NJORD

Annual report 2019

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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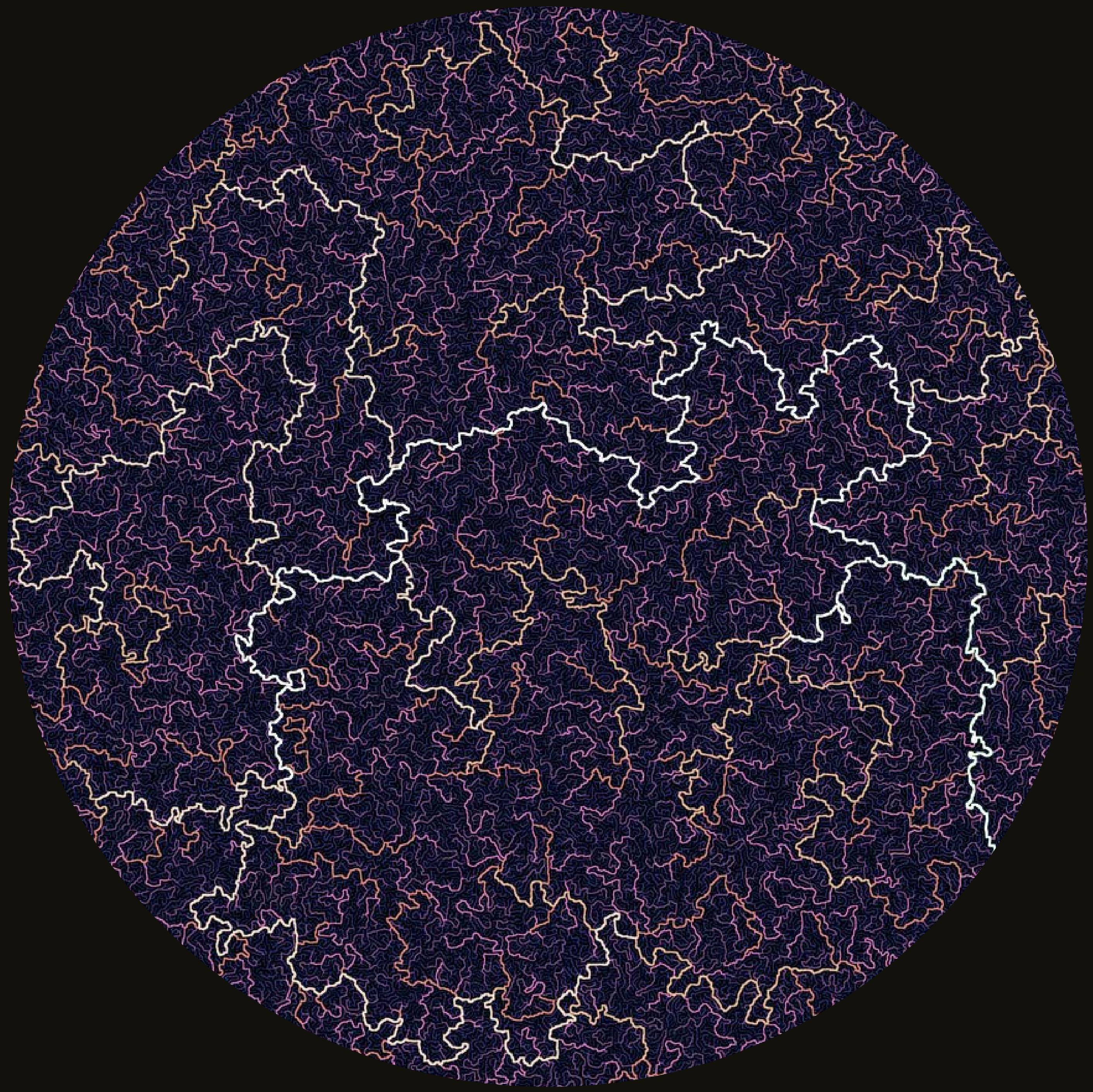
Contents



01

About Njord

Preface

Research is the process of going up alleys to see if they are blind

– Marston Bates, The Nature of Natural History

The cross-disciplinary geoscience-physics centre *Njord* was officially established on January 1st 2018. Njord is a merger of the 1st generation Norwegian Centre of Excellence (CoE) PGP ('Physics of Geological Processes', running in the period 2003-2013), and the Oslo node of the 4th generation CoE *PoreLab* ('Porous Media Laboratory', started in August 2017). Through curiosity-driven research near the interface between physics and geoscience, our ambition is 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 its second year in operation *Njord* staff produced 81 papers in international journals, including five in Nature and Science journals (2 in *Nature Communications*, 2 in *Science Advances*, and 1 in *Scientific Reports*), 1 in *Proceedings of the National Academy of Sciences* (PNAS), and 1 in *Physical Review Letters*. In addition, we have 3 in *Earth and Planetary Science Letters*, 3 in *Geophysical Research Letters*, and 2 in *Geology*. For a research centre with 10 senior staff members, this is already a remarkable production.

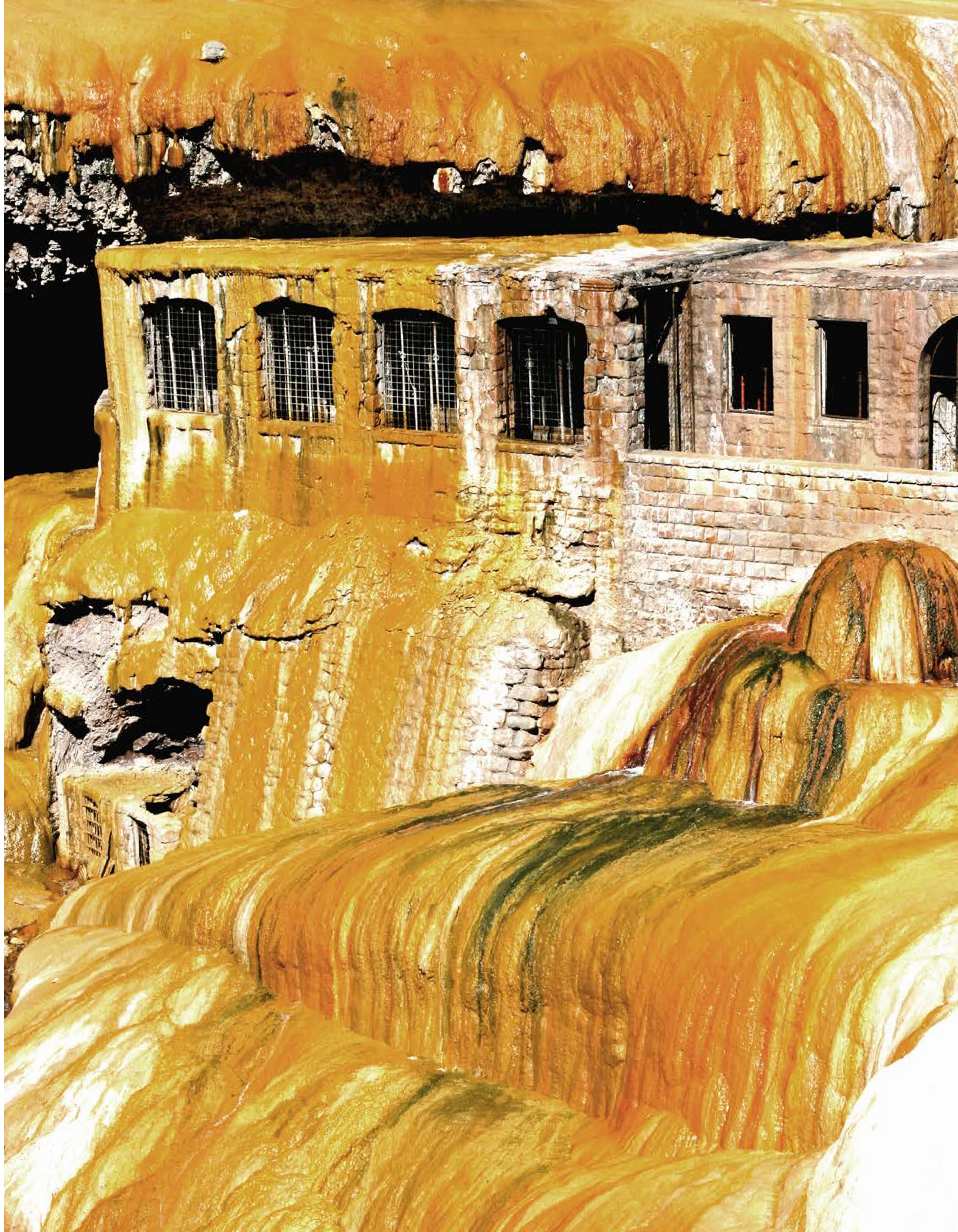
Four out of twelve PhD students who graduated in 2019, continued as post-docs or researchers in academia: *Arianne Petley-Ragan* stayed within Njord; *Henrik Sveinsson* moved to Center for Computing in Science Education; *Joanna Dziadkowiec* got a mobility grant from NRC and will share her work between University of Vienna and Njord; whereas *Xiaojiao Zheng* moved to China Academy of Sciences in Beijing. *Jesus Rodriguez Sanches*, and *Anders Hafreager* works for private companies, while *Øyvind Gløersen* is a senior engineer at Norwegian School of Sport Science.

In September, former Njord PhD candidate *Audun Skaugen* received The King's Gold Medal for the best PhD at the Faculty of Mathematics and Natural Sciences at UiO. This is the 4th Gold medal to PGP/Njord since 2009. 36 % (4/11th) of all the gold medals to a unit with less than 4 % of the scientific staff of the faculty is very 'satisfactory' indeed.

Our young researchers are our pride, and in 2020 Jess McBeck will receive a *Young Research Talent* grant from the Research Council of Norway (RCN) for the project *Emergent networks: Predicting strain localization and fracture network development*. In addition, François Renard is partner in the new NTNU-lead RCN project *PoreFlow: Visualizing multiphase flow in porous media with neutron scattering.*

During 2020, we will keep working 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



Mineralised hot springs lead to travertine precipitations, which built a natural bridge (the "Inca bridge") over the Las Cuevas river. The minerals contained in the seeping water allow the development of algae colonies, giving the bright orange colours. Location: Puente del Inca, Mendoza province, Argentina. Picture by: Olivier Galland.

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.

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 centre 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 centre accommodates researchers from the former Centre of Excellence (CoE) 'Physics of Geological Processes' and the University of Oslo's node of the new CoE 'NTNU-UiO Porous Media Laboratory'. Physics of Geological Processes (PGP) was a first generation Norwegian 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 a 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 centre in physical sciences at UiO with focus on a fundamental understanding of the dynamics of fluid-solid systems with Earth-like complexity.
- Build the next generation of computational competences and experimental laboratory facilities for the study of processes in fluid-rock / fluid porous-media systems in 4D from molecular to field scales.
- Provide a unique basis for making predictions relevant for CO2-sequestration, exploration and exploitation of natural resources, transport of contaminants in 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).

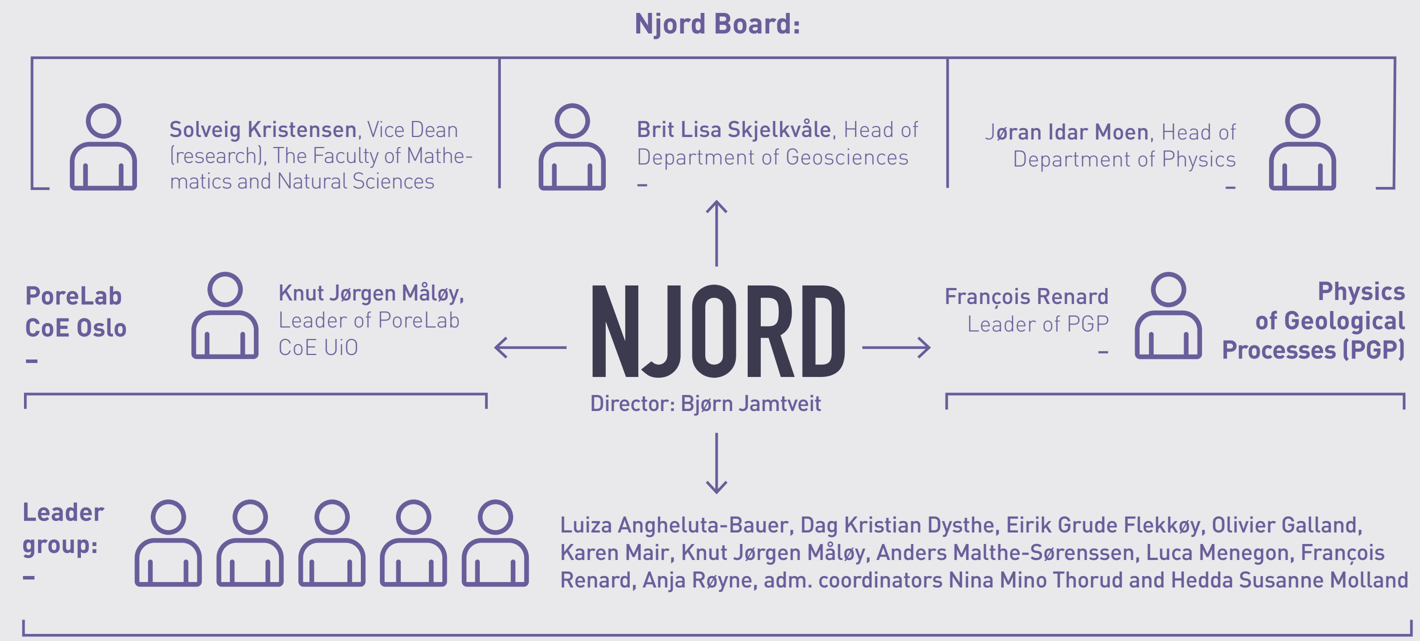
Our philosophy for education is research based: 'Learning by doing'. We are doing this in close collaboration with the Centre for Computing in Science Education (CCSE), a CoE in education directed by Njord's Anders Malthe-Sørenssen.

Organization

Njord is a cross-disciplinary geoscience-physics centre at the Faculty of Mathematics and Natural Sciences. We aim to become one of the main UiO cross-disciplinary 'drivers' for the future development of Physical Sciences in general, and Earth and Space related research in particular.

For the first 5-year period (2018-2022), Njord is directed by professor Bjørn Jamtveit. The director, assisted by the administrative coordinator, Nina Mino Thorud, is responsible for project management, administration, as well as technical and financial delivery. The director reports to the board. Our scientific organization is divided in two core groups, *PoreLab*, lead by professor Eirik Flekkøy and *PGP*, lead by professor François Renard. The Njord leader group, includes the 10 senior scientists at the centre. In total, Njord comprises ca. 65 members from the Department of Physics and the Department of Geosciences.

We believe there is a considerable potential for increased synergies between physics and geoscience at UiO by merging PGP and PoreLab CoE Oslo onto a joint organizational platform – and the results from 2019 has further increased our belief in this potential.



Staff

Geographical origins of Njord employees

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Norway

36 %

Geographical origin by percentage

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	%
Norway	36
France	16
China	08
Italy	05
Canada	03
Germany	03
Iran	03
Poland	03
Switzer-land	03
United Kingdom	03
Brazil	02
Denmark	02
India	02
Nether-lands	02
Romania	02
Russia	02
Serbia	02
Spain	02
Sweden	02
Turkey	02
USA	02

Finances and Funding

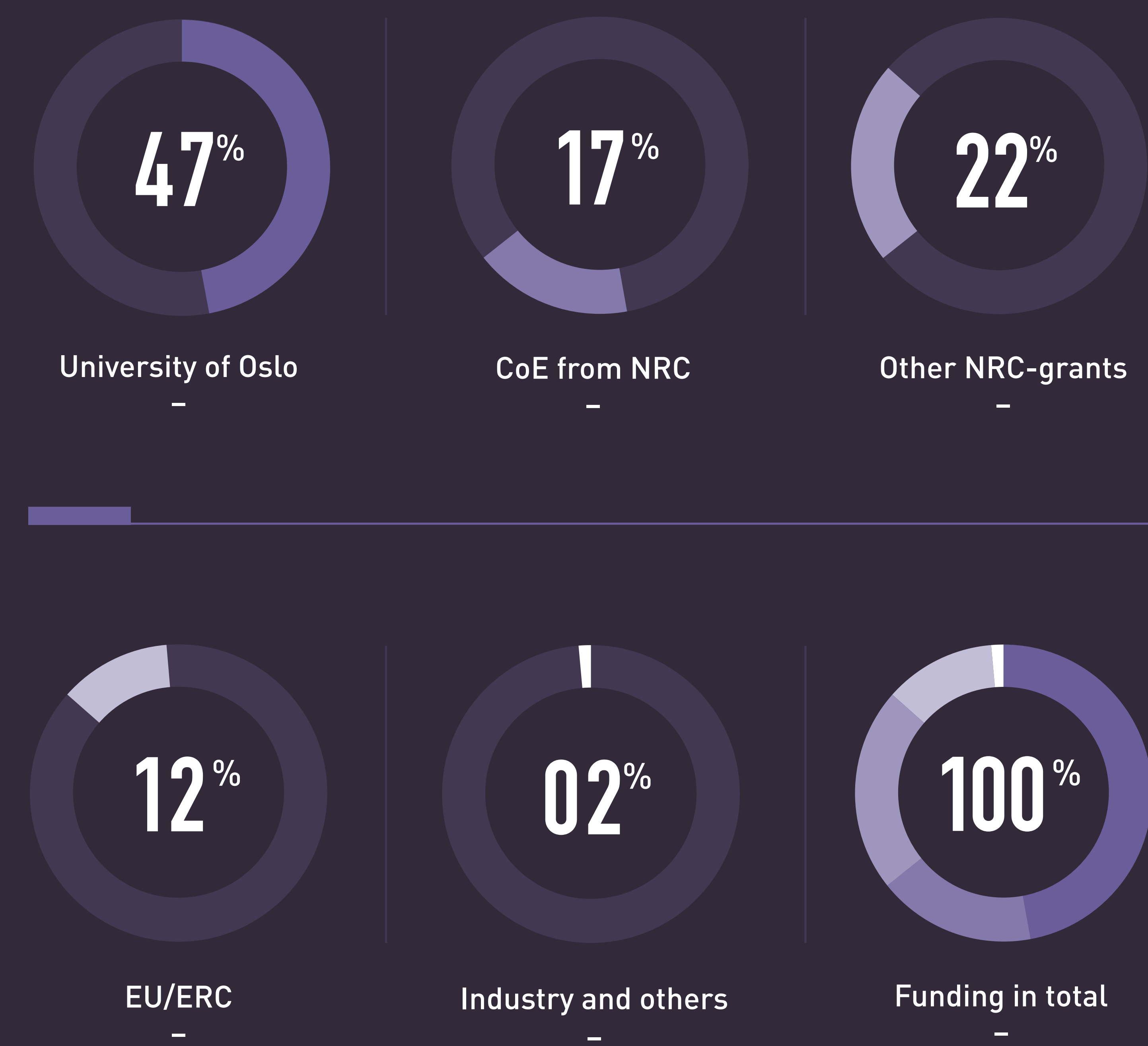
45 MNOK Funding in total in 2019

The Njord centre is financed by the Department of Physics and the Department of Geosciences at the University of Oslo. The centre receives contribution from both departments to cover the costs of running the centre. 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 centre self-sufficient.

The staff at Njord is employed by either one of the departments or by Njord. Projects led by staff at Njord, but started before the centre was established, is formally at the host department. However, since the activity is at the centre, we do consider them Njord-projects and count their funding in at Njord as well.

When including all of these factors we say that the centre and the activity at the centre is funded by the University of Oslo, the Research Council of Norway, the European Research Council and other sources of funding.

