, K.G., Austrheim, H., Ildefonse, B., and Jamtveit, B., 2017, *Transfer of olivine crystallographic orientation through a cycle of serpentinisation and dehydration*. Contrib. Mineral. Petrol., 172(8), 64

Incel, S., Labrousse, L., Hilairet, N., John, T., Gasc, J., Wang, Y., Shi, F., Andersen, T.B., Renard, F., Jamtveit, B., and Schubnel. A., 2019, *Reaction-induced faulting in granulite: Implications for the generation of earthquakes in the lower continental crust*. Geology (in press)

Jamtveit, B., Ben-Zion, Y., Renard, F., and Austrheim., H., 2018, *Earthquake-induced transformation of the lower crust*. Nature, 556, 487-493

Jamtveit, B., Moulas, E., Andersen, T.B., Austrheim, H., Corfu, F., Petley-Ragan, A., and Schmalholz, S.M., 2018, *High pressure metamorphism caused by fluid induced weakening of deep continental crust*. Scientific Reports, 8, no. 17011

Petley-Ragan, A., Dunkel, K.G., Austrheim, H., Ildefonse, B., and Jamtveit, B., 2018, *Microstructural records of intermediate-depth earthquakes and associate fluid-driven metamorphism of plagioclase-rich granulites*. Journal of Geophys. Research, 123, 3729-3746



(A) Orientation map of fragmented garnet located in the wall rocks of a seismic fault at Holsnøy, Bergen Arcs. Fragmentation without shear strain is a characteristic feature of wall rocks following an earthquake.

(B) Power law size distribution of the garnet fragments as defined by low-angle and high-angle grain boundaries in A.

The overarching goal of DIME is to provide new fundamental understanding of fluid driven metamorphism that properly connects fluid-rock interactions at the micro and nano-meter scale to lithosphere scale stresses.
–

Plümper, O., Botan, A., Los, C., Liu, Y., Malthe-Sørenssen, A., and Jamtveit, B., 2017, *Fluid-driven metamorphism of the continental crust governed by nanoscale fluid flow*. Nature Geoscience, 10, 685-690

Putnis, A., Jamtveit, B., and Austrheim, H., 2017, *Metamorphic processes and seismicity: The Bergen Arcs as a natural laboratory*. Journal of Petrology, 58, 1871-1898

Zheng, X., Cordonnier, B., Zhu, W., Renard, F., and Jamtveit, B., 2018, *Effects of confinement on reaction-induced fracturing during hydration reactions*. Geochemistry, Geophysics, Geosystems, 19, 2661-2672.

Zhong, X., Dabrowski, M., and Jamtveit, B., 2018, *Analytical solution for the stress field in elastic half space with a spherical inclusion containing eigenstrain*. Geophys. Journal International, doi.org/10.1093/gji/ggy447

Funding:
European Research Council,
Marie Sklodowska Curie European Training Network

Participants
Dag Kristian Dysthe[1], Anja Røyne[1], Håkon Austrheim[1], Jesus Rodriguez Sanchez, Lisa de Ruiter, Anette E. Gunnæs[2], Joanna Dziadkowiec[1]

Affiliation
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[2] Department of Physics, University of Oslo, Norway

NanoHeal

NanoHeal (2014-2018) brought together top academic groups (in Oslo, Copenhagen, Erlangen, Lyon, London and Haifa) and industrial research labs (LafargeHolcim, Total, National Nuclear Laboratories, Chemiplastica, Dynea and Iris). The expertise available in NanoHeal covered state of the art experimental, computational and theoretical techniques, and brought together physicists, chemists, materials scientists, engineers and industrialists working on a common theme. The NanoHeal network has trained 15 young researchers by speeding up cross-fertilisation between disciplines and sectors. At Njord 3 NanoHeal research fellows handed in their PhD thesis in 2018: Joanna Dziadkowiec, Lisa deRuiter and Jesus Rodriguez Sanchez.

Interactions between Confined Calcite Surfaces in Aqueous Solutions. A surface forces apparatus study

The strength of rocks in the Earth's crust is important for man-made infrastructure, earthquake susceptibility, and potential storage of greenhouse gases in porous rock formations. As rocks and mineral-based materials are often composed of small micro- to nanoscale grains (10^{-6} to 10^{-9} m), it is crucial to identify all major processes that begin at these very small scales before the materials fail. We have focused on nanometer-range surface forces between two mineral surfaces and on how these forces are affected by the surface reactivity in confined geometries. In order to achieve that we used a special force-measuring microscope: the Surface Forces Apparatus (SFA). SFA is very useful here because it allows us to perform experiments in geometries that are relevant for geological environments and granular materials.

The project focuses on a commonplace mineral - calcite. Modifying the calcite surfaces with organic molecules is a very promising way to improve the properties of calcite-based materials that we use daily. The far-reaching goal is to obtain calcite-based materials in which calcite possesses more advanced functions than merely a filler phase.

The main findings of this experimental project indicate that even though in theory strong adhesive forces between calcite surfaces should be present both in water and in saline solutions, this may not be the case. We generally measured only repulsive forces in a range of fluid compositions, including water. This is caused both by the displacive recrystallization of calcite surfaces and by the presence of water films strongly adsorbed onto the surfaces. Both mechanisms prevented the theoretically expected adhesion, and they may lead to a decrease in the mechanical strength of calcite-bearing rocks.

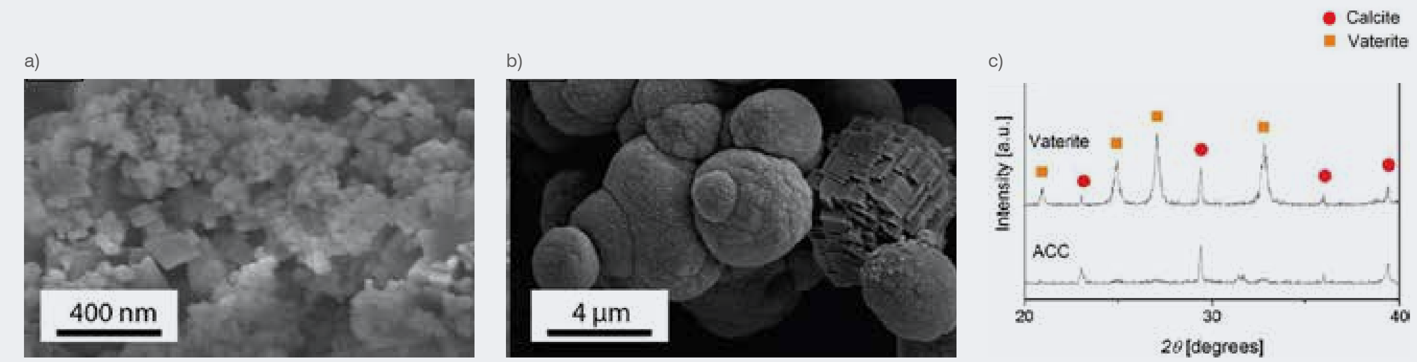
Experimental study of brittle or ductile behaviour of mineral cements

This project deals with several aspects related with pure calcium carbonate cements, ranging from the formation and strengthening mechanisms during the setting reaction to the effect of their microstructure and moisture equilibrium on the deformation behaviour. Moreover, their bioactive properties have been evaluated to assess their potential usage as a bone substitute biomaterial.

Publications in Highlights:

Surface Forces Apparatus Measurements of Interactions between Rough and Reactive Calcite Surfaces, Joanna Dziadkowiec, Shaghayegh Javadi, Jon E. Bratvold, Ola Nilsen, and Anja Røyne, Langmuir 2018 34 (25), 7248-7263. DOI: 10.1021/acs.langmuir.8b00797

Formation of magnesium silicate hydrate cement in nature. Lisa de Ruiter and Håkon Austrheim, Journal of the Geological Society, 175, 308-320, (2017) https://doi.org/10.1144/jgs2017-089

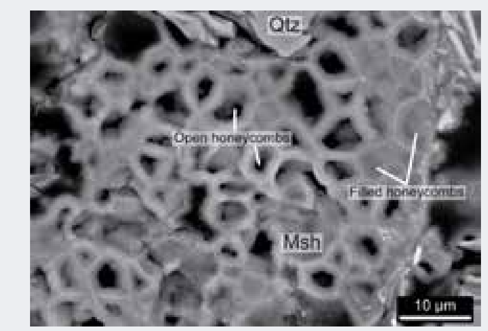


SEM micrographs of synthesized calcium carbonate powders in the form of (a) ACC phase and (b) Vaterite phase. (c) XRD patterns of (a) and (b) powders.

Calcium carbonate cements can be synthesized at laboratory scale by mixing with water two metastable calcium carbonate phases. Those recrystallize during the setting reaction and induce a transition from weak interparticle contacts between different crystals in a movable disperse system (paste with viscous-plastic behaviour) into strong phase contacts (elastoplastic behaviour) which are responsible for the final strength of the material. In order to improve our understanding of the strengthening mechanisms of this kind of cement, we have correlated the polymorphic transformations with the evolution of the viscoelastic properties of the pastes during setting and hardening processes. To follow the phase transformations, we conducted time-lapse X-ray diffraction (XRD) scans over several calcium carbonate pastes, whereas the evolution of their viscoelastic properties was addressed through rheological measurements. As a result, we found that the characteristic times of phase transformation and structural strengthening are directly correlated; being the formation of crystal bridges the main responsible mechanism for creating mechanical strength.

Rock cementation by magnesium silicate hydrate cement

Located in southeast Norway, the Feragen ultramafic body is the location of a unique magnesium silicate hydrate cement that binds ultramafic and felsic rock fragments into solid rock. The cement forms due to the extraordinary geochemical conditions in the area. The Feragen Ultramafic Body is a partly serpentinized peridotite body that is subjected to weathering which results in the continuous dissolution of brucite. This leads to high pH (9-10) and Mg-enriched surface water. The ultramafic body is partly covered by felsic glacial deposits, consisting mainly of quartz. The high pH, Mg-rich fluids react with the quartz which subsequently dissolves and is replaced by magnesium silicate hydrate cement. As the quartz is deformed and recrystallized, these fluids penetrate along intergranular boundaries which act as fluid pathways. The dissolution rate of quartz is known to increase rapidly with increasing pH, but the rate obtained from the Feragen field samples is multiple orders of magnitude higher than what experimentally obtained rate equations suggest for the prevailing conditions. The replacement reaction results in a cemented rock with felsic and ultramafic fragments that forms on a timescale of a few decades at surface conditions in a subarctic climate. This process occurs without any emission of CO_2. The cement is nanocrystalline and related to Mg-silicates like kerolite, sepiolite and serpentine. Moreover, the cement is similar in composition and structure to man-made magnesium silicate hydrate cement, also known as M-S-H cement. M-S-H cement is in an early stage of development and has potential to be utilized as an alternative low CO_2 cement and has properties highly suitable for the encapsulation of nuclear waste.



Honeycomb texture with typical 2-10 µm diameter pore spaces. The texture consists of magnesium silicate hydrate cement (Msh) and the interior is either empty (black) or filled with cement (grey) with a different contrast, signifying a different density. The size of the individual honeycomb cells does not seem to correlate with the cell being filled or not. No quartz (Qtz) is present, except for at the top of the figure.

Funding:
University of Oslo

Participants
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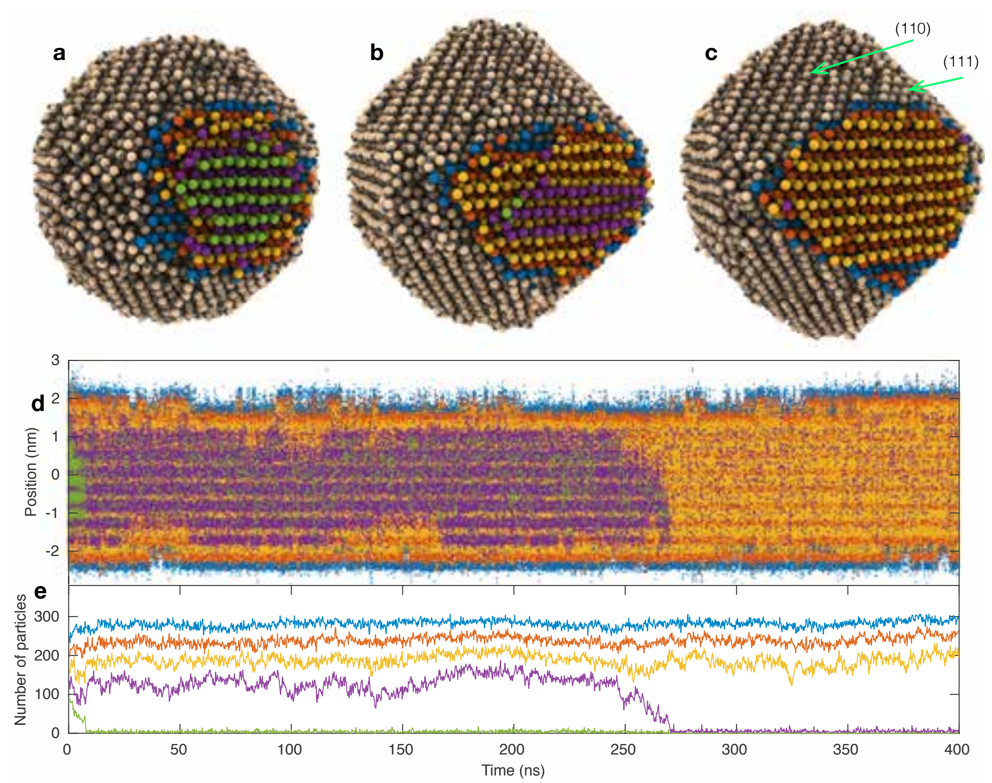
Molecular dynamics simulations of geological processes (Atomify)

The atomic nature of matter may have a first order impact on many physical and geological processes, and studies of atomic processes may provide a detailed understanding that is unavailable at larger length scales. We have initiated a research activity based on molecular dynamics simulations to address fundamental processes in geological systems. In particular, we are interested in the effects of the details of the dynamcis, including the interactions between salts, minerals, and water, on mineralogical and mechanical processes.