Distribution of funding



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Activity at Njord

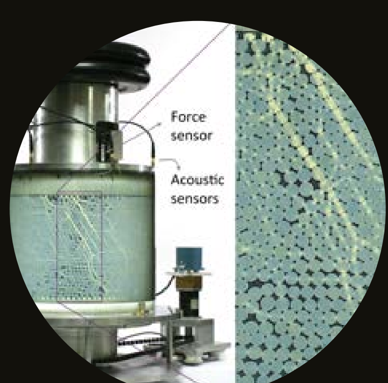
Highlights of 2019

EarthFlows is extended for a new period

4. January

31. May

S. Lherminier, et.al incl. Knut Jørgen Måløy, publish article "Continuously sheared granular matter reproduces in detail seismicity laws" in *Physical Review Letters.*



Njord seminar at Lindås: Earthquakes in the lower continental crust

5-7. June

6. June

PoreLab moves into new offices on the 3. floor of the Physics building

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19-20. June

EarthFlows Meeting 2019: Complexity in Solid Earth and Geophysical Flows

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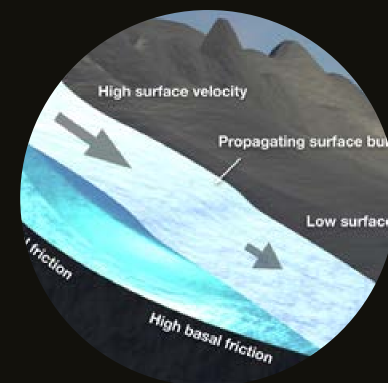

Kjetil Thøgersen et al. publish "Rate-and-state friction explains glacier surge propagation" in *Nature Communications*

27. June

Article co-authored by Måløy, on how earthquakes can be mimicked in the lab, is featured in Editors' choice in *Science*

28. June

31. July

Arianne Petley-Ragan et al. publish "Dynamic earthquake rupture in the lower crust" in *Science Advances*

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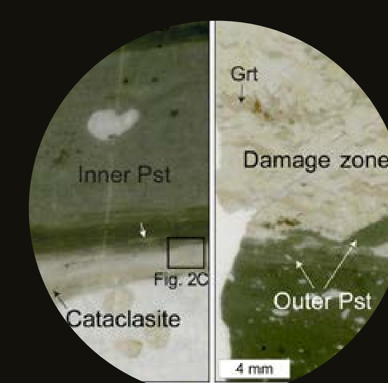

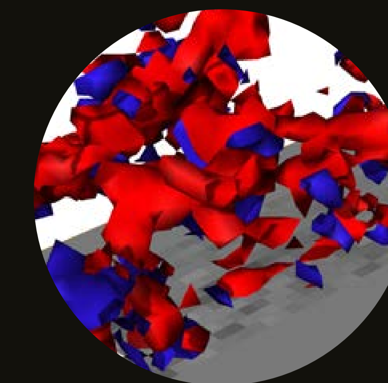

François Renard et al. publish "Volumetric and shear processes in crystalline rock approaching faulting" in *Proceedings of the National Academy of Sciences*

1. August

2. September

Audun Skaugen receives his Majesty the King's Gold Medal for his PhD thesis

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11. November

Eirik Grude Flekkøy, Jane Luu and Renaud Toussaint publish article "The Interstellar Object 'Oumuamua as a Fractal Dust Aggregate" in The Astrophysical Journal Letters, with subsequent coverage in *Popular science*

LASI VI: Malargüe – Conference on the physical geology of subvolcanic systems organized by Olivier Galland

25-29. November

Interview

Name and position:
Luca Menegon
Associate Professor

Affiliation:
Geology,
PGP

Luca Menegon

What kind of work has led you to the kind of research you do at Njord?
I am in general interested in the deformation processes of Earth's materials in faults and shear zones. I investigate the brittle deformation and the viscous flow of solid rocks in the Earth's deep crust, which fundamentally controls a variety of large-scale processes ranging from the formation of tectonic plate boundaries to the dynamics of the deepest portions of earthquake-generating faults. I try to understand how rocks flow and fracture in the crust, how they interact with fluids and with melts, and how they deform in the long term during the plate tectonic cycle that shapes our planet, as well as in the short term, during and after earthquakes.

Njord has an outstanding tradition in the study of deep crustal earthquakes, and I am looking forward to contributing to this exciting topic. Understanding deformation processes of Earth's material requires diving into their grain-scale and crystal-scale structure, for example with electron microscopy-based techniques. I am happy to use and develop the scanning electron microscopy lab at the Department of Geosciences at UiO. I am especially interested in the electron backscatter diffraction technique (EBSD), which enables detailed investigations of the crystal lattice orientation of minerals. This is very important, as rock deformation typically manifests itself at the grain scale in the form of distortions of the crystal lattice, which we can look at in detail with EBSD.

Where does your current research fit into Njord's diverse family?
My research fits into the overall Njord's goal to advance our understanding of transformation processes in Earth- and man-made porous materials. My interest in long- and short-term flow and fracturing of rocks goes hand-in-hand with the study of how deformation is coupled with fluid- and melt flow in the crust. This requires understanding of the physico-chemical processes operative at the solid-liquid interface, such as dissolution and precipitation, as well as understanding of the three-dimensional porosity and permeability structure of deforming rocks. Likewise, understanding how movement of dislocations through crystal lattice governs viscous flow of solid rocks requires diving into the physics of plasticity and of crystal defects. The interdisciplinary environment at Njord and Earthflows is ideal to tackle all these research questions in the best way, and I am looking forward to learning more about these exciting things from my new colleagues here.

Where do we find you – and how do your current projects tie in with the different sites of research at Njord?
I definitely like to glory in the field under high noon sun, and my favourite spot is Nusfjord, up in Lofoten (although high noon sun is often replaced by miserable weather there...). I have been lucky to enjoy fieldwork in a variety of stunning places around the world, from Arctic Norway, to the mighty mountains in the Alps, to the desert of Western Australia. There is no doubt that the field represents my favourite laboratory. On the other hand, we need to integrate field observations with other techniques to gain a holistic picture of what happens to rocks when they deform during long-lasting flow and during episodic earthquakes. Microscopes are my favourite investigative tool, and I love using both light microscopy and scanning electron microscopy to dive into the details of rock microstructures. Integrating field work with analytical and experimental technique is also at the core of the spirit of the European Geosciences Union Summer School in Structural Analysis of Crystalline Rocks that I contribute to organise and deliver every second year.

What opportunities do you see for interdisciplinary collaboration in your future work?
I am very keen to develop future collaborations in the field of material sciences and electron microscopy. I have recently started to do some experiments with the nanoindentation technique, where it is possible to indent minerals with a small diamond tip to explore mechanical and rheological properties such as fracture toughness, hardness, and low-temperature plasticity. Coupled with advanced electron microscopy studies, these experimental tests promise to open up new exciting avenues in the field of the micro- and nano-scale material characterization, which is increasingly important not only for the Earth's materials but also for man-made materials. Furthermore, I'm always interested to apply my studies of faults and shear zones to projects of industrial relevance, for example in the field of mining and of the long-term geological disposal of waste in deep geological repositories.

"My research fits into the overall Njord's goal to advance our understanding of transformation processes in Earth- and man-made porous materials"

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Interview

Name and position:
Marcel Moura
Researcher

Affiliation:
Physics,
PoreLab CoE

Marcel Moura

"I think I have an academic mindset. All that time reading Richard Feynman's books and watching his videos made a permanent damage on my brain and perhaps I'm now irreversibly hooked to life at a university. So, although I do not have any personal contention with the industry, I will most likely remain close to the academic life. The community is just too good to let go."

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What is your background and current position?
My background is in physics. Initially I was into theory (MSc) but later on I turned to the experimental side of the force (PhD). I am now working as a researcher at PoreLab, where I perform experiments related to the motion of fluids inside porous networks.

How did you get interested in physics?
My grandfather Mauricio is the one to blame. He spent a lot of time with me when I was a kid, and he was a pretty smart guy. We used to walk around a lot and he would always tell me some jokes or talk about science and the universe. One time I stumbled on a very round rock and I asked him how it could be so round. So he told me that it was probably much older than the edgy rocks, and that with time the edges tend to get smoothened out as the rock goes rolling around. He was teaching me an important lesson about the scientific method: how one could derive a hypothesis about things we do not know yet, based on our previous experiences, and how this kind of attitude was life enriching. Where others could only see a round rock, he could see the passage of time and how it transformed the rock. I was of course fascinated and I wanted to have eyes like his.

What does your project entail and how does it relate to your group at Njord?
My project concerns the motion of fluids through a porous network, a topic that is very connected to the overall goals of Njord and PoreLab. We have fluids moving through ramified networks in many natural systems. For example, when rain falls down, it infiltrates the soil, displacing air from the soil pores. How exactly does that motion of air-water happen? This is just one example of a natural system where the motion of fluids through a porous medium is important. I'm a physicist and the naive scenario of rain falling and making the dust wet is already way too complicated for me. Therefore, I follow *the physicist guidelines for impossible problem tackling*: I simplify things a lot until I can understand some of it. At PoreLab we do experiments with synthetic porous networks; transparent soils if you will. No plant will ever grow there, but it sure is a fertile ground for our understanding of fluid mechanics in porous media.

What do you find most interesting in working at Njord?
As a physicist, I think Njord really is a prime place to be. The idea that I mentioned before, *simplify it until you understand it*, is really in the nature of physics and it has given us quite a lot. However, it is important to remember that sometimes reality is bigger and more complex than our models. Therefore, being in close proximity to scientists who tackle nature at different scales of complexity – geologists, volcanologists, rock scientists of all types – is excellent to keep our eyes open and our antennas tuned.

Where do you see yourself in a few years? Do you have any other future plans?
I think I have an academic mindset. All that time reading Richard Feynman's books and watching his videos made a permanent damage on my brain and perhaps I'm now irreversibly hooked to life at a university. So, although I do not have any personal contention with the industry, I will most likely remain close to the academic life. The community is just too good to let go.

I am a Brazilian being, which comes with the peculiarity of being naturally bad at planning far ahead. If I try hard to look ahead, I guess I see myself leading my own research group in the future, continuing working on the bigger problems around porous media science, but with some side projects to keep things diverse. At some point in time, I will have to find some students who are really into (good) coffee, to make a project about that, from the perspective of a porous media scientist. After all, it is a known fact that an espresso machine is simply an Italian forced imbibition experimental setup.

Interview

Name and position:
Jess McBeck
Associate Professor

Affiliation:
Geology,
PGP

Jess McBeck

What is your background and how did you get interested in geology?
My background is in numerical and experimental simulations of geologic processes, focusing on fracture propagation and interaction, and the deformational energy budget of tectonic systems.

When I was 14, my Dad and I drove from Boston to Seattle in a week. Along the way, we visited outstanding National Parks and monuments like Glacier, Zion, and the Grand Canyon, where I saw (with my limited understanding) that the raw power of nature can shape rock. Then, as an undergraduate, I had an excellent geology teacher, Barb Tewksbury, who revealed to me for the first time that we can understand how nature shapes the structure of canyons and mountains using math and physics

What kind of research do you do at Njord?
I'm involved in five projects at Njord: 1) Tracking strain localization throughout in situ X-ray tomography triaxial deformation experiments, 2) Identifying the factors that control strain localization and fault development using machine learning, 3) Linking the micromechanics of propagating fracture and percolating force networks to macroscopic behavior using numerical models, 4) Fault propagation, interaction and coalescence in accretionary wedges, and 5) Deformational energy budget partitioning.

These projects require several methods, including i) X-ray tomography, ii) Triaxial compression deformation experiments, iii) Digital volume correlation, iv) Machine learning, v) Discrete element method numerical modelling, vi) Boundary element method numerical modelling, and vii) Scaled physical analog experiments. Regardless of method, my favorite activity is programming a problem that I have not solved before.

Is there a publication that has inspired you in your work?
I have a short list of some inspiring publications, which I think should be required reading for all budding tectonophysicists: Lockner et al. (1991), Quasi-static fault growth and shear fracture energy in granite. Nature 350; Segall and Pollard (1983), Nucleation and growth of strike slip faults in granite, Solid Earth 88(B1); and Sibson (1977), Fault rocks and fault mechanisms, JGS 133.

What do you find most interesting in working at Njord?
Many geology departments in the US do not have a high proportion of quants. Instead, many geologists rely on qualitative descriptions, and propose untestable hypotheses about tectonic deformation. It is quite refreshing to be surrounded by people who approach rock deformation, earthquakes and tectonics with quantitative approaches, who develop hypotheses that are explicitly testable, who are not afraid of computers, modeling, math, or expressing uncertainty.

What is the most exciting thing that has happened in your project?
My experimental work with accretionary wedges (*McBeck et al.*, 2018) and X-ray tomography experiments with intact continental rock (*McBeck et al.*, 2019) suggests that the energy consumed in sliding against friction may consume the largest portion of the overall energy of the system. This finding suggests that we may use frictional energy as a proxy for the total energy of the system. This conclusion is potentially transformative to our efforts to predict fault development because the experimental and numerical analyses I did in my PhD (*McBeck et al.*, 2016) suggests that faults propagate and interact such that they minimize the total system energy. In particular, we have accurately predicted fault development by minimizing the overall energy. Our more recent work suggests that we may predict this development by minimizing the frictional energy. This link provides a critical step toward predicting fault development in natural fault systems, because frictional energy is easier to estimate robustly than overall system efficiency.

Here are some references from my work:

- McBeck, J., Cooke, M., Souloumiac, P., Maillot, B., & Baptiste, M. (2018). The influence of detachment strength on the evolving deformational energy budget of physical accretionary prisms. *Solid Earth*, *9*(6), 1421-1436. doi: 10.5194/se-9-1421-2018.
- McBeck, J., Cordonnier, B., Mair, K., & Renard, F. (2019). The evolving energy budget of faults within continental crust. *Journal of Structural Geology*. Doi: 10.1016/j.jsg.2019.03.005
- McBeck, J.A., Madden, E.H. and Cooke, M.L., 2016. Growth by Optimization of Work (GROW): A new modeling tool that predicts fault growth through work minimization. *Computers & Geosciences*, *88*, 142-151.

What can your research do beyond academia?
By predicting fault development and identifying precursors to rock and building failure, my work sheds fundamental insights on processes critical for the safety of society.

Interview

Name and position:
Kjetil Thøgersen
Postdoctoral fellow

Affiliation:
Geology,
PGP

Kjetil Thøgersen

"I believe the part of my project with the largest potential impact, is focused on subglacial friction and drainage. We hope that our contributions in time can help improve predictions of sea level rise."

What is your background and current position?
I have a background in computational physics, where I modeled friction phenomena, fluid mechanics, and glacier dynamics. Now I'm a postdoctoral fellow in the strategic research initiative EarthFlows.

How did you get interested in geological processes?
I actually started at the university because of my interest in astrophysics. After my bachelor, I was introduced to computational physics, which I really enjoyed. For my master project, I talked to Anders Malthe-Sørenssen, who introduced me to a very interesting project in friction. Since then, my work has been at the intersection between physics and geoscience.

What does your project entail?
My current project is about understanding frictional processes in nature. This includes subglacial friction and drainage, friction along faults, as well as friction as a physics problem. My project is at the intersection between physics and geoscience, which is the essence of PGP. I mostly stick to computational methods, but I also enjoy using pen and paper for theoretical calculations. The lab I use the most is the computer lab. However, I enjoy the occasional field trips as well, as I tend to learn quite a lot from the geologists at Njord.

What is your favorite activity during research?
Testing new ideas!

Is there any particular research that has inspired you, in your research?
I would say I have been lucky to be part of a very inspiring working environment since I started my career in research. For me, Anders has been a central part in creating such environment, in particular by giving young researchers freedom to pursue their own ideas.

What do you find most fulfilling in working at Njord?
I find the interdisciplinary work at Njord very interesting. Collaborating with researchers outside of your field can of course be challenging, but it is also extremely rewarding because you learn a lot.

What is the most exciting thing that has happened in your project?
This year I had one paper published in Nature communications and one in GRL that I was quite happy about.

Do you have a notion of what your research can mean beyond academia?
I believe the part of my project with the largest potential impact, is focused on subglacial friction and drainage. We hope that our contributions in time can help improve predictions of sea level rise.

Interview

Name and position:
Kristian Stølevik Olsen
Doctoral Research Fellow

Affiliation:
Physics,
PoreLab CoE

Kristian Stølevik Olsen

"I started my education in music and art, but in the later years of high school, I had a mathematics teacher who studied quantum mechanics in Oslo. After many interesting discussions, she convinced me that physics was the way to go."

What is your background and current position?
I have a master's degree in theoretical physics, where I studied the renormalization group flow for the quantum Hall effect. The main goal in this work was to better understand effective theories for charge transport in two dimensions. I transferred many of these ideas to my current work as a PhD candidate at PoreLab.

How did you get interested in physics?
I started my education in music and art, but in the later years of high school, I had a mathematics teacher who studied quantum mechanics in Oslo. After many interesting discussions, she convinced me that physics was the way to go.

What does your project entail?
My current work revolves around theoretical statistical physics. I study diffusion, which is a simple example of a non-equilibrium process, to see how the normal laws have to be altered when the process takes place inside complicated geometries. I mostly do analytical work, guided by numerical simulations. My favorite part of doing research is the writing. I enjoy trying to find the best possible way to explain something, whether it is in a research paper, lecture or a presentation.

Is there any particular research, publication or scientist that has inspired you, in your research?
One of my favorite papers is the classic "More is different" from Philip Anderson. This paper discusses some fundamental aspects of science, when it comes to how physical laws look on different length scales in nature. The paper argues that it is not always the case that one can derive the laws governing the behavior of a complex system from a more "fundamental" microscopic theory. The argument is that there are rather new, and just as fundamental laws, emerging from complex behavior on large scales. This is of course relevant to the work done at PoreLab and Njord, but I also think it is one of the more fundamental facts about science in general.

What do you find most fulfilling in working at Njord? Are there any challenges?
One of the most important parts of a well-functioning research group is the people in it. Njord has a lot of people who contribute to a nice community, both at work and outside of work. This often results in interesting discussions with people coming from different areas of research, which is very fulfilling.

Do you have a notion of what your research can mean for industry?
At the end of the day, our research has to do with how matter is transported in complex systems. While I think the research is interesting in its own right, in principle a better understanding of such processes can have several applications, like understanding how fuel is distributed in fuel cells.

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 Centre for Computation in Science Education, led by Njord's Anders Malthe-Sørenssen.

In 2019, Njord staff was either responsible for or guest lecturers in the following courses:

Introduction to Physics
FYS1001
The course gives an introduction to fundamental concepts within a wide range of topics in physics. There is an emphasis on understanding, applications, good knowledge of units, physical argumentation and the use of mathematical and numerical methods.

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

Oscillation and Waves
FYS2130
The course introduces oscillations and waves using analytical and numerical techniques. A large part of the course is devoted to applying the theory of oscillations and waves to phenomena such as resonance, sound, water waves and optics.

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

Experimental techniques in condensed matter physics
FYS4420/FYS9420
The course contains four projects that 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.

Dynamics of complex media
FYS4465/FYS9465
The course covers hydrodynamics where capillary and visous forces play a role. It also covers simulation methods, thermodynamics and statistical physics relevant to porous media.

Geomechanics
GEO4131
This course focuses on the mechanics of earth materials (e.g. rock, soil, snow and ice), in particular, how earth materials deform, yield, flow and fail under applied loads or external forcing (both natural and man-induced).

Earthquake and Volcanic Processes
GEO4151 / GEO9151
This course focuses on the physics of Earthquake and Volcanic processes, which are both important endogenic processes accommodating the deformation of the Earth's crust.

Floods and Landslides
GEO4171
The course is split into three parts focusing on the most common geohazards in Norway: floods, landslides and avalanches. The course included 1-day field trips to selected sites and a 3-days excursion.

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

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

Petrography and Microstructures
GEO4810
The course gives a basic introduction to the optical properties of crystalline matter and to the polarizing microscope for optical mineral identification.

Advanced Petrology
GEO4860
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.

Outreach and media highlights

Anja Røyne with the book that has propelled her outreach work this year. Picture taken by Hilde Lynnebakken

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

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

At Njord we also strives towards cultivating curiosity in others. As the first interstellar object ever observed, the phenomenon 'Oumuamua has sparked a lot of curiosity in and of itself. Spotted in 2017, it was observed to pass through our solar system with an acceleration that was larger than what could be explained by gravity alone. This caused some to speculate that it was an alien space ship. It was therefore very exciting when Njord researchers Eirik Grude Flekkøy and Renaud Toussaint, as well as astronomer Jane Luu, pursued the explanation that 'Oumuamua has a porous consistency that makes it so light, even sunbeams can push it around. Porelab coined the nickname "cosmic dusty bunny" and their studies were reported in several popular science journals, both in Norway and abroad, including *Popular Science* and the Norwegian *Fra fysikkens verden.*

Physicist Anja Røyne is another of Njord's researchers who works extensively on outreach and science communication. This year she has shared of her broad scientific knowledge through a long series of talks on her popular science publication from 2018, *Menneskets grunnstoffer*, and several talks on the popular science radio show, *Ekko.* Moreover, she has a particular passion for climate action, reflected in her BioZEment project, which aims to reduce CO_2 emissions from concrete production. Along with head of the Department of Physics, Jøran Idar Moen, she also organized a workshop with employees of the department on how the they can best address the current environmental challenges and offer education that our students can use to make a positive impact for the environment.

Njord also endeavours towards interdisciplinarity beyond the scope of science, allowing people to understand the world in new ways. Geologist Karen Mair is collaborator on "Reconfiguring the Landscape", a new Artistic Research Program grant awarded to Natasha Barrett (Norwegian Academy of Music), October 2019. The project investigates how 3-D electroacoustic composition and sound art can evoke a new consciousness of the outdoor environment. The project involves an international cross-disciplinary project group including researchers and artists involved in electroacoustic composition, 3-D sound, spatial sound technology, motion capture and landscape architecture. Mair is currently on leave following an MA in Design Informatics at Edinburgh College of Art, University of Edinburgh, Scotland exploring creative ways to communicate and share science data.

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 2019, field studies were carried out in several areas across the globe, including California, Argentina, Northern Italy, Lofoten, the Bergen Arc, and Svalbard.

Field day during the LASI6 conference in Malargüe, Argentina, November 27-29, 2019

In March 2019, François Renard, Jess McBeck and Master student Pål Ferdinand Arnestad attended a field trip to California. The main objective was to collect rocks from fault zones that had undergone major damage. Near Palm Springs, new outcrops of fossil earthquakes were discovered (e.g. pseudotachylytes) and several samples were collected. During several days of fieldwork near the active San Jacinto, fault damage zones were mapped and samples collected that were later imaged in 3D using X-ray microtomographyo.

In March-April, Olivier Galland and the volcano group arranged a field trip to the Neuquén Basin in the Mendoza province, Argentina. The goals of this trip were two-fold: 1) To study Cerro Alquitrán, an eroded andesitic plug at the edge of which rivers of petroleum are seeping out. The working hypothesis was that the structures related to the emplacement of the andesitic body controlled migration of hydrocarbons. During an epic field mapping campaign, we found out that the main hydrocarbon migration pathways were syn-emplacement brittle structures within the igneous body; And 2) To study the dome structure above a buried andesitic laccolithic intrusion, in collaboration with the company ROCH S.A. The goal of the study was to constrain the extent and the thickness of the igneous body. By integrating geological data collected during a 5-day mapping campaign, 3D seismic and borehole data, Olivier established that the igneous body was 400 m, 4 km diameter, and that the deformation of the overburden was asymmetric, exhibiting a trapdoor geometry.

Fieldwork on the outermost part of Lofoten, May 23, 2019. Picture by Bjørn Jamtveit

In late May, Kristina Dunkel, François Renard, Bjørn Jamtveit and Master students Anet Zavala, Lars Vesterager Valen, Natalia Maronni, and Pål Ferdinand Arnestad conducted field work in the western parts of Lofoten. The studies focused on evidence for deep crustal earthquakes during the Caledonian orogeny.

The 2019 Njord seminar 'Earthquakes in the Lower Crust' and an associated field trip was arranged at Alver Hotel and Holsnøy 5-7 June. The seminar included 36 participants, and 15 invited speakers from Europe and USA in addition to 7 Njord speakers.

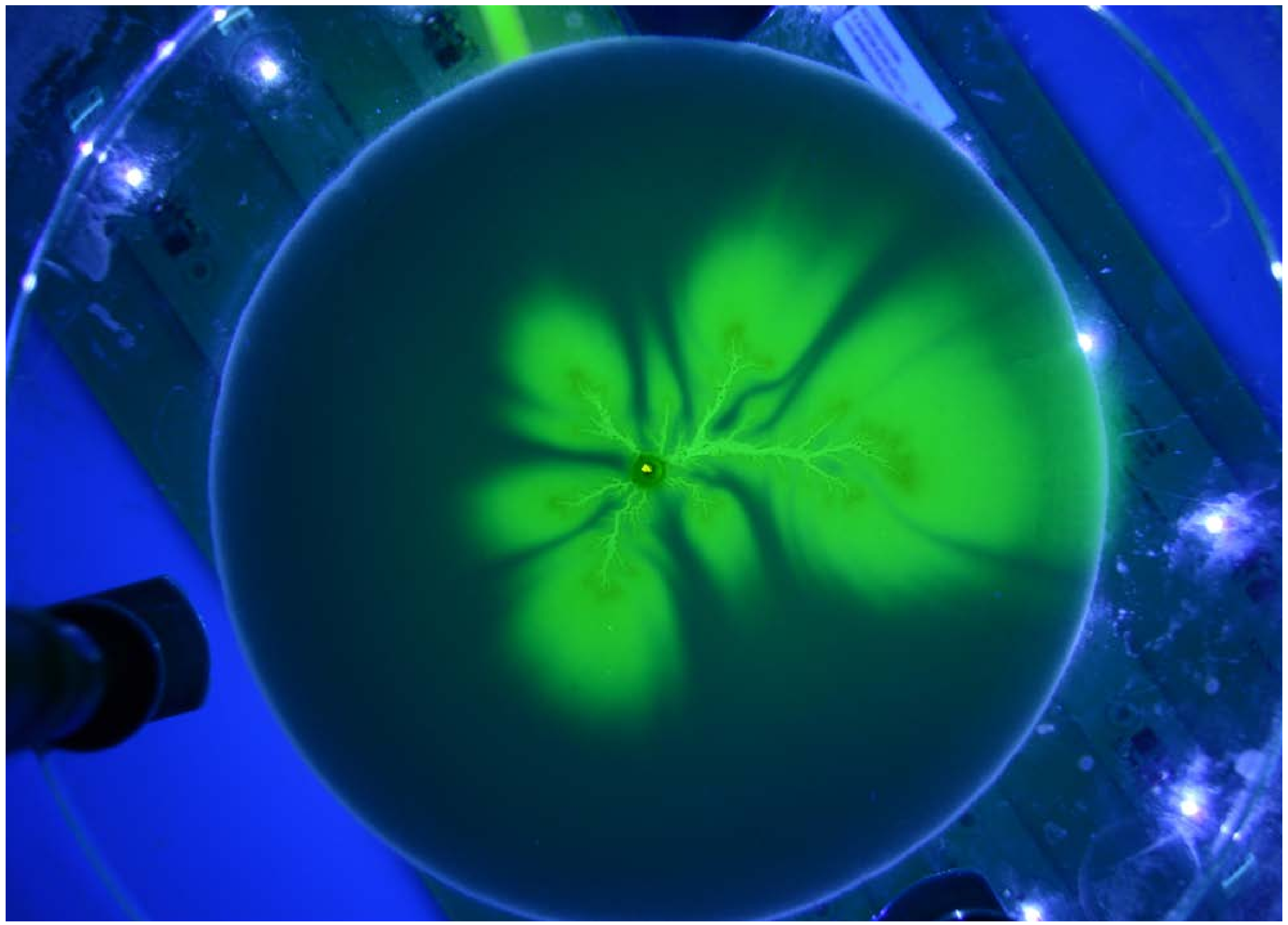
In mid-August, Ole Rabbel of Njord conducted fieldwork at Svalbard in collaboration with Dr. Kim Senger (UNIS). The goal of this field campaign was to constrain the geometry of the igneous sills associated with the Cretaceous High-Arctic Large Igneous Province. They sampled several sills for dating, and looked at metamorphic processes in the contact aureoles of the sills emplaced in organic-rich shale. They noticed a remarkable similarity with those observed in the Neuquén Basin, Argentina.

During late August, Njord researchers contributed to the 5th EGU Summer School ''Structural Analysis of Crystalline Rocks''. The European Geosciences Union (EGU) supports the Summer School and it was organised in late August by Giorgio Pennacchioni (Padova) and Neil Mancktelow (ETH Zurich), with Luca Menegon and Dani Schmid from Njord as invited teachers. They held the field course in the spectacular Nevessee (Neves Lake) area in South Tyrol, where polished outcrops at the base of the Mesule glacier expose a variety of geological structures indicative of fluid-rock interaction during brittle and viscous deformation of the lower continental crust during the Alpine mountain building process. The students examined the development of ductile shear zones that exploit a network of brittle fractures associated with fluid infiltration and mineral reactions. The field area is ideal to observe both the coupling between metamorphism and deformation in the crust, and how these two processes influence each other.

Finally, on 27-29 November, Olivier Galland, Ole Rabbel and collaborators arranged the LASI6 conference and field excursion. This was certainly the field highlight of the year for the volcano group at Njord. The meeting included 65 participants from all over the world and the field trip focused on localities studied by the Njord volcano group during the last 5 years. The field trip was a great success, as it provided high visibility of some of the latest and on-going research at Njord.

Laboratories

Water saturated with gypsum is injected into a radial disk plaster sample with a ramified dissolution pattern. The flow in the aperture above the sample is traced by fluorescence. The traced flow clearly shows the dispersion flowline influenced by the fractal-like initial ramified pattern. The high resolution digital camera caught this photo after 30 mins / 10 mins of the injection. Picture by Le Xu.



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. Surface forces can also be measured using our Atomic Force Microscope (JPK Nanowizard 4), mounted on an inverted microscope, used for force spectroscopy and nanoscale imaging in air and liquids. It is also used for Magnetic Force Microscopy to image magnetic nanoparticles in bacteria. We have a whole set of photolithographic equipment that can fabricate microfluidic channels, the 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. We also have a white light interferometer microscope, NT1100.

Frication Lab: At Frication lab we have a white light interferometer microscope from Bruker (ContourGT), 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, which 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 allows imaging rocks during deformation, at conditions of pressure and temperature up to 10 km depth, using dynamic X-ray microtomography. We have also developed three rock core holders, ARGUS, that can reach up to 10 MPa confining pressure. These core holders are installed on neutron sources (ILL in Grenoble and PSI in Villigen) for neutron tomography imaging of fluid flows in rocks (Cordonnier et al., 2019).

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, leading to a paradigm shift on dyke emplacement mechanism. Additionally, the Volcanoe Lab's equipment applies to geological systems beyond volcanic processes, including simulations of glacier, lava flow, strike-slip fault behaviour and caldera collapse.

"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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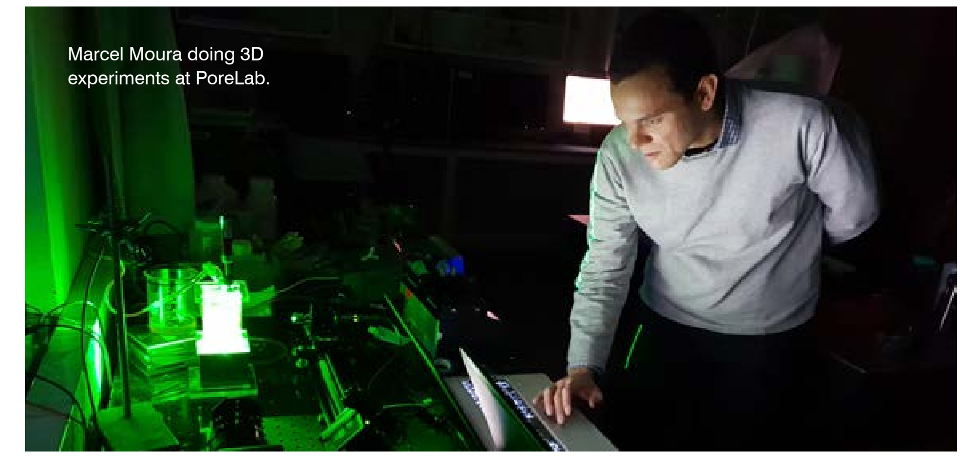


Marcel Moura doing 3D experiments at PoreLab.

PoreLab: PoreLab´s four 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, hydro-fractures 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 stereomicroscope 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 microscope 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 developed a 3D optical scanner which makes it possible to measure 3D fluid structures in refraction index matched porous media. This equipment can be used both to study dispersion in mono-phase flow and two-phase flow studies.

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.

03

Introduction

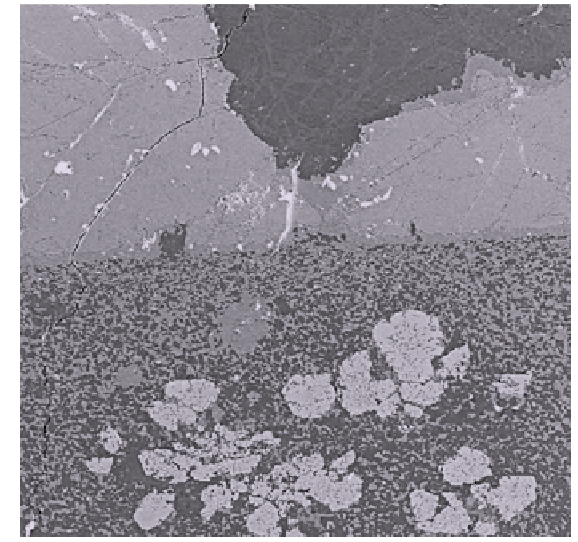
Many of the researchers at the Njord Centre focus on the dynamics of fluid migration through porous materials and geological media. Some of them focus on single or multi-phase fluid dynamics in the confinement of a complex pore space where fluid-solid interactions vary along the interfaces. In other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

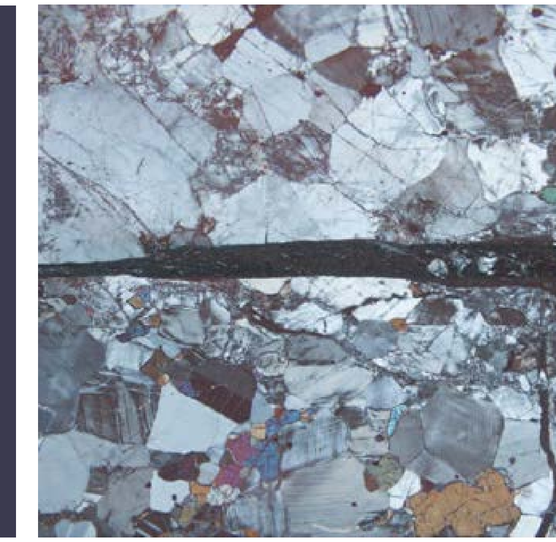
About Chapter 3

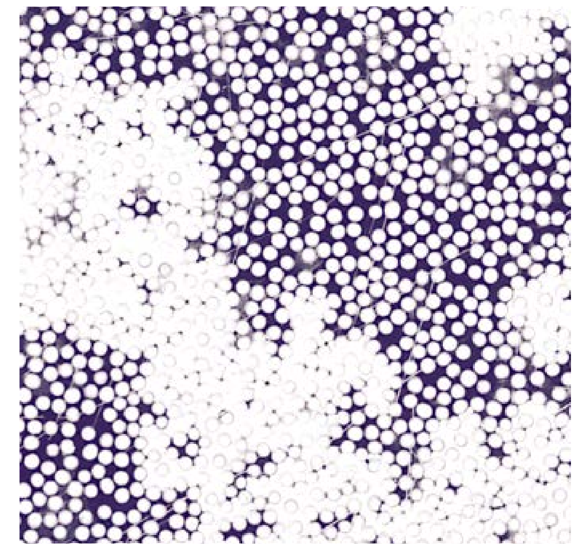
Part 1 Fluid Flows in Complex Media
Part 2 Pattern Formation and Dynamical Systems
Part 3 Fracture, Friction and Creep in Rocks and Materials
Part 4 Coupled Chemical Processes from the Nanoscale to the Scale of Continents

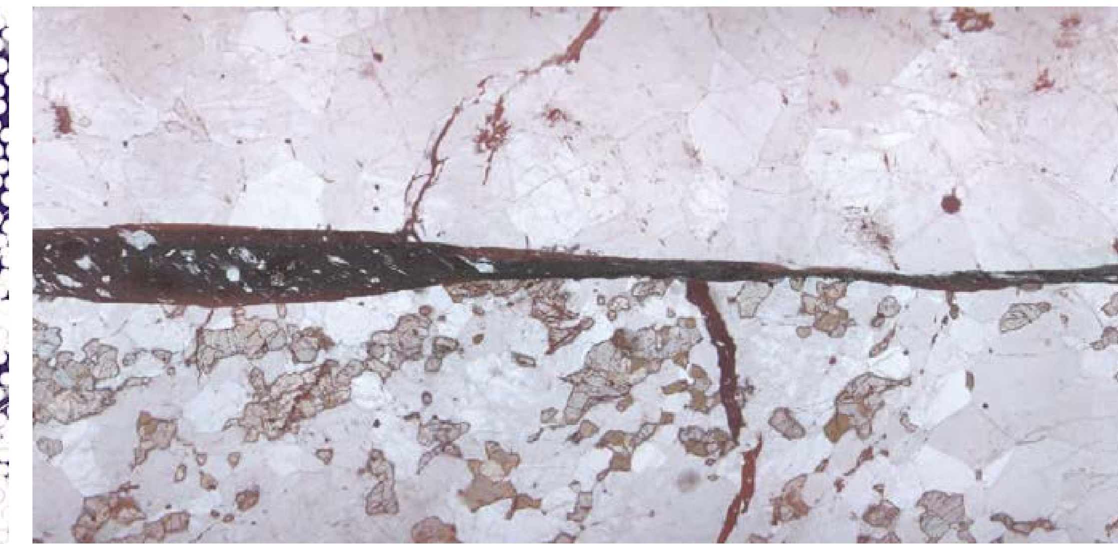
Fluids often enter the solids through fractures. Hence, the physics of fracturing is a central Njord activity. In natural systems, fracturing is often associated with displacement along the fracture surface and the frictional properties of fractured surfaces are important. This situation applies both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

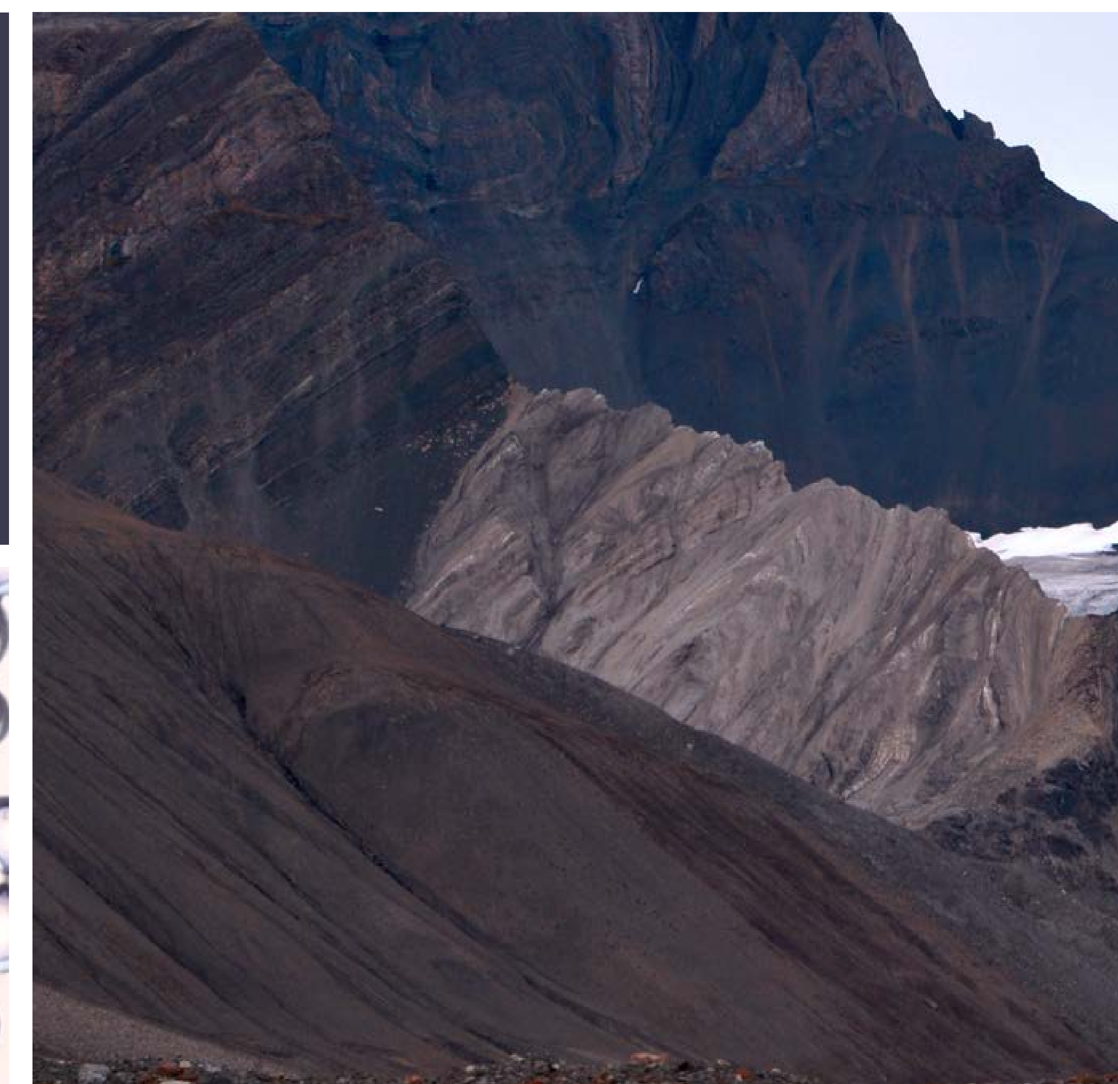
Finally, most of the systems studied at Njord evolve far from equilibrium and are often characterized by nonlinear relations between forces and fluxes and the emergence of 'self-organized' patterns. Such patterns may contain valuable information about underlying processes. This is particularly relevant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

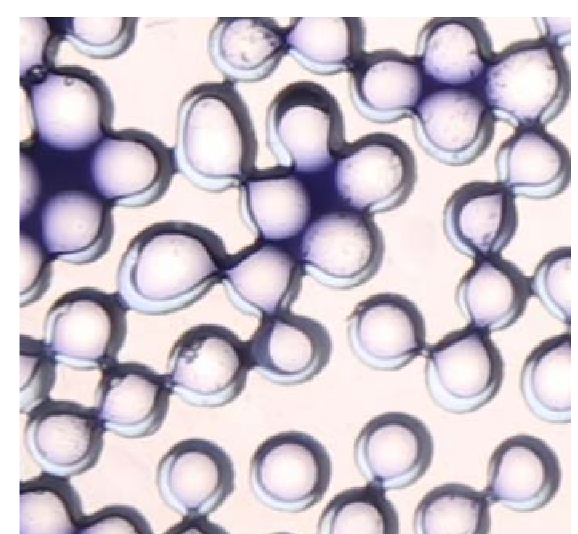












Chapter 3 | Part 1

Fluid Flows in Complex Media

1) Geometry, entropy and anomalous diffusion in frictional fingers, *2) Physics of Volcanic Plumbing Systems,* 3) Tunable interactions inside deformable porous media, *4) EarthFlows,* 5) Slow drainage experiments in porous media: from invasion bursts to thin film flow, *6) Fluid driven channel formation and acoustic emissions in confined granular media,* 7) Modelling and imaging flow in rocks across scales, *8) Developing a lattice Boltzmann method for partial dissolution of saline water in oil,* 9) Interplay between viscous, capillary and gravitational forces, in two-phase flow in 3D porous media

Funding:
The Research Council of Norway
CoE-program

Participants
Kristian S. Olsen[1], Eirik G. Flekkøy[1], James Campbell[1,2], Luiza Angheluta[1], Knut-Jørgen Måløy[1], and Bjørnar Sandnes[2]

Affiliation
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2) College of Enginering, Swansea, United Kingdom

Geometry, entropy and anomalous diffusion in frictional fingers

Diffusion is the relaxation of a non-uniform particle density towards the uniform equilibrium state, as described by Fick's law. Although diffusion is a simple example of a non-equilibrium process, complications can arise when the flow takes place inside a non-trivial geometry. In these cases there are interactions between the diffusing particles and the boundaries of the system that may lead to anomalous behavior at large space and time scales. This anomalous behavior can be characterized in many ways, for example through the temporal scaling of the mean square displacement (MSD) or the entropy production. The anomalous diffusion can be modeled by a non-Gaussian distribution, where the degree of non-Gaussianity measures the anomaly of physical quantities like the MSD and entropy from the normal diffusive case.