Subtheme: Micromechanics of facet formation

How does nanocrystals form and what are their equilibrium shape? We are the first to observe facet formation in an all-atom molecular dynamics simulation. In a series of microsecond simulations on SiC, Henrik Sveinsson and Anders Hafreager have demonstrated that facets form by surface diffusion and that the shapes of nanocrystals correspond to that of the Wulff construct. These simulations demonstrate that facet formation indeed can be studied using molecular dynamics simulations, thereby opening for studies of healing and crystal formation processes in geological processes.



The final, relaxed state of a microsecond molecular dynamics simulation of a faceted SiC crystal. The colors indicate the layers that are formed sequentially during the facet formation.

We are the first to observe facet formation in an all-atom molecular dynamics simulation.
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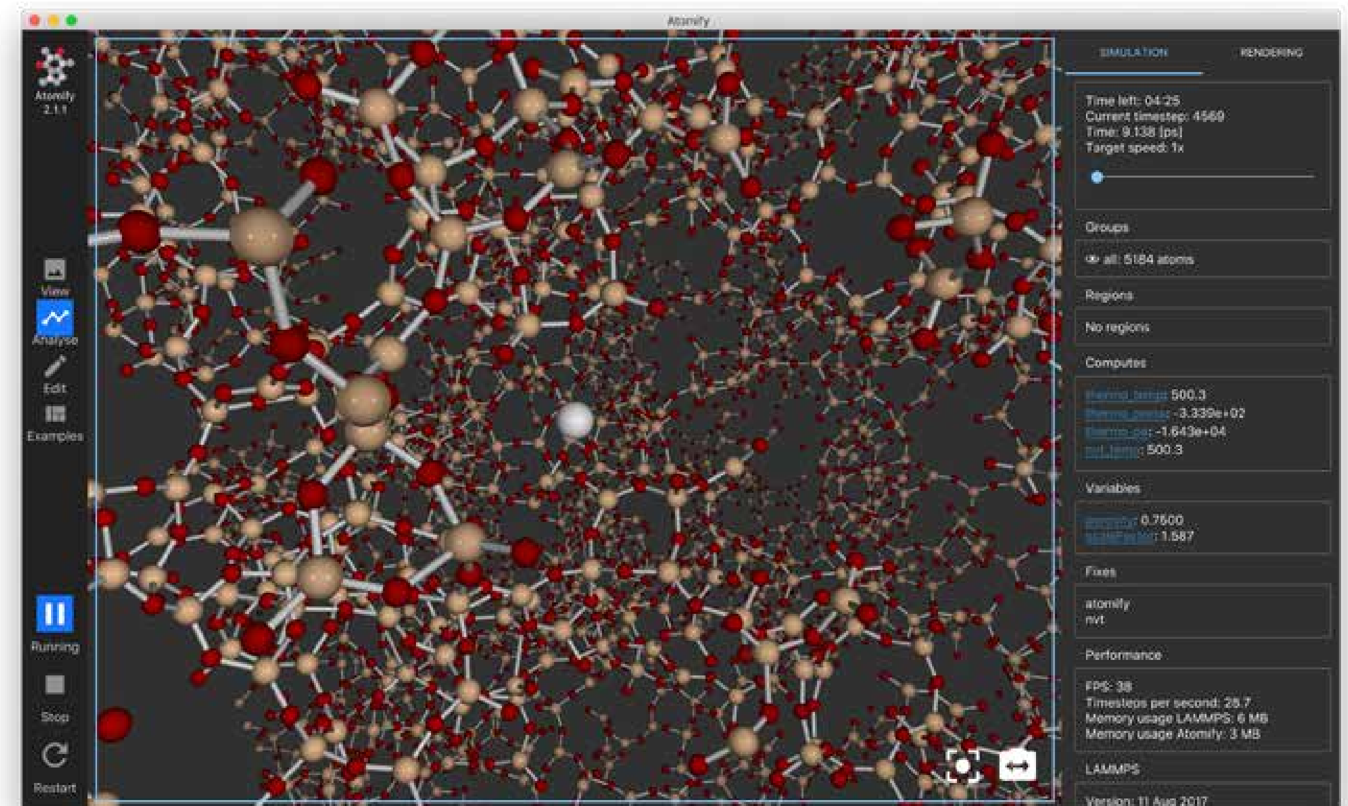

Illustration of simulation of nanoporous SiO2 in Atomify.

Products and publications:

Molecular dynamics simulations of faceting of silicon carbide nanoparticles. Henrik Sveinsson, Anders Hafreager, Priya Vashishta, Anders Malthe-Sørenssen, Rajiv Kalia, A. Nakano, APS March Meeting, Los Angeles, March 5-8 2018

Direct atomic simulations of facet formation and equilibrium shapes of SiC nanoparticles, Anders Hafreager, Henrik Andersen Sveinsson, Rajiv K. Kalia, Aiichiro Nakano, Priya Vashishta, Anders Malthe-Sørenssen, Submitted to PNAS.

Increased productivity with real time atomistic simulations using Atomify. Anders Hafreager, Svenn-Arne Dragly, Anders Malthe-Sørenssen, APS March Meeting, Los Angeles, March 5-8 2018.

05

Appendices

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PhD and Postdoc Projects

Doctoral Research Fellow	Title/Topic	Supervisor
Aupart, Claire Olga Maryse	*Mechanochemical feedbacks during hydration of ultramafic rocks.*	Bjørn Jamtveit, Håkon Austrheim, Anders Malthe-Sørenssen
Bertelsen, Håvard Svanes	*Experimental study of the validity of deformation models used in volcano geodesy.*	Olivier Galland, Karen Mair, Rikke Pedersen
de Ruiter, Lisa	*Rock cementation by magnesium silicate hydrate.*	Håkon Austrheim, Dag Kristian Dysthe, Anette Gunnæs
Dziadkowiec, Joanna	*Interactions between Confined Calcite Surfaces in Aqueous Solutions. A surface forces apparatus study.*	Anja Røyne, Dag Kristian Dysthe
Guren, Marthe Grønlie	*Nanoscale imaging and modelling of mineral surfaces during mechano-chemical transformations*	Francois Renard, Anja Røyne, Anders Malthe-Sørenssen
Hafreager, Anders	*Effective workflow in molecular dynamics simulations and applications*	Anders Malthe-Sørenssen, Dag Kristian Dysthe
Javadi, Shaghayegh	*Interaction between two calcite surfaces in aqueous solutions-Study of nano-scale interfacial forces using AFM and SFA.*	Anja Røyne, Aksel Hiorth
Johnson, James Ronald	*Microfractures in Organic Shales and their transport properties.*	Francois Renard, Nazmul Mondol
Kandula, Neelima	*X-ray micro tomographic studies on the precursors to failure in rocks at conditions relevant for earthquake nucleation*	Francois Renard, Dag Kristian Dysthe, Jerome Weiss
Li, Lei	*Nanoconfined calcite growth.*	Dag Kristian Dysthe, Anja Røyne
Olsen, Kristian Stølevik	*Statistical physics for two-dimensional complex flow*	Knut Jørgen Måløy, Eirik Grude Flekkøy
Petley-Ragan, Arianne Juliette	*The coupling between fluid driven metamorphism and tectonic stress.*	Bjørn Jamtveit, Håkon Austrheim
Rabbel, Ole	*Thermo-mechanical processes at the interface between igneous intrusions and organic-rich host rocks: Fieldwork, modelling and implications for resource exploration.*	Karen Mair, Olivier Galland
Razbani, Mohammad Amin	*Numerical Modelling of Mineral-Microbe Interactions.*	Anders Malthe-Sørenssen, Anja Røyne, Espen Jettestuen
Rodríguez Sánchez, Jesús	*Experimental study of brittle or ductile mineral cements Short summary: Investigation of the strengthening mechanisms, deformation mechanisms and bioactive properties of pure calcium carbonate cements*	Anja Røyne, Dag Kristian Dysthe
Sveinsson, Henrik Andersen	*Molecular-scale modeling of fracture and failure in methane hydrate systems*	Anders Malthe-Sørenssen, Bjørn Jamtveit
Thorens, Louison	*Tunable interactions inside deformable porous media.*	Knut Jørgen Måløy, Eirik Grude Flekkøy
Zheng, Xiaojiao	*Reaction-induced Fracturing in Confined Systems.*	Bjørn Jamtveit, Håkon Austrheim, Francois Renard

Finished in 2018

Cornet, Jan	*Analytical and numerical modeling of cavity closure in rock salt*	Daniel Walter Schmid, Marcin Dabrowski
Panahi, Hamed	*Maturation processes and simulation of fracturing and flow of organic substances from immature shales and consequence on primary migration*	Dag Kristian Dysthe, Francois Renard, Paul Meakin
Schmiedel, Tobias	*Dynamics of sub-volcanic systems in sedimentary basins and related mechanisms of host rock deformation*	Olivier Galland, Sverre Planke
Guldstrand, Frank Bo Buster	*Quantitative Laboratory Modelling of Host Rock Deformation due to the Intrusion of Magma*	Olivier Galland, Alban Souche
Skaugen, Audun.	*A unified perspective on two-dimensional quantum turbulence and plasticity.*	Luiza Angheluta-Bauer, Anders Malthe-Sørenssen

Postdoctoral Fellow	Title/Topic	Supervisor
Campbell, James	*Porous Media Physics*	Eirik Flekkøy and Knut Jørgen Måløy
Chauve, Thomas	*Numerical modeling of primary migration in shale using Discrete Elements Method (DEM)*	Francois Renard
Cordonnier, Benoit	*Argus*	Francois Renard
Demurtas, Matteo	*Granular flow and mineral anisotropy*	Karen Mair
Dumazer, Guillame	*Capillary bulldozing of a deformable porous media in axis-symmetrical confinement*	Eirik Flekkøy and Knut Jørgen Måløy
Dunkel, Kristina	*Interplay of earthquakes and metamorphism (with a focus on wall rock damage caused by lower crustal seismicity).*	Bjørn Jamtveit
Eriksen, Fredrik	*Deformation and flow in porous media*	Knut Jørgen Måløy
Guldstrand, Frank	*Laboratory modelling of the intrusion and emplacement of viscous fluids in cohesive mohr-coulomb hosts and the associated deformation applied to magmatic processes*	Olivier Galland
Incel, Sarah	*An experimental study of mass transfer and microstructural developments in wall rocks during intermediate depth earthquakes in the presence of fluids: Implications for the onset of retrograde metamorphism and shear zone development*	Bjørn Jamtveit
McBeck, Jessica Ann	*Analysing X-ray tomography deformation experiments using digital volume correlation and machine learning (part of the HADES project),*	Francois Renard
McBeck, Jessica Ann	*Linking macroscopic mechanical behaviour with the evolution of internal force and fracture networks using discrete element method simulations.*	Karen Mair
Moura, Marcel	*Intermittent burst dynamics on porous media two-phase flows.*	Eirik Flekkøy and Knut Jørgen Måløy
Thøgersen, Kjetil	*Friction controls on glacier motion*	Thomas Vikhamar Schuler, Anders Malthe-Sørenssen, Andreas Kääb
Zhing, Xin	*Theoretical study and geological applications on coupling chemical reactions and mechanical deformation from microstructural to geodynamic scales*	Bjørn Jamtveit

Guest Talks

January 17th. **Tom Mitchell, UCL.** *Cumulative co-seismic fault damage and feedbacks on earthquake rupture.*

February 2nd. **Magdalena Kersting, Department of Physics, UiO.** *Teaching general relativity in high schools through the development of a digital learning environment.*

February 15th. **Thomas Salez, CNRS; University of Bordeaux; Hokkaido University**. *Glass Transition at Interfaces.*

February 20th. **Claudia Fracchiolla, National University of Ireland Galway.** *University students' negotiation of physics identity in informal physics programs.*

March 9th. **Francesco Caruso, Department of Archaeology, Conservation and History, UiO.** *The crystallization pressure of soluble salts and the conservation of built cultural heritage: previous research and present challenges.*

March 16th. **Laszlo Erdodi, Department of Informatics, UiO.** *Protecting computer systems from cyber threats: Ethical hacking in the practice and research.*

March 23rd. **Irene Pinilla Herrero, Centre for Materials Science and Nanotechonology Chemistry, UiO.** *Use of a fluidized bed reactor to produce hydrocarbons.*

April 24th. **Oliver Eisermann, University of Hamburg.** *A new approach in analogue modelling for studying kinematic complexities of transpression using the „MultiBox".*

April 26th. **John Dehl, NGU.** *InSAR.no: A National InSAR Deformation Mapping Service.*

April 27th. **Alexander Refsum Jensenius, Department of Musicology, UiO.** *Studying "nothing": complexities of human music-related micromotion.*

May 4th. **Tom Lindstrøm, Department of Mathematics, UiO.** *What is the value of an option?*

May 15th. **Yehuda Ben-Zion, USC.** *Imaging and monitoring large crustal fault zones.*

May 25th. **Irene Brox Nilsen, NVE.** *How will river floods change in a warmer climate?*

June 1st. **Victor Modamio, Department of Physics, UiO.** *Shapes of atomic nuclei.*

June 8th. **Philip M. Weiser, Department of Physics, UiO.** *Fourier Transform Infrared Spectroscopy: Basics and Applications.*

August 30th. **Tom-Vincent Dospital, University of Strasbourg.** *Thermal weakening of cracks*

November 12th. **Bjorn Birnir, UCSB.** *Mathematics of Turbulent Flow and Comparison with Experiment.*

November 28th. **Gaute Linga, SINTEF.** *Two-phase electrohydrodynamics in complex geometries – modelling and simulation.*

December 4th. **Mogens Jensen, Niels Bohr Institute.** *Coupled Oscillators and Chaos in Biology.*

December 6th. **Josh McGraw, ENS.** *Friction with self assembled monolayers: hydrodynamic slip and activated solid/solid friction.*

Production list 2018:

Publications

-

1. Aslan, Gokhan; Cakir, Ziyadin; Ergintav, Semih; Lasserre, Cécile; **Renard, Francois**. *Analysis of secular ground motions in istanbul from a long-term InSAR time-series (1992-2017)*. Remote Sensing 2018 ;Volum 10.(3) p. 408.
2. **Aupart, Claire; Dunkel, Kristina G; Angheluta, Luiza; Austrheim, Håkon Olaf**; Ildefonse, Benoit; **Malthe-Sørenssen, Anders; Jamtveit, Bjørn**. *Olivine Grain Size Distributions in Faults and Shear Zones: Evidence for Nonsteady State Deformation.* Journal of Geophysical Research - Solid Earth 2018 ;Volum 123.(9) p. 7421-7443.
3. Beinlich, Andreas; **Austrheim, Håkon Olaf**; Mavromatis, Vasileios; Grguric, Ben; Putnis, Christine V; Putnis, Andrew. *Peridotite weathering is the missing ingredient of Earth's continental crust composition.* Nature Communications 2018; Volum 9.(1), p. 634.
4. **Bertelsen, Håvard Svanes; Rogers, Benjamin David; Galland, Olivier; Dumazer, Guillaume Henri**; Benanni, Alexandre Abbana. *Laboratory Modeling of Coeval Brittle and Ductile Deformation During Magma Emplacement Into Viscoelastic Rocks.* Frontiers in Earth Science 2018 ;Volum 6.(199)
5. Centrella, Stephen; Putnis, Andrew; Lanari, Pierre; **Austrheim, Håkon Olaf**. *Textural and chemical evolution of pyroxene during hydration and deformation: A consequence of retrograde metamorphism.* Lithos 2018; Volum 296-299. p. 245-264.
6. Clement, Colin P.; **Toussaint, Renaud**; Stojanova, Menka; Aharonov, Einat. *Sinking during earthquakes: Critical acceleration criteria control drained soil liquefaction.* Physical review. E 2018; Volum 97.(2) p. 022905.
7. Clerc, Adriane; **Renard, Francois; Austrheim, Håkon Olaf; Jamtveit, Bjørn**. *Spatial and size distributions of garnets grown in a pseudotachylyte generated during a lower crust earthquake.* Tectonophysics 2018; Volum 733. p. 159-170.
8. Cochard, Alain; Lengliné, Olivier; **Måløy, Knut Jørgen; Toussaint, Renaud**. *Thermally activated crack fronts propagating in pinning disorder: simultaneous brittle/creep behaviour depending on scale.* Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 2018 ;Volum 377.(2136) p. 1-23.
9. Collignon, Marine; Mazzini, Adriano; **Schmid, Daniel Walter**; Lupi, Matteo. *Modelling fluid flow in active clastic piercements: challenges and approaches.* Marine and Petroleum Geology 2018 ;Volum 90. p. 157-172.
10. Collignon, Marine; **Schmid, Daniel Walter**; Galerne, Christophe Yann; Lupi, Matteo; Mazzini, Adriano. *Modelling fluid flow in clastic eruptions: Application to the Lusi mud eruption.* Marine and Petroleum Geology 2018 ;Volum 90. p. 173-190.
11. **Cornet, Jan; Dabrowski, Marcin**. *Nonlinear Viscoelastic Closure of Salt Cavities.* Rock Mechanics and Rock Engineering 2018 p. 1-19.
12. **Cornet, Jan; Dabrowski, Marcin; Schmid, Daniel Walter**. *Long term creep closure of salt cavities.* International Journal of Rock Mechanics And Mining Sciences 2018 ;Volum 103. p. 96-106.
13. **de Ruiter, Lisa; Austrheim, Håkon Olaf**. *Formation of magnesium silicate hydrate cement in nature.* Journal of the Geological Society, London. 175, p. 308–320.
14. Dragly, Svenn-Arne; Mobarhan, Milad; Lepperød, Mikkel Elle; Tennøe, Simen; Fyhn, Marianne; Hafting, Torkel; **Malthe-Sørenssen, Anders**. *Experimental directory structure (Exdir): An alternative to HDF5 without introducing a new file format.* Frontiers in Neuroinformatics 2018 ;Volum 12. p. 16.
15. **Dziadkowiec, Joanna; Javadi, Shaghayegh**; Bratvold, Jon E.; Nilsen, Ola; **Røyne, Anja**. *Surface Forces Apparatus Measurements of Interactions between Rough and Reactive Calcite Surfaces.* Langmuir 2018 ;Volum 34.(25) p. 7248-7263.
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21. Incel, Sarah; Labrousse, Loïc; Hilairet, Nadège; John, Timm; Gasc, Julien; Shi, Feng; Wang, Yanbin; Andersen, Torgeir Bjørge; Renard, Francois; Jamtveit, Bjørn, Schubnel, Alexandre. *Reaction-induced embrittlement of the lower continental crust*. Gordon Research Conference on Rock Deformation; August 19th-24th.

22. Dziadkowiec, Joanna; Javadi, Shaghayegh; Bratvold, Jon E.; Nilsen, Ola; Røyne, Anja. *Adhesive and repulsive forces between calcite surfaces*. 32nd European Colloid & Interface Society Conference; September 2nd-7th.

23. Jahanbani Ghahfarokhi, Ashkan; Torsæter, Ole. *Numerical Simulation Of Low Salinity Water Flooding: Wettability Alteration Considerations*. ECMOR XVI - 16th European Conference on the Mathematics of Oil Recovery; September 3rd-6th.

24. Dunkel, Kristina G; Austrheim, Håkon; Plümper, Oliver; Jamtveit, Bjørn. *Fragmentation and growth processes in ultramafic pseudotachylytes and their wall rocks – open questions*. TIGeR Conference 2018; September 12th-14th.

25. Aupart, Claire; Schlindwein, Vera; Ben-Zion Yehuda; Renard, François; Jamtveit, Bjørn. *Microseismicity on an ultraslow ridge segment: implications for serpentinization*. 2018 TIGeR conference: Coupling between Metamorphism and Deformation; September 12th-14th.

26. Golestan, Mohammad Hossein; Aursjø, Olav; Berg, Carl Fredrik. Lattice-Boltzmann *Simulation of Osmosis Effect During Low-Salinity Waterflooding*. Interpore Norway 2018; September 9th.

27. Dziadkowiec, Joanna; Javadi, Shaghayegh; Bratvold, Jon E.; Nilsen, Ola; Røyne, Anja. *Nucleation in solution confined between reactive surfaces can generate long-range repulsive forces*. 2nd Norwegian Interpore workshop; November 9th.

Invited talks

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1. Jamtveit, Bjørn. *Earthquakes controls on metamorphism of the lower crust*. University of Lausanne. March 5th.

2. Jamtveit, Bjørn. *Earthquakes controls on metamorphism of the lower crust*. EGU, Vienna, Austria. April 9th.

3. Renard, Francois. *Fault anatomy and surface creep dynamics along a continental plate boundary: the North Anatolian Fault, Turkey*, Institut de Physique du Globe, Paris. April 17th.