This connection between complex geometry and properties of diffusion processes is in this project explored for frictional finger patterns. These patterns arise due to instabilities in fluid-particle mixtures as the fluid in withdrawn from a 2D Hele-Shaw cell. This leaves behind compactified walls of particles and channels of air which make up the finger pattern. To better understand this geometry, we have used methods that were originally developed for classifying the topology of river networks. The system is found to be in the same geometric universality class as 2D minimum spanning trees. By combining this geometric insight with the non-Gaussian modeling we have derived analytical expressions for the MSD and entropy of the diffusion process, which have been compared with numerical simulations.

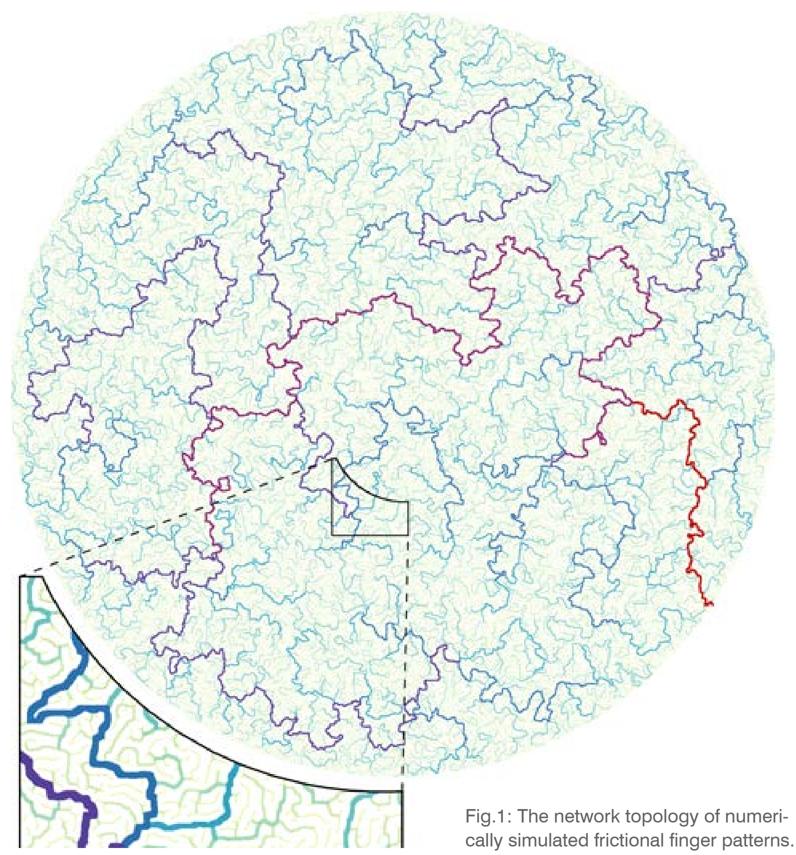

Fig.1: The network topology of numerically simulated frictional finger patterns.

Publications:

1) *"Geometric universality and anomalous diffusion in frictional fingers"*, New Journal of Physics (2019), Kristian S. Olsen, Eirik G. Flekkøy, Luiza Angheluta, James Campbell, Knut-Jørgen Måløy, and Bjørnar Sandnes. doi: 10.1088/1367-2630/ab25bf

2) Paper entitled *"Diffusion entropy and the topology of tree structures"* in review at *Physical Review E*.

PoreLab
NTNU-UiO Porous Media Laboratory

Funding:
Njord;
University of Oslo

Participants
Olivier Galland[1], Karen Mair[1], Frank Guldstrand[1], Håvard S. Bertelsen[1], Ole Rabbel[1], Sam Poppe[2], Hans Jørgen Kjøll[3] and several international collaborators

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2) Department of Geography, Vrije Universiteit Brussel Belgium.
3) Department of Geosciences, University of Oslo, Norway

Physics of Volcanic Plumbing Systems

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

Emplacement of magmatic intrusions

Tabular intrusions are common features in the Earth's brittle crust. Common models of dyke emplacement assume a linear elastic host rock deformation and tensile opening. However, field observation show that non-negligible plastic deformation and shear failure of the host rock can accommodate the emplacement of felsic magma. 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) and lobate morphologies.

We investigate the effects of the host rock's Coulomb properties on magma by fluid intrusion into dry cohesive flour laboratory models. Deformation analysis of host rock of varying cohesion in 2D laboratory intrusion models reveal that sheet intrusions can be associated with uplift and shear bands extending from the intrusion tip. (Guldstrand et al., in preparation). Our results are in good agreement with field observations (Magee et al., 2018), results from 3D laboratory experiments (Guldstrand et al., 2017; Poppe et al., 2019) and numerical models (Souche et al., 2019). Schmiedel et al (2019) showed through combing laboratory and limit analysis numerical model that both sheet and massive tabular intrusions initiate as a sill. The sill then triggers shear failure of its overburden along an inclined shear damage zone at a critical sill radius *R*, depending on the emplacement depth and the overburden cohesion. Suggesting that the emplacement of sheet and massive tabular intrusions are parts of the same mechanical regime.

To integrate our modelling results several field studies have been performed. Small dykes emplaced in sedimentary rocks at Hovedøya, in the Oslo fjord (Poppe et al., in revision). The outcrop, polished by glaciers, exposes structures accommodating the emplacement of the dykes, and the interpretations are in good agreement our model results. Finally, we collaborated with CEED scientists to interpret the geological and physical meaning of spectacularly exposed dyke swarm in Sarek, northern Sweden. There, the dyke swarm was emplaced close to the brittle-ductile transition, and we show that significant ductile deformation accommodated the formation of the dykes (Kjøll et al., 2019). Detailed structural mapping on an exceptional sill, easily accessible 1-km long outcrop in the Neuquén Basin, Argentina, allows for study of its contacts and the structures in the finely layered sedimentary host rock (Galland et al., 2019)(Figure 1). 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.

Volcano geodesy

Volcanic edifices deform as a result of ascending magma and is monitored using GPS and InSAR. The deformation data is commonly inverted using geodetic models. However, these apply some harsh assumptions such as a single dyke emplacement mechanism, based on tensile opening in a homogeneous host. Our results listed above question these assumptions. To test the effects of the physical assumptions of established geodetic models, we performed two laboratory experiments of dyke emplacement. In one experiment, the dyke forms as tensile fracture in elastic gelatin, whereas in the other the dyke forms as an indenter in a plastic host. Even if both experiments produce dykes of very similar geometry, the resulting surface deformation patterns are drastically different. Our experiments show the severe limitations of widely used geodetic models and call for the design of new, physically sound models. This study has been the topic of an invited manuscript to Journal of Volcanology and Geothermal Research (Bertelsen et al., in revision).

Publication highlights:

Bertelsen, H.S., Guldstrand, F.B.B., Galland, O., Sigmundsson, F., Pedersen, R., Mair, K., submitted. *Beyond Elasticity: Are Coulomb properties of the Earth's crust important for volcano geodesy?.* Journal of Volcanology and Geothermal Research.

Poppe, S., Galland, O., de Winter, N., Goderis, S., Claeys, P., Debaille, V., Boulvais, P., Kervyn, M., submitted. *Structural and geochemical interactions between magma and sedimentary host rock: the Hovedøya case, Oslo Rift, Norway.* Geochemistry, Geophysics, Geosystems

Funding:
Njord;
University of Oslo

Participants
Olivier Galland[1], Karen Mair[1], Frank Guldstrand[1], Håvard S. Bertelsen[1], Ole Rabbel[1], Sam Poppe[2], Hans Jørgen Kjøll[3] and several international collaborators

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[1] PGP, The Njord Centre, Department of Physics, University of Oslo, Norway
[2] Department of Geography, Vrije Universiteit Brussel Belgium.
[3] Department of Geosciences, University of Oslo, Norway

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 study shows 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., 2019), (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., 2018).

Our group also investigates the effects of igneous intrusions when they are emplaced in organic-rich shale: the heat brought by the magma triggers fast maturation of the organic matter contained in the surrounding host rock. Such fast maturation is expected to leading to fast production of hydrocarbons and generate high fluid pressures, controlling fast fracturing of the rock. Rabbel investigates the dynamics of fracture network growth in such systems (Rabbel et al., in preparation).

In March 2019, Olivier Galland lead a field expedition in southern Mendoza province, Argentina, to study the peculiar Cerro Alquitrán, an igneous andesitic conduit at the rims of which large volumes of petroleum are seeping out (Galland et al., in prep.). Field observations show that magmatic fractures and magmatic breccia within the conduit serve as migration pathways. Cerro Alquitrán is an exceptional field case study highlighting the high relevance of igneous intrusions on hydrocarbon migrations.

Organized Conferences and Workshops

- The physical geology of subvolcanic systems – Laccoliths, Sills and Dykes (LASI6), Malargüe, Argentina (25-26 Nov.) (conference leader: Olivier Galland, 90 Participants). The meeting is followed by 3-day field excursion in the Andes of the Neuquén Basin (67 participants), lead by Njord Olivier Galland.

“Learning by doing in the laboratory” workshop in the framework of GeoLearning seminar. It is an initiative of iEarth, a Norwegian consortium of scientists/teachers aiming at improve teaching in Earth Sciences. The hope is that our teaching philosophy based on laboratory experiments will be a component of iEarth, a solid candidate to a SFU grant.

Fig.1: Two overlapping dykelet tips intruded into sedimentary host rock on Hovedøya Island, Oslo Rift, Norway. Note the tapering geometry of the magma-filled fractures as well as the shear displacement along pre-existing fractures in the central, competent limestone layer (from Poppe et al., in revision). The ruler scales 30 cm.

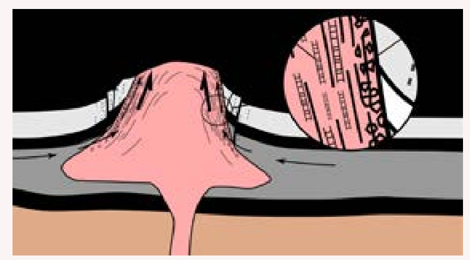

Fig. 2: Details of petroleum flows at the edge of Cerro Alquitrán, southern Mendoza province, Argentina. Inlay, Schematic drawing illustrating the structural control of magmatic fracturing and breccia control hydrocarbon migration (Galland et al., in preparation).

Publication highlights:

Palma, J.O., Burchardt, S., Galland, O., Schmiedel, T., Jerram, D., Mair, K., Leanza, H.A., submitted, *Structure and evolution of the shallow plumbing system of a back-arc volcano – The case of Chachahuén Volcano, Argentina.* Journal of South American Earth Sciences.

Kjøll, H. J., Galland, O., Labrousse, L., Andersen, T., 2019, Emplacement mechanisms of a dyke swarm across the Britte-Ductile boundary and geodynamics implications for magma-rich margins. Earth and Planetary Science Letters, 518, 223-235, doi: 10.1016/j.epsl.2019.04.016.

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Tunable interactions inside deformable porous media

Interactions between grains are known to affect the shape and the behavior of a granular assembly and, we believe, the behavior of a deformable porous media as well. We propose to use ferromagnetic grains (steel for example), which will acquire a magnetic momentum under the influence of an external magnetic field, leading to grain/grain interactions inside the medium.

We restudied the *bulldozing* instability described by (Dumazer et al. 2016) where a thin tube is filled with immersed grains in a slowly drained out water/glycerol mixture. Nevertheless, we noticed that in our case of a steel and glass beads mixture, the instability can be triggered by the use of an external magnetic field, as shown in fig. (1), and we propose to study the fundamental of ferromagnetic granular physics.

Indeed, the formation of plugs and their evolution has been shown to depend on the Janssen coefficient, a constant of the system depending on the type and geometry of the grains used. We believe that the interactions between grains will affect the redistribution of forces inside the granular medium, and thus change the Janssen coefficient according to the external magnetic field. We have conducted measurements of the Janssen coefficient using the set-up proposed by (Vanel and Cl 1999) by adding a magnetic field around the sample, as shown in fig (2). Our results show that, indeed, the Janssen model is greatly affected by the magnetic interactions inside the medium.

We are also performing DEM simulation to understand the role of these microscopic interactions on the macroscopic scale.

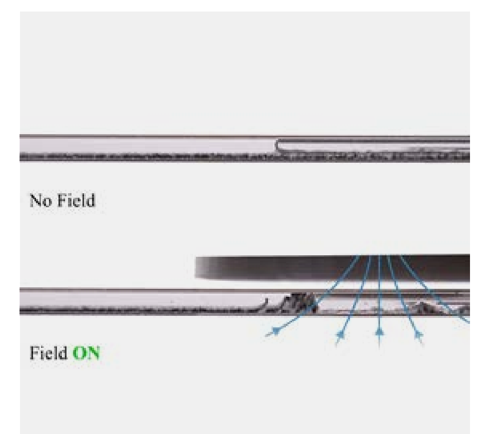

Fig. 1: Comparison of the same tube without and with an external magnetic field, necessary to trigger the buldozing instability

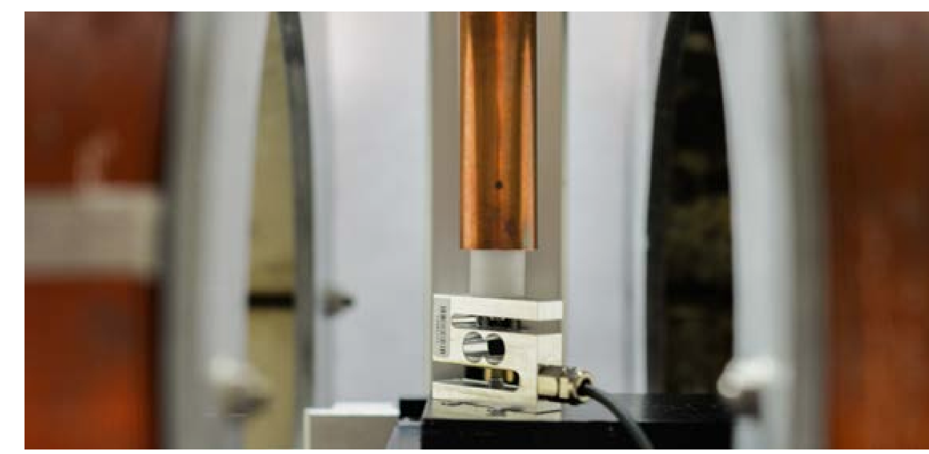

Fig. 2: Measurement of the Janssen coefficient under an external magnetic field generated by two coils in an horizontal Helmoltz configuration. A ferromagnetic grains assembly is filled inside a tube and moved down by a piston mounted on a mass sensor.

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Publications:

Dumazer, G., Sandnes, B., Ayaz, M., Måløy, K.J., and Flekkøy, E.G. 2016. *“Frictional Fluid Dynamics and Plug Formation in Multiphase Millifluidic Flow.”* Physical Review Letters 117 (2): 028002.

Vanel, L., and Clément, E. 1999. *“Pressure Screening and Fluctuations at the Bottom of a Granular Column.”* Physical Journal B 533: 525–33.

Funding:
The University of Oslo's 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 fluid flow processes on all scales. These boundaries between solid and fluid matter can be highly complex and have punctuated dynamics as a result of the nonlinear couplings between fluid flows and solid deformations and their chemical reactions. Moreover, nonlinear physical processes like friction and plasticity of complex materials stand out as important and yet unsolved problems in classical condensed matter physics and their application to the Earth's materials is an open and challenging field of research that provides opportunities for breakthroughs with very broad implications.

The EarthFlows is a strategic initiative at UiO that promotes a new paradigm of "complex Earth systems" through interdisciplinary research and using an integrated approach of linking flow, deformations and chemical reactions across relevant lengthscales. EarthFlows has already enabled a successful synergy and cross-disciplinary research across five interlinked themes including magma dynamics, ice wedging, glacial surges, fluid migration in stressed rocks and multiphase turbulent flows. In the second phase of the EarthFlows, we focus on understanding the evolution of fluid-solid interfaces in geosystems and the tipping point phenomena related to interfacial dynamics. The new concepts and theoretical developments on tipping points dynamics will concern three geosystems with a highly complex dynamics: friction and surge of glaciers, avalanches of dislocations in small-scale crystal plasticity, and dynamics of fluid flow during fracturing of rocks. Albeit these are different systems, the crosslinks between them rely on analogous statistical physics models and similar theoretical approaches based on nonequilibrium phase transitions and critical phenomena.

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. Our novel approach is to apply a rate-and-state type friction law at the glacier/bedrock interface. This framework allows for direct modeling of both transient glacier dynamics and glacier-flow instabilities through the introduction of unstable velocity-weakening branches.

With this new approach to of the ice/rock friction, we have been able to predict 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. As a next step, we aim develop a framework for the interaction between subglacial friction and the drainage system through a common state-parameter. We will investigate how this interaction governs different glacier flow regimes, with particular focus on glacier instabilities.

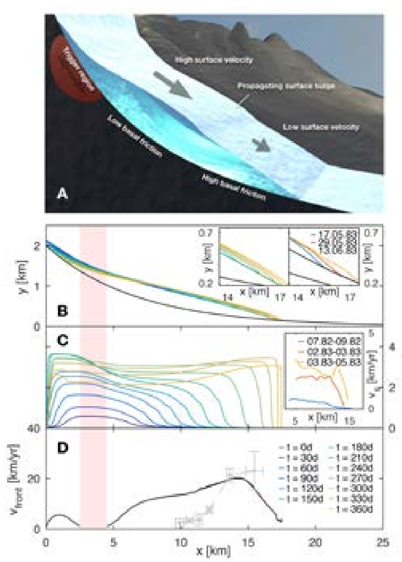

Fig. 1: Summary of our main findings: (A) a sketch of the propagation of glacier surges. (B): Modeled surface elevation during a glacier surge, with a zoom in the left inset and observations from the Variegated glacier in the right inset. (C): Modeled surface velocity with observed surface velocity in the inset. (D) modeled surge propagation speed with crosses showing observations from the Variegated glacier. The red rectangle shows the trigger region (From Thøgersen et. al, Nature Communications, 2019).

Publications:

Thøgersen, K., Sveinsson, HA., Scheibert, J., Renard, F., Malthe-Sørenssen, A. (2019). *The moment duration scaling relation for slow rupture arises from transient rupture speeds.* Geophysical Research Letters 46.

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Slow drainage experiments in porous media: from invasion bursts to thin film flow

Consider a tea bag. A wet one. Now if you place the tea bag on top of a napkin, you will notice that as the napkin dries the water away from it, sudden pockets of air are sucked from the surrounding environment into the void spaces (pores) between the tea leaves. This interesting burst activity is always present in the case of slow drainage experiments in porous media, irrespective if the medium is a porous rock, a bucket of soil, or the English-man friendly example from above. In this project, we have studied this burst activity in detail, by employing artificial transparent porous media that allowed us to have full visual inspection of the dynamics. We have considered the influence of boundary conditions to the dynamics and measured both the visual aspect of the invasion bursts, and their characteristic pressure signatures.

Another interesting aspect of slow drainage experiments is the fact that, quite frequently, some thin films of liquid are still found in the porous medium even after it has been invaded by air. If you look close enough at the tea leaves, they are not completely dry after the napkin sucks the water away: thin liquid films still cover the surface of the leaves. Again, there's nothing special about tea leaves and this kind of phenomenon can be observed in many other natural or engineered systems. Even more interesting: sometimes these thin liquid films are found to be interconnected, creating a link between different parts of the porous medium. These links can be used as a secondary network for transporting fluids from one area of the porous medium to another (transport via film flow). We have employed our transparent porous networks to characterize this interesting secondary transport mechanism.

Fig. 1: The tea bag experiment. As the wet tea bag dries, pockets of air suddenly invade the voids (pores) between the leaves, in a typical example of the intermittent burst activity observed in drainage experiments. The inset on the top right shows a macro image of the porous matrix.