4. Dziadkowiec, Joanna; Javadi, Shaghayegh; Zareeipolgardani, Bahareh; Bratvold, Jon E.; Nilsen, Ola; Røyne, Anja. *Adhesive and repulsive forces between calcite surfaces in the Surface Forces Apparatus*, NanoHeal ITN network, Norway. April 24th.

5. Renard, Francois. *From damage to failure in rocks*, 3rd EarthFlow Seminar, Oslo, Norway. June 14th-15th.

6. Renard, Francois. *Unravelling the Dynamics of Precursors to Rupture by Imaging the Evolution of Damage Towards System-Size Failure in Rocks*, Gordon Conference on Rock Deformation, Andover, USA. August 20th-25th.

7. Incel, Sarah; Labrousse, Loïc; Hilairet, Nadège; John, Timm; Gasc, Julien; Shi, Feng; Wang, Yanbin; Andersen, Torgeir Bjørge; Renard, Francois; Jamtveit, Bjørn; Schubnel, Alexandre. *Reaction-induced faulting in granulite causes earthquakes in the lower continental crust*. GeoBonn. September 4th.

8. Renard, Francois. *Hydration of periclase breaks peridotite under serpentinization conditions*. The 4th TiGer Conference, Perth, Australia. September 12th-14th.

9. Jamtveit, Bjørn. *Earthquakes-driven metamorphism*. 2018 TIGeR conference, Curtin University, Perth, Australia. September 14th.

10. Guren, Marthe G.; Putnis, Christine V.; Renard. Francois. *Atomic force microscopy imaging of coupled dissolution-precipitation on a calcite surface when exposed to a chromium-rich fluid*. Granada-Münster Discussion Meeting, in Münster, Germany. November.

11. Jamtveit, Bjørn. *Earthquakes, Fluids & Metamorphism*. School of Earth and Environment, University of Leeds. November 2nd.

12. Renard, Francois. *Porosity evolution in rocks when approaching failure is a critical phenomenon*, InterPore Norway, Oslo, Norway. November 9th.

13. Jamtveit, Bjørn. *Organisering og ledelse av forskning*. Seminar for forskningsledere i kreftforskning, Oslo Universitetssykehus, Asker, Norway. November 26th.

Other talks

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1. Rabbel, Ole; Galland, Olivier; Mair, Karen; Lecomte, Isabelle; Spacapan, Juan Bautista. *Improving seismic interpretation of igneous sill complexes via seismic modelling*. Nordic Geological Winter Meeting. January 9th-12th.

2. Schmiedel, Tobias; Galland, Olivier; Haug, Øystein Thorden; Breitkreuz, Christoph. *How do sills become laccoliths? An answer from integrated laboratory and numerical modelling*. 33rd Nordic Geological Winter Meeting. January 10th-12th.

3. Solbrå, Andreas Våvang; Bergersen, Aslak Wigdahl; van den Brink, Jonas; Malthe-Sørenssen, Anders; Einevoll, Gaute; Halnes, Geir. *Modeling electrodiffusion in the extracellular space around a morphologically detailed neuron*. Workshop "Mathematical Modeling of Cortical Spreading Depression (SD) and Related Phenomena. February 12th.

4. Hafreager, Anders; Dragly, Svenn-Arne; Malthe-Sørenssen, Anders. *Increased productivity with real time atomistic simulations using Atomify*. APS March Meeting 2018. March 5th-9th.

5. Sveinsson, Henrik Andersen; Hafreager, Anders; Vashishta, Priya; Malthe-Sørenssen, Anders; Kalia, Rajiv K. *Molecular dynamics simulations of faceting of silicon carbide nanoparticles*. APS March Meeting 2018. March 5th-9th.

6. Moura, Marcel; Måløy, Knut Jørgen; Flekkøy, Eirik Grude; Toussaint, Renaud. *Burst dynamics in porous media drainage flows*, Workshop LIA D-FFRACT, Courmayeur, Italy. March 11th-14th.

7. Eriksen, Fredrik Kvalheim. *Granular media on drop interfaces: Deformation, patterns & flow driven by electric fields*. LIA D-FFRACT (France-Norway) international workshop, Courmayeur, Italy. March 11th-14th.

8. Måløy, Knut Jørgen; Eriksen, Jon Alm; Flekkøy, Eirik Grude; Sandnes, Bjørnar; Galland, Olivier. *Pattern formation of frictional fingers in a gravitational potential*, Workshop, LIA D-Fract, Courmayer. March 12th.

9. de Ruiter, Lisa. Talk at the NanoHeal ITN Meeting. April 2018

10. Ulven, Ole Ivar; Austrheim, Håkon Olaf; Jamtveit, Bjørn. *Self-induced serpentine deformation and its effect on weathering*. EGU 2018. April 4th-13th.

11. Jamtveit, Bjørn; Petley-Ragan, Arianne; Renard, Francois; Austrheim, Håkon. *Earthquake-controls on metamorphism of the lower continental crust*. EGU General Assembly Conference Abstracts (vol. 20, p. 4763). April 6th-11th.

12. McBeck, Jessica; Mair, Karen; Renard, Francois. *Investigating the impact of preexisting weaknesses on macroscopic geomechanical response using discrete element method simulations*. EGU General Assembly Conference Abstracts (vol. 20, p. 7337). April 6th-11th.

13. Aslan, Gokhan; Cakir, Zeyadin; Ergintav, Semih; Lassarre, Cécile; Renard, Francois. *Identification of secular ground motions in Istanbul by long-term time-resolved InSAR analysis (1992-2017)*. EGU General Assembly Conference Abstracts (vol. 20, p. 18018). April 6th-11th.

14. Putnis, Christine V., Ruiz-Agudo, Encarnacion, Wang, Lijun, Renard, Francois. *Nanoscale imaging of coupled dissolution and precipitation reactions at the mineral-fluid interface*. EGU General Assembly Conference Abstracts (vol. 20, p. 3313). April 6th-11th.

15. Aslan, Gokhan, Cakir, Ziyadin, Lasserre, Cécile, Renard, Francois. *Surface creep along the 1999 Izmit earthquake's rupture (Turkey) from high temporal resolution interferometric synthetic-aperture radar data*. EGU General Assembly Conference Abstracts (vol. 20 p. 181489. April 6th-11th.

16. Incel, Sarah; Labrousse, Loic; Hilaret, Nadege; John, Timm; Gase, Julien; Yanbin, Wang; Shi, Feng; Andersen, Torgeir Bjørge; Renard, Francois; Jamtveit, Bjørn; Schubnel, Alexandre. *Reaction-induced faulting in granulite: New insights for the generation of intermediate-depth earthquakes in lower continental crust*. EGU 2018; General Assembly Conference Abstracts (vol. 20, p. 4672). April 9th.

17. Moura, Marcel; Måløy, Knut Jørgen; Flekkøy, Eirik Grude; Toussaint, Renaud. *Burst dynamics slow drainage in porous media*, Workshop Crackling Noise in Materials, NORDITA, Stockholm, Sweden. April 30th-May11th.

18. Austrheim, Håkon Olaf. *Fluids, Metamorphism and Seismicity*. Lund University Lecture. May 3rd.

19. Moura, Marcel; Måløy, Knut Jørgen; Flekkøy, Eirik Grude; Toussaint, Renaud. *Direct experimental measurement of the pair correlation function during the slow drainage of a porous medium*, InterPore 10th International Conference on Porous Media & Annual Meeting, New Orleans, USA. May 14th-17th.