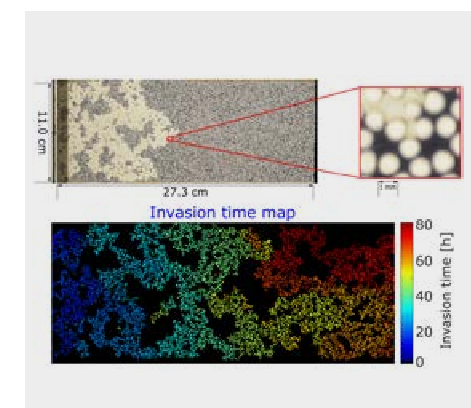

Fig. 2: The intermittent drainage dynamics is studied in a transparent model where air invades a porous medium filled with a viscous liquid. The invasion map shows the time a pore is invaded by air.

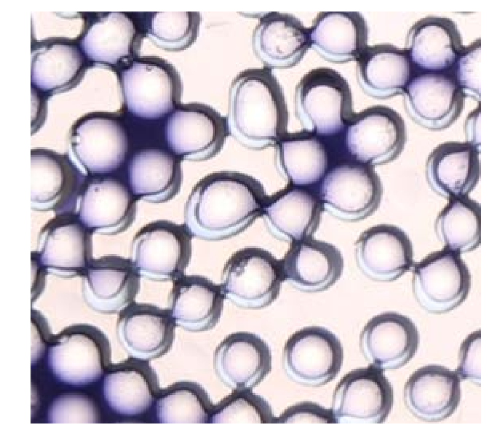

Fig. 3: Thin liquid films left on the surface of the porous matrix can merge and interconnect different parts of the medium, acting as a secondary pathway for fluid transport.

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Publications:

Marcel Moura, Knut Jørgen Måløy, Eirik Grude Flekkøy, and Renaud Toussaint, *"Intermittent dynamics of slow drainage experiments in porous media: characterization under different boundary conditions"*, Frontiers in Physics 7:217, (2020).

Marcel Moura, Eirik Grude Flekkøy, Knut Jørgen Måløy, Gerhard Schäfer, and Renaud Toussaint, *"Connectivity enhancement due to film flow in porous media"*, Physical Review Fluids 4, 094102 (2019)

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Fluid driven channel formation and acoustic emissions 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. 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 as well as measuring the acoustic emissions with accelerometers. We have characterized the channel structures and deformation over time from the images, evaluated the pore pressure evolution numerically, identified characteristic acoustic signals and their sources. Currently, we attempt to link our observations with real-world seismic events.

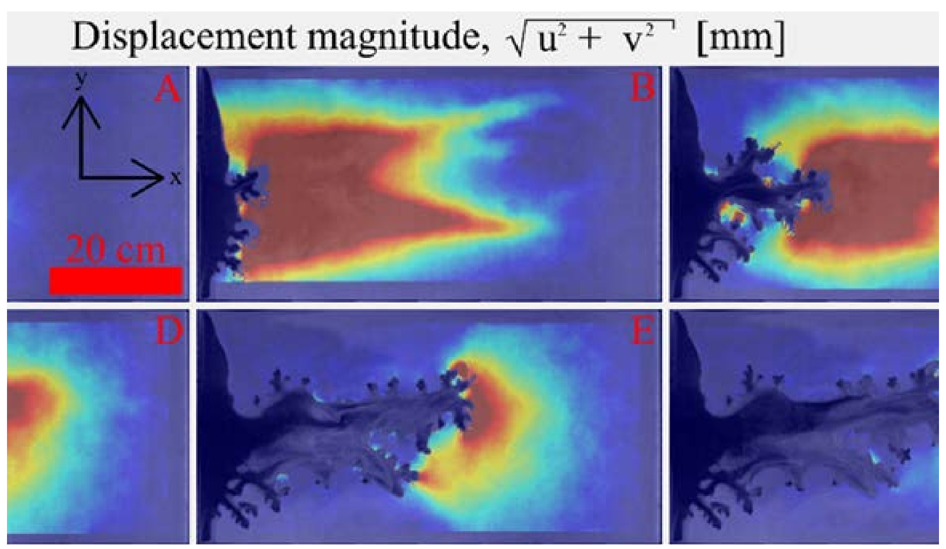

Fig.: Snapshots of experimentally obtained deformation of the granular medium surrounding the evolving channel. The figure shows the magnitude of displacement during 10 ms time steps at subsequent stages in the experiment (from A to F).

Publications:

Eriksen, F.K., Toussaint, R., Turquet, A.L., Måløy, K.J., and Flekkøy, E.G. Phys. Rev. E 95, 062901 (2017).

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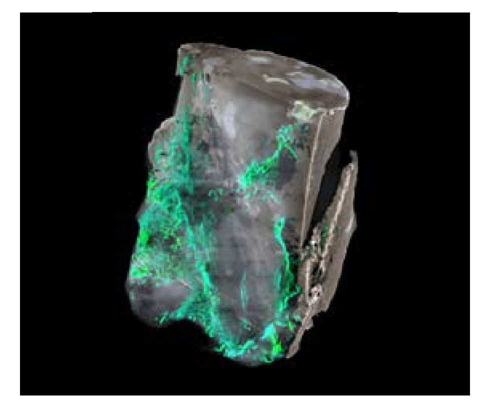
Modelling and imaging flow in rocks across scales

Understanding how multiphase fluids flow in fracturing porous rock is critical to several geological and industrially relevant processes, such as CO_2 sequestration and induced seismicity. In this project, we use pore-scale numerical modelling to increase the understanding of, and characterize, how growing fractures changes transport properties of the rock, and secondly, how this couples back to the fracture growth. We are particularly interested in (a) the distribution of velocities, which govern the large scale notion of permeability and tortuosity, and (b) the interplay between a changing geometry and multiphase flow on the dispersion of chemical tracers. We attack these problems from multiple sides: using 4D imaging techniques (dynamic X-ray and neutron tomography) we have access to real rock samples that can be used as geometrical input to our simulations (Figure 1). Secondly, simplified systems, such as idealized running fractures where theoretical descriptions are available, provide benchmarks for the numerical models and gives insight into the basic properties. Thirdly, molecular-scale simulations can be compared and provide constitutive input to the pore-scale simulations undertaken in this project.

So far, we have focused on processing of voxelated data (see Figure 2), i.e. turning 4D tomography data into unstructured tetrahedral meshes in a robust and automated way. This provides the main input to large-scale Stokes flow simulations. Secondly, by extending a finite element framework for multi-physics flow [1, 4] we have studied single- and two-phase flow in an opening fracture. The framework is in the process of being extended to account for compressibility and phase transition effects [2], which, as our simulations also show, are bound to become crucial for sufficiently fast fracture propagation speeds. Finally, the flow simulation will be coupled to a dynamically opening fracture (i.e. deformation depending on fluid stress) to numerically study the closed loop between flow and deformation.



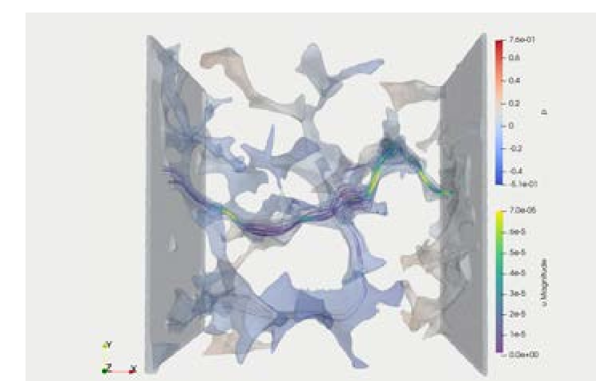


Fig. 2: Three-dimensional simulation (finite element method) of fluid flow into a core sample of Fontainebleau sandstone. Streamlines with velocity magnitude are shown on top of the (partly transparent) non-hydrostatic pressure. (The solid phase is completely transparent.)

Fig. 1 (above): X-ray microtomography image of fractures in a 5 mm diameter crystalline rock sample (beamline ID19, ESRF). The fracture network (in green) is used as an input for flow simulations. Courtesy of B. Cordonnier).

Publications:

[1] Linga, G., Bolet, A., Mathiesen, J. Bernaise: *A flexible framework for simulating two-phase electrohydrodynamic flows in complex domains.* Front. Phys. 7 21, (2019), doi: 10.3389/fphy.2019.00021

[2] Linga, G., Flåtten, T. A *Hierarchy of Non-Equilibrium Two-Phase Flow Models,* ESAIM: Proceedings and Surveys 66, 109-143 (2019)

[3] Linga, G., Møyner, O., Nilsen, H.M., Moncorgé, A., Lie, K-A. *An implicit local time-stepping method based on cell reordering for multiphase flow in porous media.* J. Comp. Phys (in review)

[4] Linga, G., Bolet, A., Mathiesen, J. *Transient electrohydrodynamic flow with concentration dependent fluid properties: modelling and energy-stable numerical schemes,* J. Comp. Phys. (in review)

[5] Linga, G., Angheluta, L., Mathiesen, J. *Transitional flow in self-affine rough channels*, to be submitted.

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Developing a lattice Boltzmann method for partial dissolution of saline water in oil

In this project we are developing a lattice Boltzmann method aiming to describe the osmotic effects between water droplets of varying salinity submerged in oil.

The partial dissolution of water in oil is set by an effective Henry's law. This states that the concentration threshold of dissolved water directly outside the droplet is proportional to the partial water pressure inside the water droplet. The partial pressure of water inside a droplet is here given by the total fluid pressure, but subtracting the pressure contribution of the salt, i.e., the partial water pressure decreases with increasing salinity. Following Henry's law, more water is allowed to dissolved into oil from a water droplet with a higher partial water pressure. In a system with water droplets of different total fluid pressures and salinities, this mechanism leads to a net flux of dissolved water diffusing through the oil towards water droplets with lower partial water pressures. This in turn results in these droplets growing, decreasing their salinities.

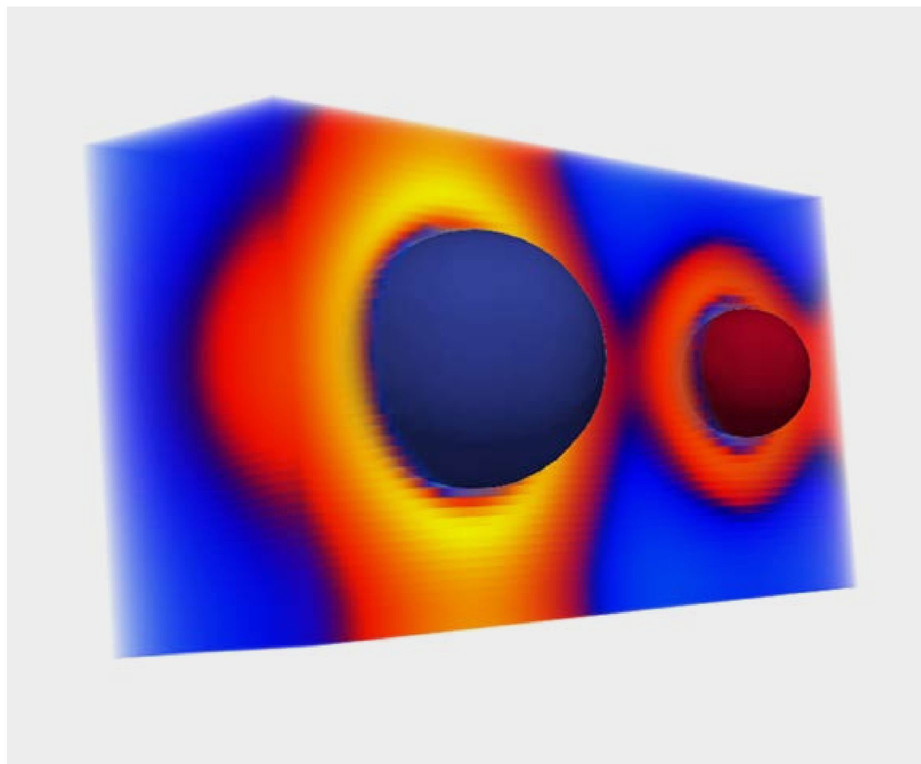

Fig. 1: The picture shows the early onset of two water droplets partially dissolving in oil. The red sphere represents a high salinity droplet, while the blue represents a low salinity one. Due to the higher partial water pressure in the low salinity droplet, higher dissolution occurs around this droplet.

Publications:

Golestan, M. H., Aursjø, O., Berg, C. F., Jettestuen, E., and Flekkøy, E.G. (2019), *Lattice-Boltzmann modeling of osmosis during low-salinity flooding.* Poster Interpore, 2019

Aursjø, O., Jettestuen, E., Vinningland, J. L., & Hiorth, A. (2018). *On the Inclusion of Mass Source Terms in a Single-Relaxation-Time Lattice Boltzmann Method.* Physics of Fluids, 30, 057104.

Aursjø, O., Jettestuen, E., Vinningland, J. L., & Hiorth, A. (2017). *An improved lattice Boltzmann method for simulating advective–diffusive processes in fluids.* Journal of Computational Physics, 332, 363-375.

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Funding:
The Research Council of Norway
CoE-program

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Interplay between viscous, capillary and gravitational forces, in two-phase flow in 3D porous media

The interplay of forces in two-phase flow in porous media has been an active topic in 2D experimental studies, using the Hele Shaw cell. The findings lead to a level of understanding of the circumstances related to different flow regimes and to connections between the geometry of flow structures and system parameters, such as the flow velocity, the pressure gradient or the viscosity contrast.

Using our newly developed 3D optical flow scanner, see figures (1-3), we wish to confront the findings from the 2D experiments with the 3D scenario. In the first series of experiments we investigate deriving a meaningful dimensionless Bond number, to quantify the balance of viscous, capillary and gravitational forces and we explore the possibility that such a dimensionless number could figure in a function describing geometric parameters of the flow structures. This work will relate to studies conducted in 2D (see references), where a relation between a modified Bond number and a characteristic width, of the invasion pattern, has been derived.

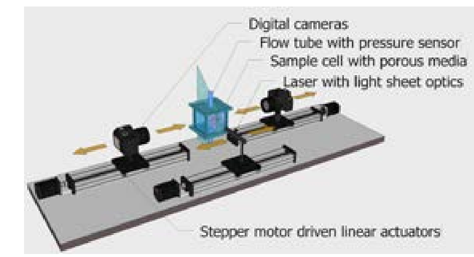

Fig. 1: The experimental set-up. The scanner is based on optical index matching and fluorescence. The porous medium is made up of 3 mm glass beads in a random packing, index matched with two immiscible fluids. The fluids each contain different fluorescent dyes that are excited with a 2D laser sheet, which is driven through the sample during a scan. The fluid phases appear on the images with different colors, making them distinguishable through imaging and processing.

Fig. 2: Raw 3D data. The 2D images captured as frames by the cameras are put together to build up the third dimension.

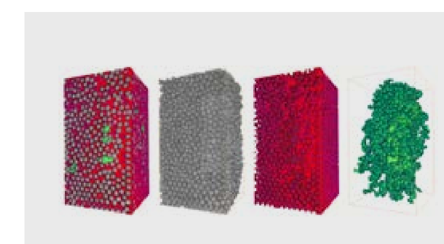

Fig. 3: Segmented phases. The porous medium and the two liquid phases are fully separated, as binary digital bodies.

Publications:

Birovljev, A., Furuberg, L., Feder, J., Jøssang, T., Måløy, K.J., and Aharony, A. *Gravity invasion percolation in two dimensions: Experiment and simulation.* Physical Review Letters, 1991. doi: 10.1103/PhysRevLett.67.584.

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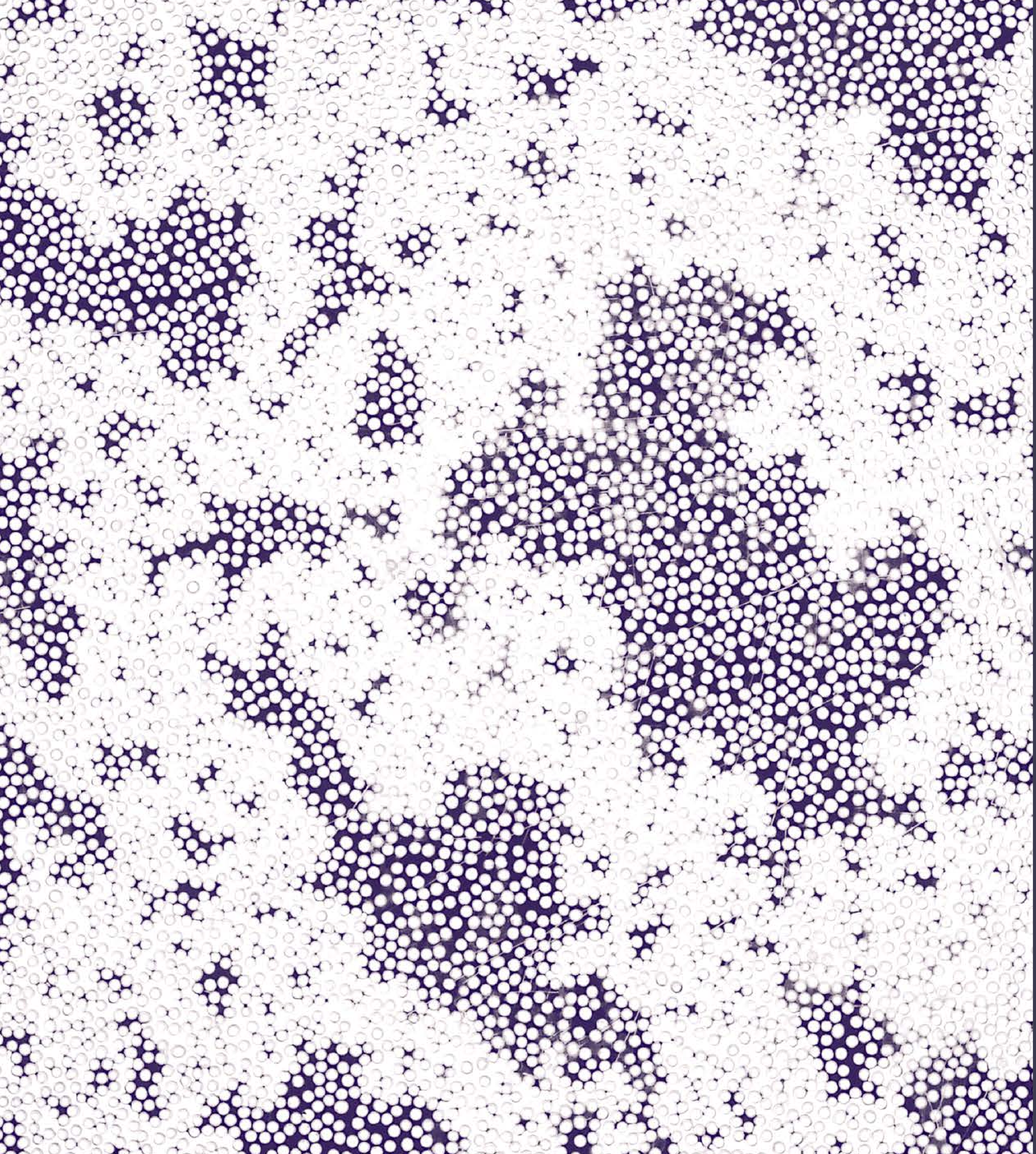
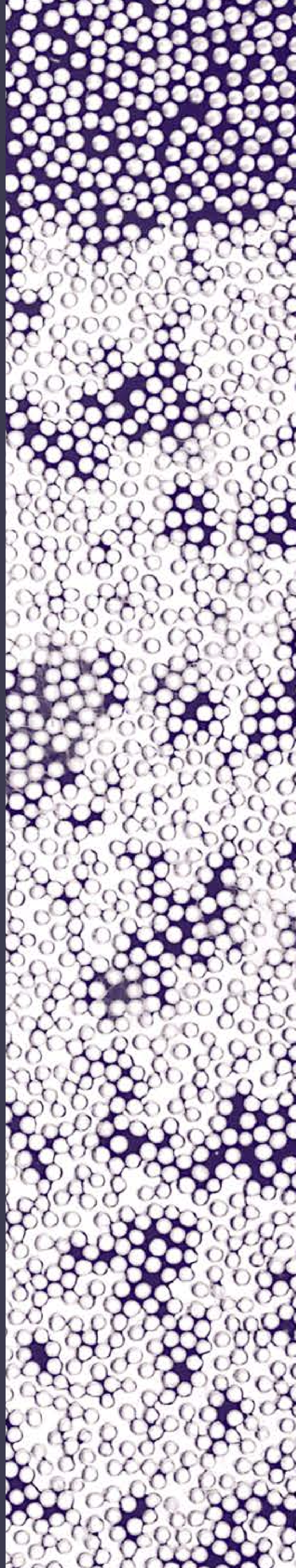


Chapter 3 | Part 2

Pattern Formation and Dynamical Systems

1) Phase diagrams of three-component systems in two and three dimensions, *2) A cosmic dust-bunny: 'Oumuamua as a space fractal,* 3) The flying chain strikes again, *4) Dissolution in Porous Media and Fractures,* 5) Dislocation dynamics and plasticity in small crystals, *6) Flow in Networks*



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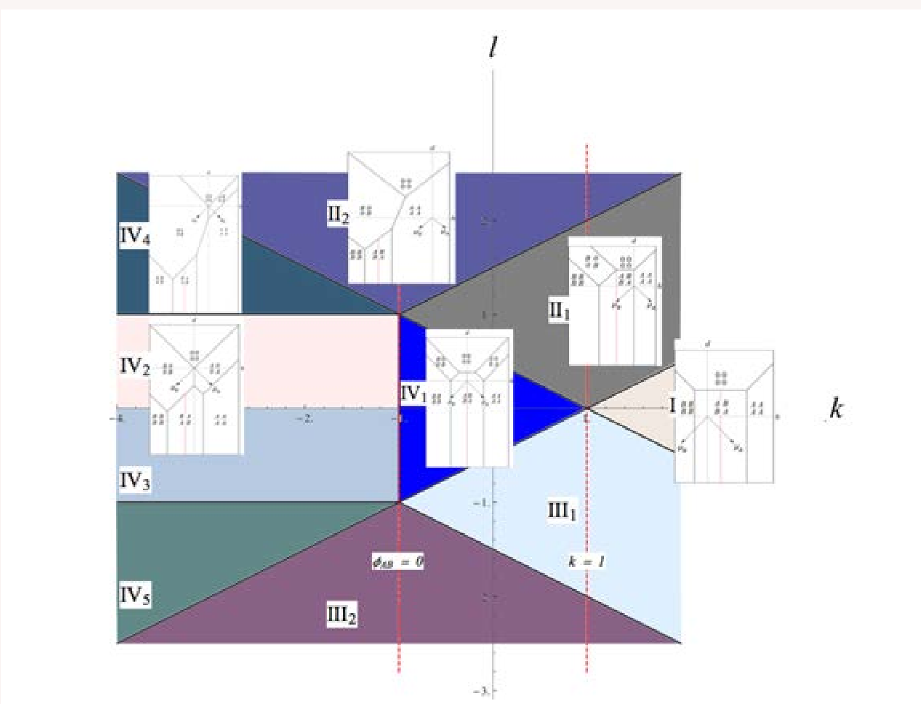
Phase diagrams of three-component systems in two and three dimensions

Many physical and chemical systems can be described using a network consisting of sites that can take a discrete number of states that interact with each other in pairs. In this project we study the phase behaviors of three-state models on two-dimensional square or three-dimensional cubic lattices. A common application of this model is to a porous mixture of sites occupied by one of two substances, A and B, together with vacant sites, 0. This situation can be described by the *lattice-gas Hamiltonian* (energy function)

$$E = -J\sum_{<i,j>} p_i p_j - K\sum_{<i,j>} p_i^2 p_j^2 - L\sum_{<i,j>}(p_i p_j^2 + p_j p_i^2) + D\sum_i p_i^2 - H\sum_i p_i$$

Here, $p_i = +1$ represents A, $p_i = -1$ represents B, and $p_i = 0$ represents a vacant site. The first three sums represent pair interactions and are taken over all nearest-neighbor site pairs, <i,j>. Depending on the values of the interaction constants, *J*, *K*, and *L*, the model can display a large number of phase diagrams in terms of the field-like variables, *D* and *H*.



Recent results

A recent result from this project is a complete list of the possible, topologically different zero-temperature phase diagrams (ground-state diagrams) generated by this model on a two-dimensional square lattice. These analytical results were published in the international journal of the Royal Chemical Society, *Physical Chemistry Chemical Physics* in 2019 [1]. Some results are illustrated in the figure.

Currently, a Monte Carlo simulation study of finite-temperature phase diagrams of this model on a three-dimensional, cubic lattice is under way. Among the interesting results are re-entrant phase behavior and the existence of a discontinuous phase transition that separates two ordered AB phases with different particle densities. Results are expected to be submitted for publication in 2020.

Fig. 1: Results for the case of mutually repulsive A and B particles (*J < 0*). The colored background shows ten regions in the plane of $k = K/|J|$ and $l = L/|J|$, in which the ground states are topologically different. A region of mixed AB checkerboard phase is seen between the uniform A and B phases. Phase diagrams for positive and negative values of l are symmetric under reflection about the d *axis*. Results for l < 0 are therefore not shown.

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Publications:

[1] Silva, D. and Rikvold, P.A. *Complete Catalog of Ground-state Diagrams for the General Three-state Lattice-gas Model with Nearest-neighbor Interactions on a Square Lattice.* Phys. Chem. Chem. Phys. 21, 6216-6223 (2019).

Funding:
The Research Council of Norway CoE-program

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

In 2017 the first interstellar visitor was observed within our solar system. Since the observation was made from a Hawaii based telescope the object was given the Polynesian name ‘Oumuamua, meaning guest or scout from afar. It was about 400 meters long and had an elongated shape. Its hyperbolic orbit implied that unlike comets and asteroids, it would only visit once. However, the detailed shape of the orbit could not be entirely explained by gravity from our solar system. An extra acceleration away from the sun could, for lack of observable outgassing, only be explained by the suns radiation pressure. This pressure could only have the observed effect if ‘Oumuamua was extremely light, that is, if it has a mass density around 1 % of air at sea level. Such extremely light structures could naturally arise by dust aggregation in young solar systems. They would be fractal over large range of length scales and probably the most porous structure ever observed, with an overall porosity of 99.999 %. We have shown that such filamentary structures could indeed survive the mechanical forces it would be subjected to on its journey past our sun. These forces include centrifugal, tidal and radiation pressure forces, and our results shows that space, in a sense, is a gentle environment compared to say, earth. In particular, we have demonstrated that a fractal of dimension D=2.3-2.4 which is made up of micron sized particles that connect with by van der Waals forces could indeed withstand the forces it would be subjected to.

After the observation of ‘Oumuamua another interstellar visitor known as Borisov, has passed through our solar system, this time with a coma and a comets tail. We are currently exploring the possibility that ‘Oumuamua too was initially a comet that lost its water to radiation and produced a dust aggregate in the process.

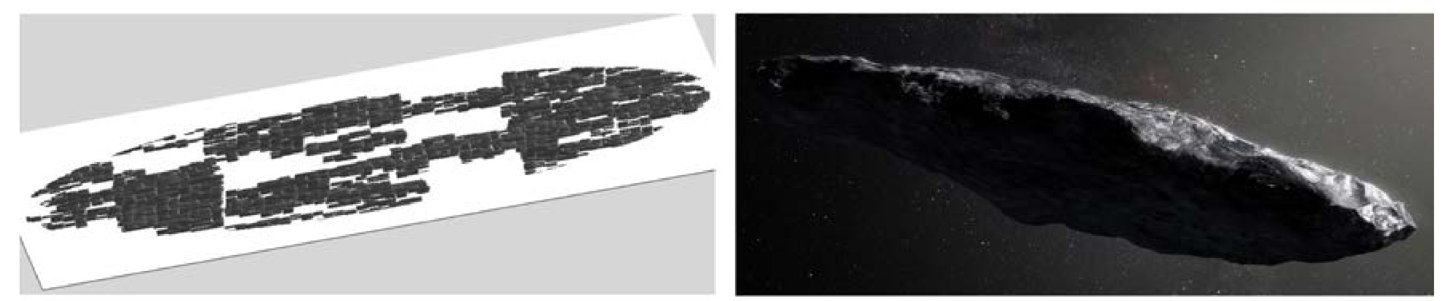

Fig. 1: The interstellar guest Oumuamua considered as a fractal aggregate (left) and as a rock (right). Both images are hypothetical.

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Publications:

Eirik G. Flekkøy, Jane Luu and Renaud Toussaint, *The Interstellar Object ’Oumuamua as a Fractal Dust Aggregate* Astrophys. J. Lett., 885: L41 (6pp), 2019

Funding:
The Research Council of Norway CoE-program

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The flying chain strikes again

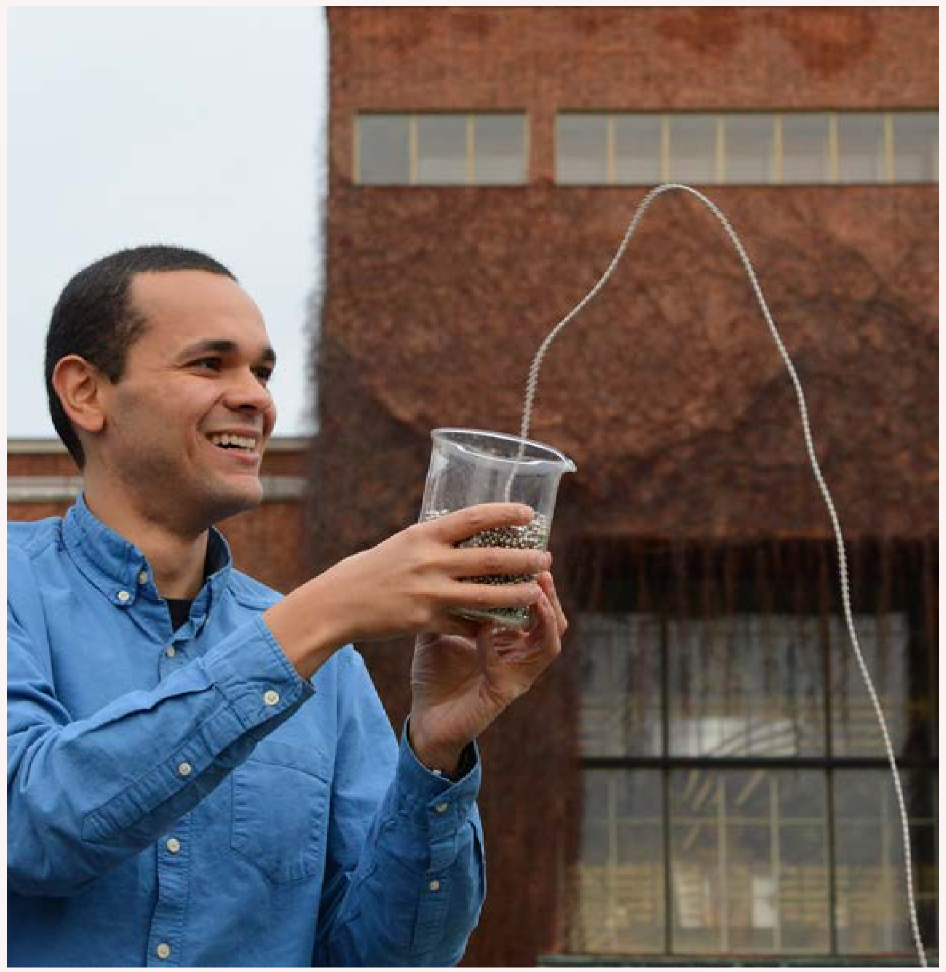

Fig. 1: A remarkable self-sustained arch is formed when a long chain of metallic beads is dropped from a container. The chain reaches a statistical steady state but fluctuations along its length are always present, as seen in the image. In the background we see the Physics Department at the University of Oslo. Picture credit: Hilde Lynnebakken.

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.

In this project, we have produced a new theoretical model for explaining the phenomenon that included the effects of fluctuations along the chain length. This model, backed up by experiments and numerical simulations, successfully predicted a number of features of the system, including the final height and velocity of the falling chain.

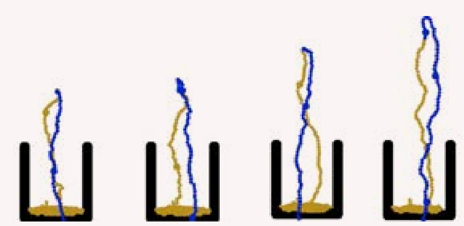

Fig. 2: Numerical simulations showing the evolution of the arch formation. The beads are all of equal size and properties, the larger beads are only drawn in order to track the beads which are colored blue when they are outside the horizontal extent of the container and given a brass color when they are not.

Publications:

Flekkøy, E.G., Moura, M., and Måløy, K.J. *"Mechanisms of the flying chain fountain,"* Frontiers in Physics 6, 84 (2018), doi: 10.3389/fphy.2018.00084.

Eirik Grude Flekkøy, Marcel Moura and Knut Jørgen Måløy, *"Dynamics of the fluctuating flying chain,"* Front. Phys. 7, 187, (2019).

Popular science article written by Hilde Lynnebakken on Titan.uio.no: *"YouTube-hit om metallkjeder ble forskning på toppnivå"*.

Mould Steve, *"Self siphoning beads"*, YouTube, February 20, 2013.

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Funding:
EU's Seventh Framework Programme; Research Council of Norway CoE-program

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Dissolution in Porous Media and Fractures

Reaction-infiltration instability refers to the morphological instability of a reactive fluid front flowing in a soluble porous medium. This process is important for many naturally occurring phenomena, such as the weathering and diagenesis of rocks, dissolution in salt deposits and melt extraction from the mantle. This project is focused on experiments on dissolution in radial geometries in an analog fracture. In the experiments, pure water dissolves a plaster sample forming one of the fracture walls in a Hele-Shaw cell with controlled injection rate and aperture.

Our experimental results show a number of features consistent with the theoretical and numerical predictions on the finger growth dynamics such as screening and selection between the fingers. Statistical properties of the dissolved part evolution with time are also investigated. We obtain different dissolution patterns depending on the timescales for diffusion, convection and reaction. Different dissolution patterns are presented in a phase diagram depending on the flow rate and fracture aperture.

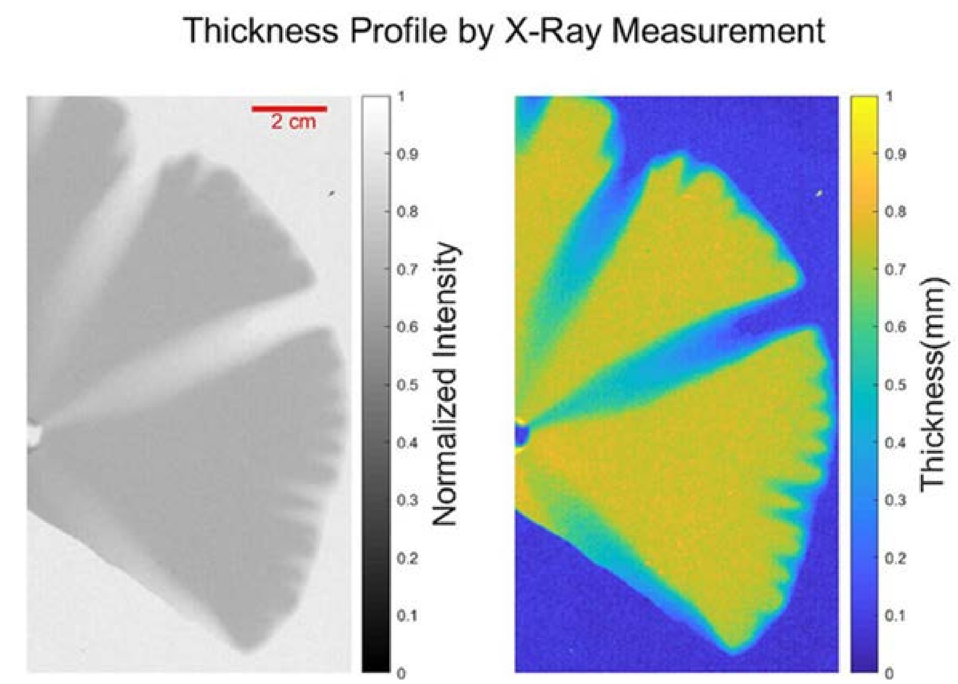

Fig. 1: (Left) X-ray image of dissolved plaster sample captured by X-ray thickness gauge REX-CELL 4X from Flow Capture. The gray-scaled picture shown in the left panel is the normalized intensity of the X-ray measurement together with the color bar. (Right) Thickness profile of the dissolved plaster sample is displayed with the gradient-color picture together with the color bar.

Publications:

Xu, L., Szymczak, P., Toussaint, R., Flekkøy, E.G., Måløy K.J. *Experimental Observation of Dissolution Finger Growth in Radial Geometry.* Frontiers in Physics 7, 96 (2019)

Xu, L., Szymczak, P., Toussaint, R., Flekkøy, E.G., Måløy, K.J. *Dissolution Phase Diagram in Radial Geometry*. In preparation.

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Funding:
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Dislocation dynamics and plasticity in small crystals

On large scales, simple solids tend to deform smoothly and predictable in accord to continuum mechanics theories. In contrast, crystals that are submicron in size have a complex deformation behavior characterized by crackling noise, unpredictable failure point and increased strength.

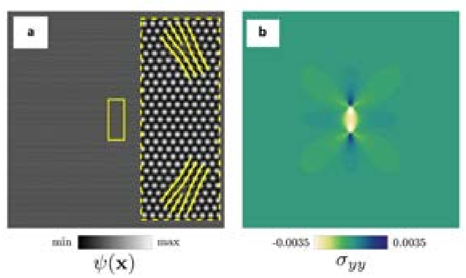

Fig. 1: Order parameter for the crystal symmetry (a) with a close-up view near a dislocation dipole. (b) The elastic stress field induced by the dislocation dipole (taken from Ref 3)

How come that the yield stress increases as the crystals get smaller? And why is that the yield stress varies wildly from sample to sample, even when they have same size? What causes seismic-like events during crystal's deformation? It turns out that crystal defects, like dislocations, are at the origin for wild deformations of submicron crystals. Like in other complex systems with crackling noise, the deformation of submicron crystals may be *emergent* from the collective properties of interacting and moving dislocations. Current research is devoted to formulate such an emergent theory for microplasticity in crystalline matter.

At variance with empirical models that explicitly track dislocation and grain boundaries, we propose a more fundamental framework based on the phase field crystal (PFC) modelling approach. The PFC model is based on describing the crystal lattice through a free energy which determines the crystal lattice symmetry and the evolution of its associated order parameter. In Ref. [1], we have shown that dislocations occur as topological defects in the crystal order parameter, and, moreover, that their overdamped dynamics can be deduced directly from the diffusive evolution of the order parameter. We proposed a variational method to compute the elastic stress in a crystal with hexagonal lattice (like ice) and showed that the dislocations move under the Peach-Kohler force induced by elastic stress fields. By allowing for independent mass motion and lattice distortion, the crystal can maintain elastic equilibrium on the timescale of plastic motion. In Ref. [2], we showed that the plastic strains are determined by the PFC order parameter, while the smooth elastic distortions need to be constrainted to satisfy elastic equilibrium. In Ref. [3], we extended our model to tackle larger scales and come closer to the continuum limit, by using amplitude expansion of the order parameter. We analyze in detail the elastic distortion and stress regularization at a dislocation core and show how the Burgers vector density can be directly computed from the topological singularities of the phase-field amplitudes. We also compare our results with those given by other extensions of classical elasticity theory, such as strain-gradient elasticity and methods based on the smoothing of Burgers vector densities near defect cores.

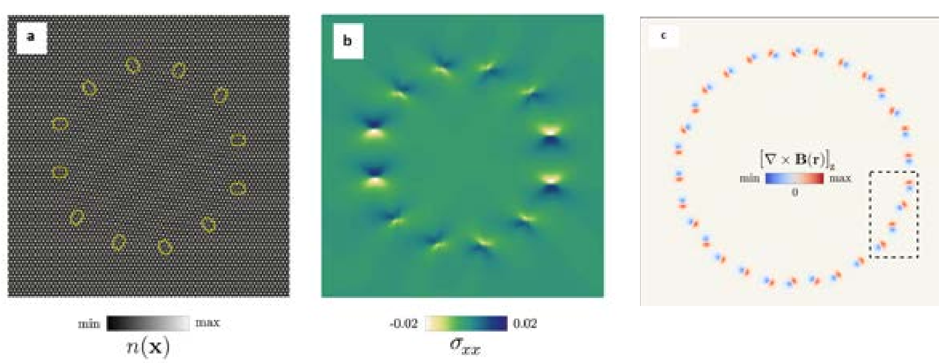

Fig. 2: Lattice deformation for a rotated crystal inclusion embedded in a crystal matrix. (a) Order parameter of the two crystals. (b) the associated stress field σ_{xx} for the dislocations at the subgrain boundary; (c) the curl of the Burger vector density corresponding to the dislocations (taken from Ref 3)

Publications:

1. Skaugen, L. Angheluta, J. Vinals, "*Dislocation dynamics and crystal plasticity in the phase field crystal model*", Phys. Rev. B 97, 054113 (2018)

2. Skaugen, L. Angheluta, J. Vinals, "*Separation of Elastic and Plastic Timescales in a Phase Field Crystal Model*", Phys. Rev. Lett. 121, 255501 (2018)

3. M. Salvalaglio, L. Angheluta, Z.-F. Huang, A. Voigt, K.R. Elder, J. Vinals, "*A coarse-grained phase field crystal model of plastic motion*", submitted to Journal of the Mechanics and Physics of Solids 2019 (archived)

Funding:
The Research Council of Norway CoE-program; the U.S. National Science Foundation.

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Flow in Networks

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 description of a system of many interacting entities in terms of *nodes* connected by *edges* has found diverse applications in natural and social science and technology, including the Internet and the World Wide Web, transportation systems, ecological interaction and food networks, and flow in porous media.

Recent results

Centralities quantify the "importance" of individual nodes and are among the most useful concepts in network theory. As there are many ways, in which a node can be important, many different centrality measures are used, ranging from the simple Degree Centrality (the number of neighbors connected to a particular node) to the sophisticated ranking algorithms of web-search engines. In this project, we focus on so-called *Betweenness* and *Closeness* centralities. The former measure the fraction of paths between all pairs of nodes that pass through a given node, while the latter measure an average inverse "distance" between a particular node and all others. We introduce a method, based on the theory of *Absorbing Markov Chains*, to continuously interpolate each of these centrality measures between one limit, in which all possible paths through the network are active, and one, in which only *shortest paths (geodesics)* count. The interpolation is in terms of a Death Parameter for random walkers on the network. For small death parameter, the walkers explore all paths like currents in an electric circuit, while increasing the *death parameter* gradually restricts the surviving walkers to shorter paths. The results are described in Ref. [1].