20. Halpaap, Felix; Rondenay, Stéphane; Ottemöller, Lars; Perrin, Alexander; Goes, Saskia; Austrheim, Håkon Olaf. *Seismicity, Metamorphism & Fluid Migration in the Western Hellenic Subduction Zone*. Observatoire Cote d'Azur Geoscience Seminar. June 8th.

21. Jahanbani Ghahfarokhi, Ashkan; Kleppe, Jon; Torsæter, Ole. *In-Depth Reservoir Placement of pH-Sensitive Polymer Gels – Importance of Geochemical Reactions in Numerical Simulations*. 80th EAGE Conference and Exhibition 2018. June 11th-14th.

22. Thøgersen, Kjetil. *Glacier surges as frictional tipping points*. EarthFlows 2018: Complexity in Geophysical Flows. June 14th-15th.

23. Gilbert, Adrien; Thøgersen, Kjetil; Kääb, Andreas; Nuth, Christopher; Schuler, Thomas; Gimbert, Florent. *Stable and unstable glacier flows: Role of friction law and feedback mechanisms at the basal interface*. EarthFlow seminar. June 14th.

24. Jamtveit, Bjørn. *Flow induced metamorphism and stress*, Earthflows seminar, Oslo, Norway. June 14th.

25. de Ruiter, Lisa; Austrheim, Håkon Olaf; Dysthe, Dag Kristian; Gunnæs, Anette Eleonora. *Quartz weathering associated with magnesium silicate hydrate cement precipitation*. Goldschmidt. August 12th-17th.

26. Petley-Ragan, Arianne; Ben-Zion, Yehuda; Renard, Francois; Austrheim, Håkon; Jamtveit, Bjørn. *Asymmetric damage and metamorphism across a lower crustal fault from the Bergen Arcs, western Norway*. Tiger Conference in Perth, Australia. September.

27. Hosseinzade Khanamiri, Hamid; Berg, Carl Fredrik; Slotte, Per Arne; Torsæter, Ole; Schlüter, Steffen. *Energy Description for Immiscible Two-Fluid Flow in Porous Media by Integral Geometry and Thermodynamics*. European Fluid Mechanics Conference (EFMC2018). November 9th-13th.

28. Stølevik Olsen, Kristian; Flekkøy, Eirik Grude; Angheluta, Luiza; Campbell, James Matthew; Måløy, Knut Jørgen; Sandnes, Bjørnar. *Geometry and Anomalous diffusion in frictional fingers*. 2nd National Workshop on Porous Media. November 9th.

29. Dunkel, Kristina G; Petley-Ragan, Arianne; Jamtveit, Bjørn, Austrheim, Håkon; Renard, François. *Microstructural Records of Intermediate-Depth Earthquakes*. Intermediate and Deep Earthquakes: Observations and Modeling; Paris, France. November 19th-20th.

30. Guren, Marthe G.; Putnis, Christine V.; Renard, Francois. *Atomic force microscopy imaging of coupled dissolution-precipitation on a calcite surface when exposed to a chromium-rich fluid*, 6th Granada Münster Discussion Meeting, Münster, Germany. November 24th-25th.

31. de Ruiter, Lisa; Gunnæs, Anette E.; Putnis, Christine V.; Hövelmann, Jörn; Dysthe; Dag K.; Austrheim, Håkon. *The interplay between quartz weathering and magnesium silicate hydrate cement precipitation*, Grenade-Münster Discussion-Meeting 2018, Münster, Germany. November 29th-30th.

32. Incel, Sarah; Labrousse, Loic; Hilairet, Nadège; John, Timm; Gasc, Julien; Shi, Feng; Wang, Yanbin; Andersen, Torgeir Bjørge; Renard, Francois; Jamtveit, Bjørn; Schubnel, Alexandre. *Reaction-induced faulting in granulite causes earthquakes in the lower continental crust*. AGU annual meeting 2018. December 10th-14th.

33. Sleveland, Arve Rein Nes; Galland, Olivier; Leanza, Hector Armando; Midtkandal, Ivar. *Architecture of mixed-process mouth-bar deposits; compensational stacking in the Mulichinco Formation, Neuquén Basin, Argentina*. 57th BSRG Annual General Meeting. December 17th-20th.

34. Zuchuat, Valentin; Sleveland, Arve Rein Nes; Rabbel, Ole; Braathen, Alvar; Midtkandal, Ivar; Pettigrew, Ross P.; Dodd, Thomas J.H.; Clarke, Stuart M. *Why you should care about neighbouring sedimentary systems: Overprinted allocyclic processes by tidal resonance in the Upper Jurassic Curtis Formation, Utah, USA*. BSRG Annual General Meeting 2018. December 17th-19th.

Outreach

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1. Dziadkowiec, Joanna. *Popular Science Presentation Contest for PhD students organized by Academy of Young Scientists*, Polish Academy of Sciences, Jablonna, Poland. September 18th.

2. Johansen, Finn-Eirik; Brautaset, Trygve; Aune, Marie Hjelmseth; Patriksson, Alexandra; Falkenberg, Liv Eggset; Kleppe, Rune; Dick, Gunnar; Strand, Berit Løkensgard; Eijsink, Vincent; Røyne, Anja; Goksøyr, Anders; Svendsen, John Sigurd Mjøen; Fyhn, Marianne; Vik, Jon Olav; Wentzel, Alexander; Aksnes, Astrid; Bruheim, Per; Carlsen, Sven Magnus; Åm, Heidrun. *Centre for Digital Life Norway – Annual report 2017*. : Senter for Digialt Liv Norge 2018.

3. Mair, Karen; Barrett, Natasha. *"Rock music – Exploring Geology using sound"*, Listening Lab, National Museum, Edinburgh, Scotland. November, 2018

4. Moura, Marcel. *"Kompleksitet – "More is Different" also in Norway"*, Norske Fysikkstudenters Konferanse 2018, Oslo, Norway. March 9th-11th, 2018

5. Moura, Marcel. *"Kjedefontene"*, published by Department of Physics, UiO, youtube.com. November 22th.

6. Moura, Marcel. *"Complexity: more is different, also in your classroom"*, UiO Faglig-pedagogisk dag, Oslo, Norway. November 1st.

7. Moura, Marcel. *“Kompleksitet - “More is Different” also at UiO””*, Fysikk i Origo, Oslo, Norway.

8. Renard, Francois. *"How earthquakes work?"*, GeoOnsdag, Science Library, UiO, Oslo, Norway. January 24th.

9. Renard, Francois. *"How earthquakes work?"*, NORSAR, Kjeller, Norway. April 9th.

10. Røyne, Anja. *"Bærekraftig betong laget av bakterier."* Ungforsk 2018, Oslo, UiO, Oslo, Norway. September 26th-27th.

11. Røyne, Anja. *"Fysikk og fascinasjon, en blogg om ny og gammel forskning, og den fantastiske naturen"*, anjafysikk.wordpress.com/.