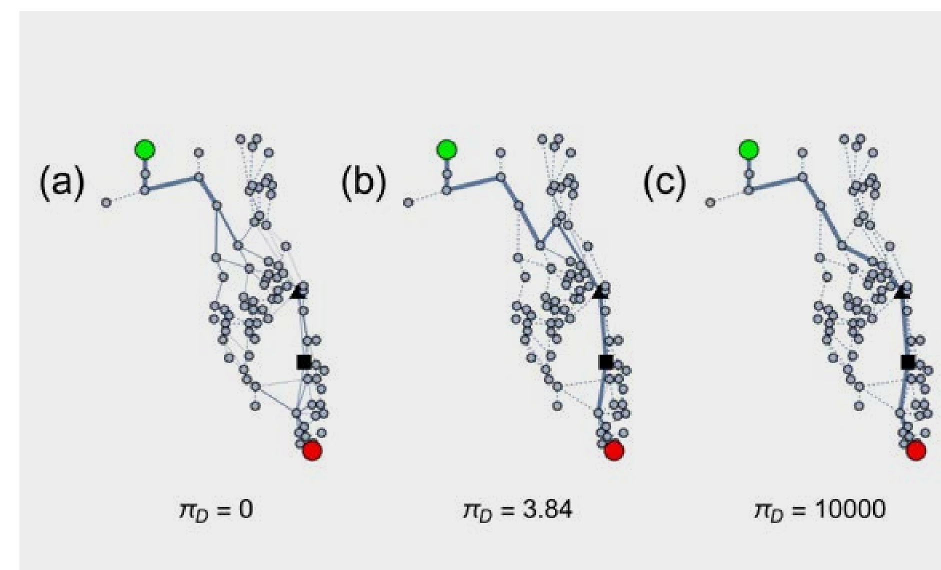

Fig. 1: Flows across a network representation of the high-voltage power grid of the U.S. state of Florida for a range of the walker-death parameter. (a): No walker death. (b): Intermediate death rate. (c): High death rate. The flow is gradually constricted from the whole network to the shortest path between the endpoints as the death rate increases. The nodes marked by triangle and square have the highest betweenness centralities only in the medium parameter range. From [1].

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Publications:

[1] Gurfinkel A.J., and Rikvold, P.A., *Absorbing Random Walks Interpolating Between Centrality Measures on Complex Networks.* Phys. Rev. E, under review. Preprint: arXiv:1904.05790.

Chapter 3 | Part 3

Fracture, Friction and Creep in Rocks and Materials

1) Neutron imaging of pollutant flows in porous rocks, *2) Thermal effects in fracture propagation,* 3) Maturation and fracturing of organic-rich shale during primary migration, *4) Continuously sheared granular matter and comparison with Seismicity Laws,* 5) The road to failure in rocks, *6) Predicting fracture propagation and coalescence leading to macroscopic failure in rocks using machine learning,* 7) Brittle-viscous deformation cycles at the base of the seismogenic crust, *8) Role of grain scale heterogeneity on macroscopic deformation in granular systems*

Funding:
The Research Council of Norway

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[6] University Grenoble Alpes, University Savoie Mont Blanc, CNRS, IRD, IFFSTTAR, ISTerre, 38000, Grenoble, France

Neutron imaging of pollutant flows in porous rocks

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

With ARGUS, we use in-situ neutron imaging of Cd-doped flow experiments in limestone and sandstone samples. We explored the potential and limits of in-situ neutron imaging in porous rocks in the presence of cadmium. Samples were placed in the apparatus and pressurized at 1 MPa confining pressure with a nitrogen bottle. Two pore volumes of water were first injected for Fontainebleau sandstone and Indiana limestone at a flow rate of 3 mL/h and 8 mL/h respectively. Then, two pore volumes of diluted Cd at 0.5 mol/liter were injected. We then 'washed' the sample by injecting again two pores volumes of water. While the Fontainebleau sandstone was completely washed and no traces of cadmium remained in the rock, the Indiana limestone has demonstrated a real potential in retaining cadmium due to two different porous network sizes and permeabilities. At the end of the experiment about 30% of the injected cadmium remained in the rock, unevenly distributed in the rock, highlighting some areas of stagnant fluids. It provides a potential new perception of the capture of pollutant where only a fraction of the rock structure contributes to the sorption of heavy metals.

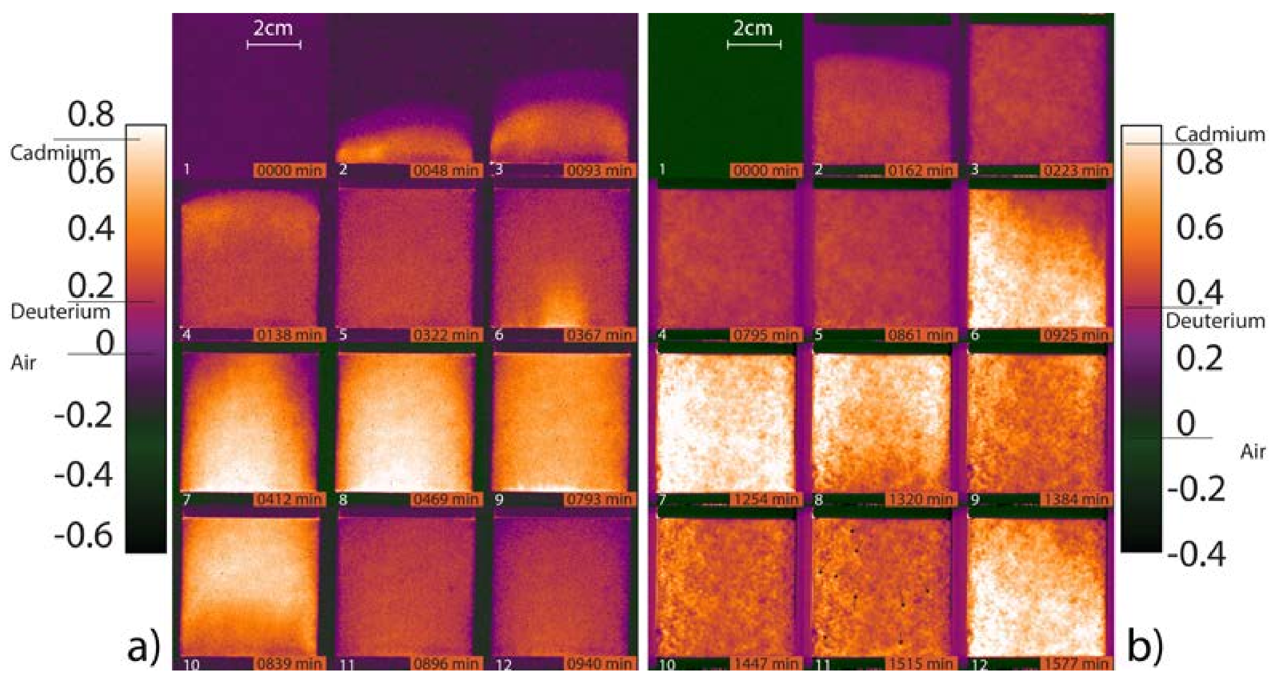

Fig. 1: Time-lapse 2D radiographs of injection of cadmium in a) Fontainebleau sandstone and b) Indiana limestone. The first injection of D2O was followed by an injection of D2O +Cd. Samples were then washed with a second injection of D2O. For the limestone only, a second injection of D2O+Cd has been performed at the end of the experiment. The color code shows the range expected for air, D2O, and D2O+Cd. Arrows in slide 11, section b, evidence the spots where 'unwashed' cadmium is maximum. Note however that comparing slide 11 and 5, most of the sample contains some unwashed cadmium.

Funding:
University of Strasbourg; the Research Council of Norway CoE-program

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Thermal effects in fracture propagation

Fractures propagating in brittle media, whether artificial or natural, usually transit between slow propagation (creep), and "catastrophic" fast rupture. The alternation between these modes of rupture generates noise during fracture propagation, e.g. when a piece of glass or polymer is broken, or when polymeric glue in a tape is torn apart. Similarly, faults in the Earth crust happen in disordered media, where asperities induce intermittency, and their mechanical functioning results in an alteration of aseismic and seismic phases. The result of this intermittency is a distribution of the events whose shape and width depends on the scale of observation. During comparisons between models and experiments, it was shown that the mechanics of fracture in disordered media depends both on the toughness distribution for the heterogeneities on the fracture way, and of the thermal fluctuations that allow the fracture to go through these hard parts or asperities. Taking into account these two types of disorder, material and thermal, allows accounting for many aspects of interfacial fracture, in the statistics of events, the fast dynamics and the slow creeping one. We study the influence of the dynamics of the evolution of the temperature field due to heat transport and generation, and to the transport of pressurized fluid along the fault. We developed a model of the heating of fracture tips due to energy released during fracture, and of the influence of temperature elevation on the velocity of rupture, expressed as a chemico-physical process taking into account energy barrier, that depend on the local stress state, and temperature at local scale. This proved to reproduce the velocity regimes of fracture, from very slow creep to dynamic fracture, including the jump from slow to fast velocities. The model reproduces experiments done in mode I rupture of polymers, namely Plexiglas and polymeric glue in adhesive tape (Vincent-Dospital et al., 2019a). This also explains features such as fractoluminescence during fast rupture. It also renders for a transition between brittle and ductile fracture mode and explains this transition as a critical point (Vincent Dospital et al., 2020). In a case where heating is negligible, we could also explain the distribution of local velocities (Cochard et al., 2019) and the distribution of global velocities and jumps (Santucci et al., 2019).

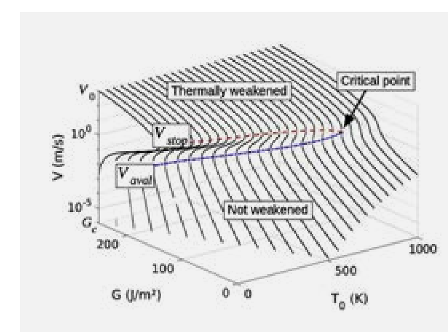

Fig.1: Characteristic (G,*v*) predicted by Eqs. (2,3), at different background temperatures. The unstable branch corresponds to G(v) decreasing, its presence is associated to a stick-slip instability. The crack velocity suddenly jumps to much higher values when G increases: the behaviour is brittle. Above a certain background temperature T0, G(v) becomes monotonous, and the instability disappears: the mechanical behaviour becomes ductile. The point at which this happens After Tom Vincent-Dospital et al., 2020.

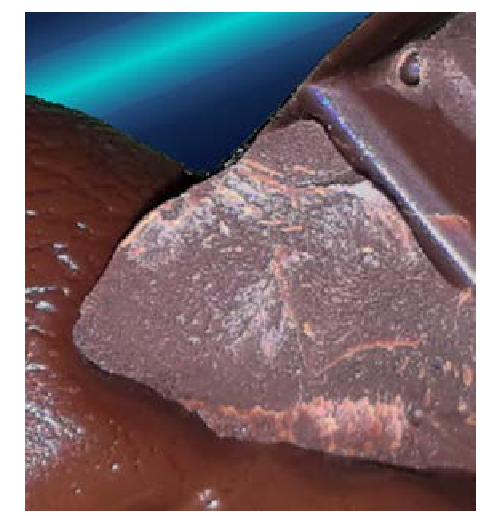

Fig. 2: A material (chocolate) deformed in a brittle way at low room temperature (top right), or in a ductile way (in the bulk) at higher room temperature (left).

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Publications:

Vincent-Dospital, T., Toussaint, R., Santucci, S., Vanel, L., Bonamy, D., Hattali, L., Cochard, A., Flekkøy, E.G., Måløy, K.J. *From thermal creeping to thermal weakening: How crushing plastic and unrolling tape unravels fracture physics*. arXiv preprint arXiv:1905.07180. Submitted to PRX. 2019a

Vincent-Dospital, T., Toussaint, R., Cochard, A., Måløy, K.J., Flekkøy, E.G. *Thermal weakening of cracks: a phase transition model. arXiv preprint arXiv*:1901.04202. Accepted to Phys. Rev. Mat., 2020.

Cochard, A., Lengliné, O., Måløy, K.J., Toussaint, R. *Thermally activated crack fronts propagating in pinning disorder: simultaneous brittle/creep behaviour depending on scale*. Philosophical Transactions of the Royal Society A 377 (2136), 20170399

Santucci, S., Tallakstad, K.T., Angheluta, L., Laurson, L., Toussaint, R., Måløy, K.J. *Avalanches and extreme value statistics in interfacial crackling dynamics*. Philosophical Transactions of the Royal Society A 377 (2136), 20170394

Funding:
The Research Council of Norway

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Maturation and fracturing of organic-rich shale during primary migration

How hydrocarbons are expelled from source rocks, also called shales, control how much oil and gas could migrate toward reservoir rocks during burial in sedimentary basins. Shales are layered sedimentary rocks, which can be almost impermeable for fluids and act as seals and cap-rock, or, if a shale layer host a fracture network, it can work as a fluid reservoir and/or conduit. Organic-rich shales contain organic matter – kerogen, which can transform from solid state to oil and gas during burial and exposure to heat. When the organic matter is decomposing into lighter molecular weight hydrocarbons, the pore-pressure inside the shale rock increases and can drive propagation of hydraulic fractures. Properties of the final fracture network (such as density, geometry, extension, connectivity, etc.) depend on the combination of the heating conditions and history of external loading experienced by the shale reservoir.

Here, we have reproduced natural conditions of the shale deformation processes using combination of vertical load, confining and heating of the shale samples while we monitored the fracture network development with time-resolved X-rays micro-tomography, an advanced dynamic 3D imaging technique. Shales features natural mineral and silt lamination and hydraulic fractures easily propagate parallel to these laminae if no overburden stress is applied. However if the principal external load becomes vertical, perpendicular to the shale lamination, the fracture propagation direction can deviate from the horizontal one. Together horizontal and vertical fractures form a connected fracture network, which provides escaping pathways for generated oil and gas. In this project, we collaborate with the European Synchrotron Radiation Facility (ESRF), beamline ID19, and we used the high-energy X-ray beam to monitor different modes of the shale deformation in-situ in 3D. We also reproduced some of the results using Discrete Element Method numerical modelling and rock physics template from data of the Norwegian Continental Shelf.

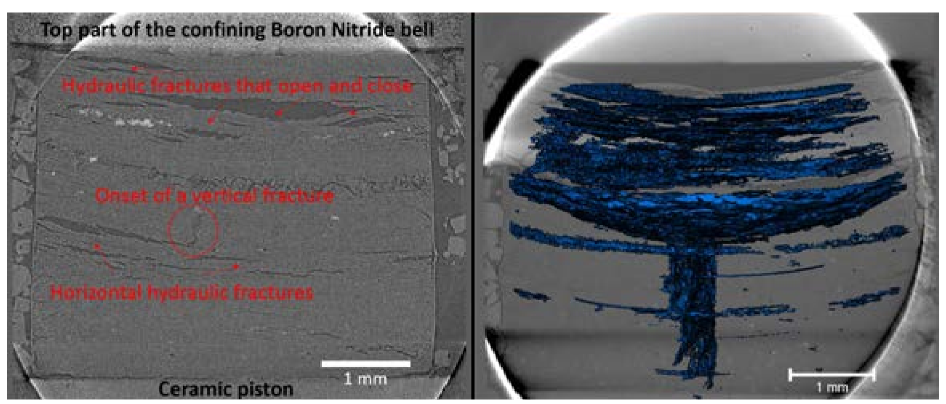

Fig. 1: Left: Different modes of hydraulic fracturing inside a confined shale sample heated under vertical load and imaged at in situ conditions using synchrotron X-ray microtomography. The field of view is 5 mm.

Fig. 1: Right: 3D rendering of a set of hydraulic fractures, which developed inside organic-rich shale sample during heating. Many hydraulic fractures propagated in horizontal direction parallel to the natural shale lamination. Load and confinement of the sample during heating triggered propagation of a vertical fracture, perpendicular to the shale lamination and originated earlier horizontal fractures.

Publications:

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*, 235, 1-16, doi: 10.1016/j.fuel.2018.07.069. Featured in the web site Advances in Engineering.

Johnson, J., Hansen, J., Renard, F., Mondol, N. (2019) *Modeling maturation, elastic, and geomechanical properties of the Draupne Formation, offshore Norway*, SEG Technical Program Expanded Abstracts 2019, doi: 10.1190/segam2019-3215340.1.

Johnson, J., Hansen, J., Renard, F., Mondol, N. (2019) *Geomechanical Analysis of Maturation for the Draupne Shale, Offshore Norway, Sixth EAGE Shale Workshop*, doi: 10.3997/2214-4609.201900272.

Huang, L., Baud, P., Cordonnier, B., Renard, F., Liu, L., Wong, T.-F. (2019). Synchrotron X-ray imaging in 4D: *Multiscale failure and compaction localization in triaxially compressed porous limestone*, Earth and Planetary Science Letters, doi: 10.1016/j.epsl.2019.115831.

Funding:
The Research Council of Norway

Participants
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Continuously sheared granular matter and comparison with seismicity laws

The frequency and sizes of earthquakes follow universal statistical laws which has been difficult to replicate with lab experiments. In our experiments small disks confined to a 2D cylindrical shell has compiled a huge number of "labquakes". By continuously and slowly shearing a compressed monolayer of photoelastic discs, we have been able to replicate several statistical features of earthquakes like the Gutenberg-Richter law, the Omori law and interevent time distribution. In our system, the granular force network provides an emergent and evolving heterogeneity in terms of energy thresholds that is the key ingredient of the dynamics, and it is responsible for a distribution of events that resembles the Gutenberg-Richter law. In this experiments we used a 2D system of 3500 disks that were 7mm or less in diameter. These disks were confined in the narrow gap between two concentric, vertical cylinders. The top edge was covered with a weighted ring to induce pressure on the disks, while the bottom edge was rotated slowly with a rotation period of about 18 hours. Having a system that matches geological observations may lead to the essential ingredients that control the dynamics of real earthquakes.

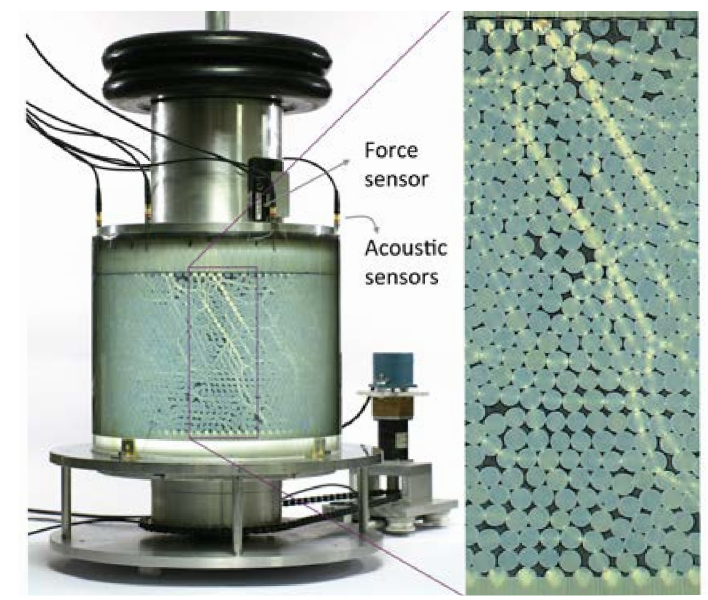

Fig. 1: Photograph of the setup, displaying the mechanical and acoustic sensors. Inset: force chains in the granular layer observed thanks to photoelasticity.

PoreLab
NTNU-UiO Porous Media Laboratory

Publications:

S. Lherminier, R. Planet, V. Levy dit Vehel, G. Simon, K. J. Måløy, L. Vanel and O. Ramos, *Continuously sheared granular matter reproduces in detail seismicity laws,* Phys. Rev. Lett. 122, 218501 (2019). PRL Editors' Suggestion, Focus on Physics, Highlighted in PhysicsWorld, and Science Editor's Choice

Funding:
The Research Council of Norway

Participants
François Renard[1], Benoît Cordonnier[1], Jess McBeck[1], Neelima Kandula[1], Xiaojiao Zheng[1], Bjørn Jamtveit[1], Jérôme Weiss[2], Wenlu Zhu[3], Yehuda Ben-Zion[4], Paul Meakin[5]

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The road to failure in rocks

The physical controls of the onset of major slip instabilities in rocks, such as earthquakes or landslides, remain open questions in geophysics. Our goal is to quantify the dynamics of microfractures in rocks to predict the onset of major ruptures and earthquake nucleation. We have developed a combined experimental and numerical approach to unravel how ruptures nucleate in rock samples, how earthquake have damage wall rocks in natural earthquakes, and whether precursory signals exist that would indicate the propagation of an earthquake before it happens. Using dynamic X-ray tomography imaging at the European Synchrotron Facility and a home-designed rock deformation apparatus we imaged in 4D the evolution of microfracture in rocks before system-size failure. These microfractures represent precursory signals to the main rupture. They follow a dynamics reminiscent of a dynamic phase transition described in many systems in physics: the rock sample evolves from an unbroken phase to a broken phase and the dynamics follow that of other phase transitions observed in nature, for example, when rocks acquire magnetic properties when cooled below the Curie temperature. Our experiments produce large amounts of data (more than 150 TB so far) and we have developed new data processing techniques to follow the evolution of microfractures in a sample during deformation. Among these techniques, we have developed a machine learning workflow to unravel which parameters control microfracture propagation in rocks.