12. Røyne, Anja. *"Hvordan kan du bruke BioTech til å skape et nullutslippssamfunn?"* LØRN.TECH. September 28th.

13. Ulven, Ole Ivar. *"Oman Drilling Project. Pub med forsker"*, Oslo, Norway. May 2nd.

In Media

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1. de Ruiter, Lisa. Article in Røros' local newspaper Fjell Ljom. [NEWSPAPER]

2. de Ruiter, Lisa. *"Røros-funn kan gi miljøvennlig sement"*, geoforskning.no, July 22nd.

3. Flekkøy, Eirik Grude. Expert on the infotainment tv-show "Brille", NRK1. [TV]

4. Galland, Olivier; Guldstrand, Frank; Schmiedel, Tobias. *"Jakter på jordens dypeste mysterier i en plexiglassboks"*, titan.uio.no, January 8th. [MAGAZINE]

5. Jemterud, Torkild; Røyne, Anja; Gadmar, Tone Charlotte; Brodal, Per. Abels tårn, NRK Radio: *"Hva skjer når moderne kropper, fylt med silikon og gudene vet hva, en dag skal begraves?"*. Ekko, NRK P2. April 6th. [RADIO]

6. Jemterud, Torkild; Røyne, Anja; Madsen, Steinar; Bjorå, Charlotte Sletten. Abels tårn, NRK P2: *"Baby-lukt, vannkraft og hvorfor det å være på bærtur er negativt"*. NRK P2. August 24th. [RADIO]

7. Jemterud, Torkild; Swang, Ole; Delsett, Lene Liebe; Røyne, Anja. Abels Tårn, NRK P2: *"Alfa-hanners kurtise, trampolinehopping i solskinn, kefir-fyll – og forsøk på å løse et klokkemysterium!"*. NRK P2. May 25th. [RADIO]

8. Moura, Marcel. Radio Cultura do Nordeste: *"Energy and environmental challenges in Brazil and Norway and the importance of basic science in this context"*, Brazil. June. [RADIO]

9. Moura, Marcel. *"YouTube-hit om metallkjeder ble forskning på toppnivå"*, titan.uio.no. December 13th. [MAGAZINE]

10. Njord. *"NJORD, et nytt tverrfaglig forskningssenter ved Universitetet i Oslo"*, titan.uio.no. February 23th. [MAGAZINE]

11. Røyne, Anja. *"To UiO-forskere fikk Else-Ragnhild Neumann Award for Women in Geosciences 2018"*, titan.uio.no, December 10th. [MAGAZINE]

12. Røyne, Anja. *"Kan vi gå tom for råstoffer? Er plan B å hente dem fra verdensrommet?"*, Aftenposten Viten. October 2nd. [MAGAZINE]

13. Røyne, Anja; Eivind, Torgersen; Guro, Tarjem. *"Ekko - Grunnstoffer 1:6 Gull."* NRK P2. November 14th. [RADIO]

14. Røyne, Anja; Torgersen, Eivind; Tarjem, Guro. *"Ekko - Grunnstoffer 2:6 Oksygen: Livsfarlig og essensielt."* NRK P2. December 19th. [RADIO]

15. Ursin, Lars; Røyne, Anja. *"Ekspertintervju-et: Bygg med bakterier."*, energiogklima.no [Internett]. May 31st. [MAGAZINE]

16. Thorens, Louison; Bernard, Jeanne. *“Le mystère des écoulements ramifiés.”* La Recherche (Imprimé) 2018 ;Volum 540. [MAGAZINE]

17. Jamtveit; Bjørn. *"Etterskjelv sparker hardt mot jordens dyp"*, titan.uio.no. April 26th. [MAGAZINE]

18. Renard, Francois. *"Comment les séismes transforment la croûte terrestre en profondeur"*, sciencesetavenir.fr. April 26th. [MAGAZINE]

19. Renard, Francois. *"Comment les séimes transforment la croûte inférieure terrestre"*, univ-grenoble-alpes.fr/. April 26th. [MAGAZINE]

20. Renard, Francois. *"Les séismes de surface endommagent la croûte terrestre en profondeur"*, pourlascience.fr/. May 16th. [MAGAZINE]

Other productions

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Halpaap, Felix; Rondenay, Stéphane; Goes, Saskia; Perrin, Alexander; Ottemöller, Lars; **Austrheim, Håkon Olaf**; Shaw, Robert; Eeken, Thomas. *Western Hellenic Subduction Zone: deep earthquake activity 2000 - 2017, plate interface geometry and thermal model.* PANGAEA Bremen, Germany 2018. Database.

Project portfolio

Host	Project title	Project leader	Source	Accounting 2018 (NOK in 1000)	Project Start dato	Project End date	Total external financing (NOK in 1000)
The Njord center	EarthFlows 1 (EarthFlows 2 continues 2019-2023)	Angheluta-Bauer, Luiza; Jamtveit, Bjørn	UiO	113	01.01.15	31.12.18	N/A
Dept. of Geosciences	Subduction zone water and metamorphism; a Modelling	Austrheim, Håkon	NRC	62	01.09.14	31.08.18	168
Dept. of Physics	NanoHeal	Dysthe, Dag	ERC	3 076	01.01.15	31.12.18	9 380
The Njord center	Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity.	Dziadkowiec, Joanna	NRC	0	01.04.19	31.03.22	3 234
Dept. of Geosciences	Fracture characterization of intrusions and the	Galland, Olivier	NRC	24	01.01.18	31.12.18	35
Dept. of Geosciences	Natural Fracture Characterization in the intrusive systems	Galland, Olivier	YPF S.A	0	19.02.16	20.02.18	260
Dept. of Geosciences	Dynamics of Igneous Plumbing Systems in	Galland, Olivier	NRC	1 443	01.01.15	31.03.19	8 493
Dept. of Geosciences	Disequilibirum meta-morphism of stressed	Jamtveit, Bjørn	ERC	5 613	01.09.15	31.08.20	21 200
Dept. of Geosciences	ABYSS	Jamtveit, Bjørn	ERC	84	01.03.14	28.02.18	2 578
Dept. of Physics	US-Norwegian collabor-ation on fluid-consuming	Malthe-Sørenssen, Anders	NRC	645	01.01.16	31.12.19	3 915
Dept. of Physics	Porous Media Laboratory	Måløy, Knut Jørgen	NRC	5 850	01.07.17	31.12.27	66 400
Dept. of Geosciences	Advanced X-ray and neutron imaging of fractured and	Renard, Francois	NRC	808	01.01.18	31.12.20	3 093
Dept. of Geosciences	Microfractures in black shales and their transport	Renard, Francois	NRC	2 826	01.04.17	30.06.21	11 201
Dept. of Geosciences	Unravelling the spatio-temporal nature of	Renard, Francois	NRC	2 793	01.05.16	31.10.19	8 989
The Njord center	Akademia: Flow across scales	Renard, Francois; Jamtveit, Bjørn	Equinor	0	01.01.19	31.12.23	9 048
Dept. of Physics	Systems analysis and fundamental control of	Røyne, Anja	NRC	1 612	01.05.17	30.09.20	4 726

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PoreLab
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