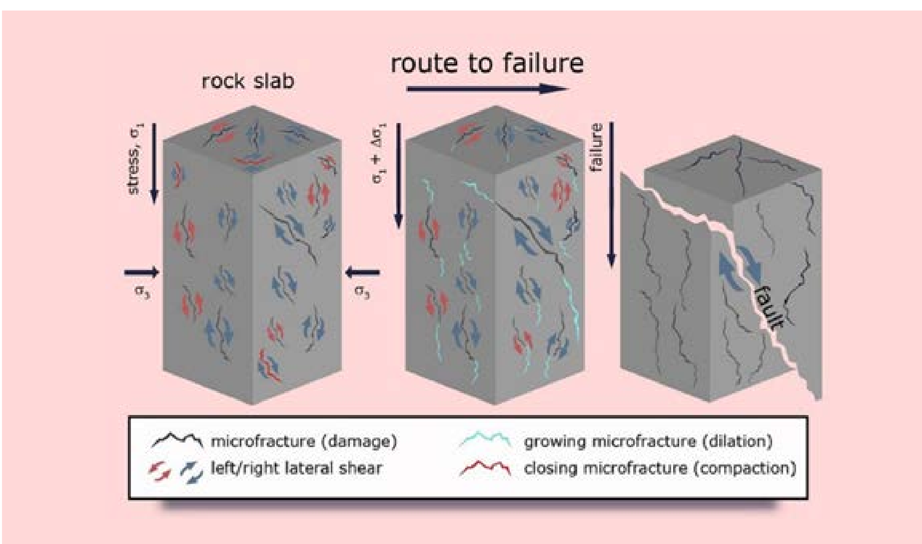

Fig.1: The route to failure in crystalline rock. Under a state of differential stress (σ_1-σ_3), damage accumulates in the form of microfractures that may open, close and slip in a right-lateral or left lateral sense. As failure is approached, one slip mode becomes dominant, right-lateral on this sketch, leading to macroscopic faulting.

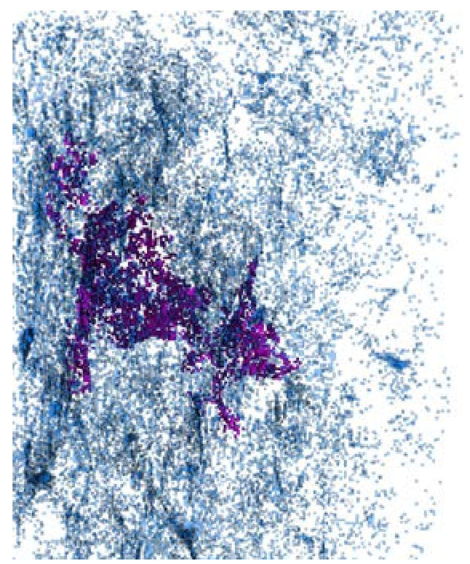

Fig.2: Synchrotron X-ray 3D imaging of a sample of Westerly granite at 99.5% of failure stress. The rock is rendered transparent and microfractures are represented in blue and purple and their dynamics control the final failure (width of the sample: 4 mm).

Publications:

McBeck, J., Kandula, N., Aiken, J. M., Cordonnier, B., Renard, F. (2019). *Isolating the factors that govern fracture development in rocks throughout dynamic in situ X-ray tomography experiments,* Geophysical Research Letters, in press.

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Petley-Ragan, A., Ben-Zion, Y., Austrheim, H., Ildefonse, B., Renard, F. & Jamtveit, B. (2019). *Dynamic earthquake rupture in the lower crust.* Science Advances, 5, doi: 10.1126/sciadv.aaw0913.

Kandula, N., Cordonnier, B., Weiss, J., Dysthe, D. K., Renard, F. (2019). *Dynamics of microscale precursors during brittle compressive failure in Carrara marble,* Journal of Geophysical Research, doi: 10.1029/2019JB017381.

Zheng, X., Cordonnier, B., McBeck, J., Jamtveit, B., Zhu, W., Renard, F. (2019). *Mixed-mode strain localization generated by hydration reaction at crustal conditions,* Journal of Geophysical Research, doi: 10.1029/2018JB017008.

Funding:
The Research Council of Norway; European Synchrotron Radiation Facility

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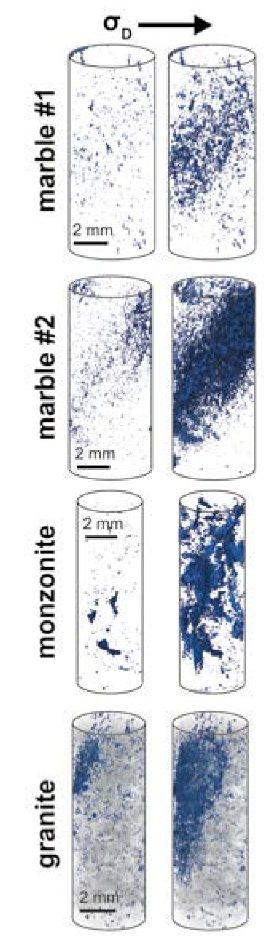
Predicting fracture propagation and coalescence leading to macroscopic failure in rocks using machine learning

The central goal of this project is to identify the factors that control strain localization and fracture propagation. We employ machine learning to extract the characteristics that control deformation in data collected during in situ X-ray tomography triaxial deformation experiments on rocks. *McBeck et al.* (2019) used characteristics of the coalescing fracture networks to identify the factors that control the likelihood of propagation of individual fractures (**Figure 1**). Although varying analytical formulations grounded in linear elastic fracture mechanics suggest the importance of varying characteristics of fractures in predicting growth, none of these formulations or subsequent approaches had provided a quantitative means of directly comparing the importance of these characteristics. One major advance of our machine learning analysis (*McBeck et al.*, 2019) is that we developed a method of quantitatively and efficiently comparing the accuracy of preexisting failure criteria. The other significant advance was identifying the characteristics that provide the highest predictive power in determining the likelihood of fracture propagation (**Figure 2**).

Fig. 1 (right): Fractures (blue) identified in four in situ dynamic X-ray tomography experiments at lower and higher differential stresses



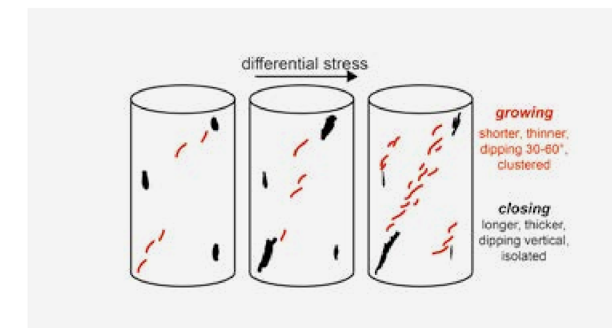


Fig. 2: Characteristics of growing and not growing fractures identified with machine learning.

Publications:

McBeck, J., Kandula, N., Aiken, J. M., Cordonnier, B., & Renard, F. (2019). *Isolating the factors that govern fracture development in rocks throughout dynamic in situ X-ray tomography experiments.* Geophysical Research Letters, doi:10.1029/2019GL084613.

Funding:
Posiva Oy, Finland; University of Plymouth, UK; University of Bologna, Italy

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

Most of continental earthquakes nucleate at the *brittle-viscous transition*, where the strength of crustal rocks is at its maximum. Crustal deformation near the *brittle-viscous transition* involves the competition between fracturing and viscous flow, and a prominent role of variations in fluid pressure is often invoked to explain the mechanics of fault zones at depth. This project uses a network of fault zones that were active across the brittle-viscous transition at 10-15 km of depth and that are now exhumed in southwestern Finland. The study area is located in Onkalo, the site of a deep geological repository for high-grade nuclear waste. The project aims to (i) determine the mechanical evolution of long-lived faults active at the *brittle-viscous transition*, (ii) determine the extent of fluid pressure oscillations during deep faulting, (iii) characterize the multi-scale fluid pathways of a fault system.

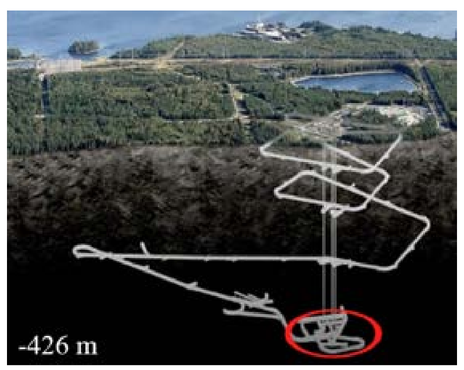

Fig. 1: Panoramic photograph of the Onkalo site in SW Finland, with an overlay drawing of the underground infrastructure (photo courtesy of Posiva Oy). The red circle shows the depth location of the samples used in the project.

By combining fluid-inclusion studies with electron backscatter diffraction (EBSD) analysis of crystallographic orientations of minerals, we found out that: (i) faulting was associated with the ingress of multiple batches of fluid of different compositions in the fault zone; (ii) transient fluid overpressure triggered a switch to brittle and seismic fault behavior in the deep, 'ductile' crust; and (iii) the stress history of the ductile flow of a fault can be preserved in its microstructure (for example, in the grain size of quartz). We are currently investigating the distribution and interconnection of porosity in the fault rocks using Hg-porosimetry combined with x-ray microtomography.

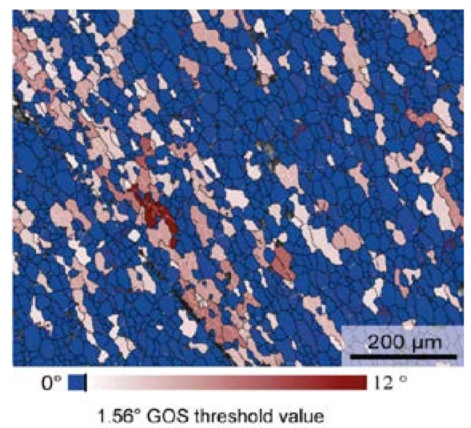

Fig. 2: Grain size map of quartz located in one of the shear zones at Onkalo acquired with electron backscatter diffraction (EBSD). The map is colour coded according to the Grain Orientation Spread (GOS) of each grain, which is a measure of the lattice distortion accumulated during creep. Blue grains deformed during a higher stress event than red and pink grains.

Publications:

Marchesini, B., Garofalo, P.S., Menegon, L., Mattila, J., Viola, G., 2019. *Fluid-mediated, brittle ductile deformation at seismogenic depth – Part 1: Fluid record and deformation history of fault veins in a nucler waste repository (Olkiluoto Island, Finland).* Solid Earth, 10, 809-838, doi: 10.5194/se-10-809-2019.

Prando, F., Menegon, L., Anderson, M.W., Marchesini, B., Mattila, J., Viola, G., 2019. *Fluid-mediated, brittle ductile deformation at seismogenic depth – Part 2: Stress history and fluid pressure variations in a shear zone in a nuclear waste repository (Olkiluoto Island, Finland).* Solid Earth Discussions, doi: 10.5194/se-2019-142.

Funding:
The Research Council of Norway; University of Oslo

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Role of grain scale heterogeneity on macroscopic deformation in granular systems

Numerical simulations using 3D Discrete Element Modelling (DEM) are a powerful tool that allow us to link microscopic grain scale processes the macroscopic deformation of granular materials. Here, we build geomaterials from aggregates of particles that can break, evolve or interact with their neighbours. Ongoing work investigates the role of compositional and crystallographic anisotropy on the grain size/shape evolution of granular material, and its effect on the development and evolution force chains during frictional sliding in shear. Preliminary results suggest a primary role of crystallographic weaknesses (e.g. cleavage planes) on the evolution of force networks, and occurrence of selective fracturing during deformation of bimaterial gouges.

Our numerical simulations of the triaxial compression of sandstone of varying porosity was one of the first numerical analyses to investigate fracture development and percolating force networks within models composed of interlocking, cemented and breakable grains (*McBeck et al.*, 2019). This analysis demonstrates that enabling grain breakage fundamentally controls the fracture localization process, and that numerical simulations of sandstone deformation that do not include such breakage may fail to capture the relevant physics. The analysis also shows how porosity changes the localization of the percolating force chain network, thereby promoting failure at lower macroscopic differential stress **(see fig.)**. This analysis enables an exploration of the micromechanics that remain unavailable experimentally and so provides constraints on the applicability of vary micromechanical models of the deformation of porous rock.

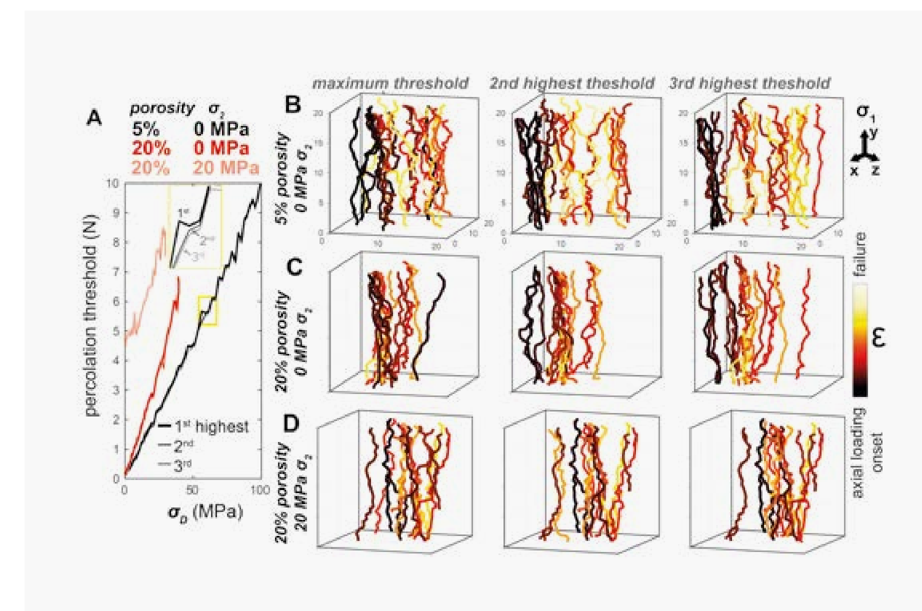
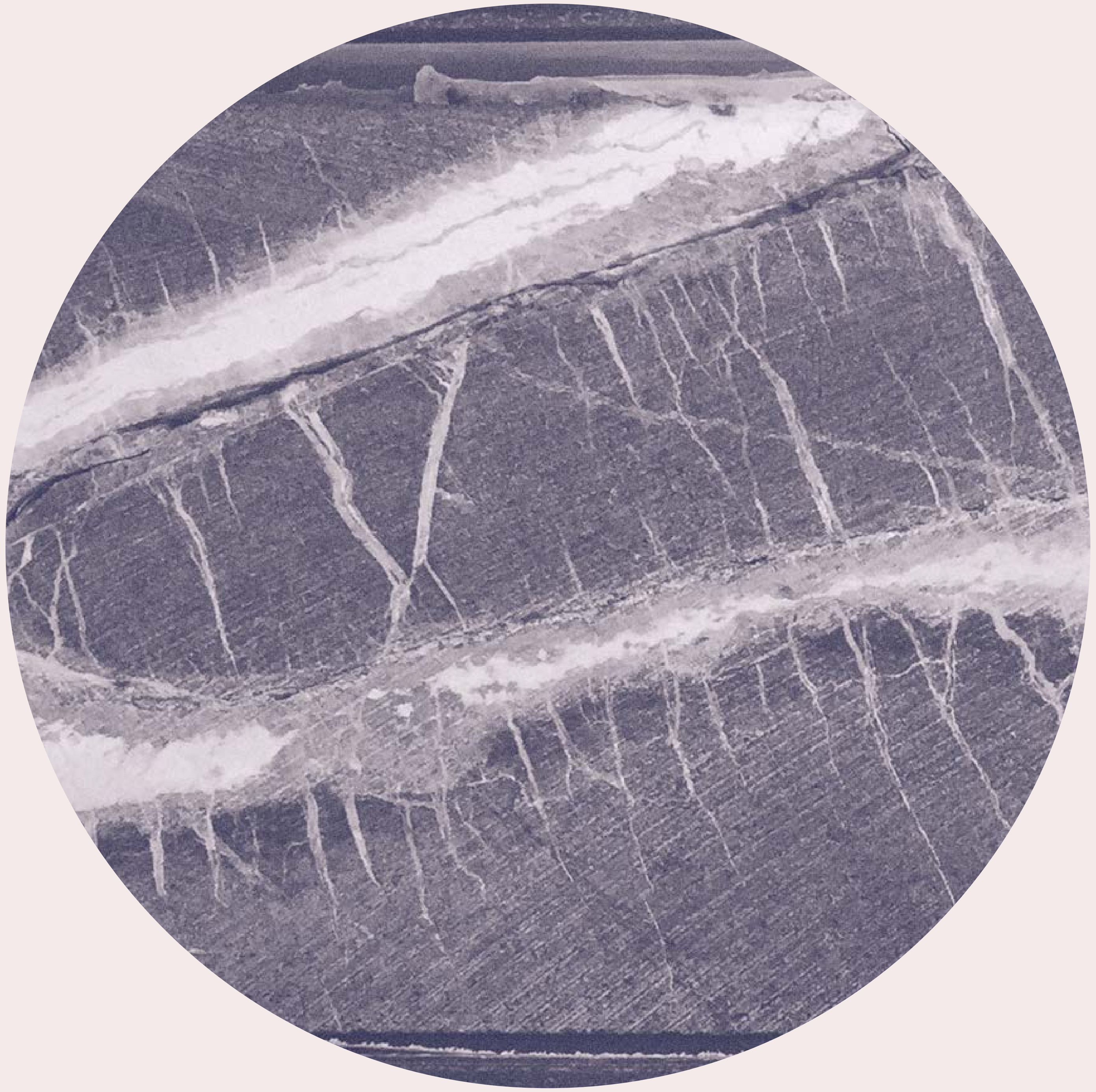


Fig. 1: Evolution of the percolating threshold force, and location of the percolating force chains that support this force.

Publications:

McBeck, J., Mair, K., & Renard, F. (2019). *How porosity controls macroscopic failure via propagating fractures and percolating force chains in porous granular* rocks. Journal of Geophysical Research: Solid Earth.



Chapter 3 | Part 4

Coupled Chemical Processes from the Nanoscale to the Scale of Continents

1) Nanoscale imaging and modelling of mineral-water interface, *2) Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity,* 3) BioZEment 2.0 – Systems analysis and fundamental control of bacterial processes in the production of bio-concrete for construction purposes, *4) Structural and Metamorphic Transformation Processes in the Lower Continental Crust and Upper Mantle,* 5) Thermally activated fractures in methane hydrates

Funding:
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Nanoscale imaging and modelling of mineral-water interface

Incorporation of toxic elements into a mineral has proven to be an effective technique to remove toxic elements from aqueous solutions, for example chromium. Dissolution of carbonate minerals and precipitation of nanoparticles occurs easily on the mineral surfaces. This coupled dissolution-precipitation mechanism occurs in a boundary layer at the mineral-fluid interface and nanoparticles might contain the toxic element (Figure 1 a), immobilizing it from the aqueous solution. Another way to immobilize the toxic elements is to let the host mineral grow in the presence of this element. The toxic elements can then be incorporated into the crystal structure, observed by irregularities from the normal growth (Figure 1 b). We developed several experimental approaches to study these fluid-mineral interactions over time (atomic force microscopy, stirred flow-through reactors) and to analyze the final products (Raman spectroscopy, SEM, ICP-MS). These experiments are performed in collaboration with the Universities of Münster and Grenoble Alpes.

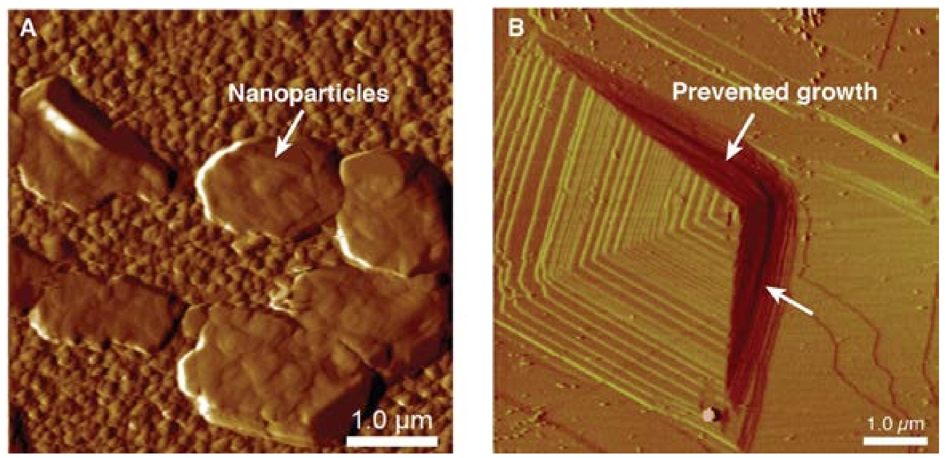

Fig. 1: The effect of chromium-rich fluids on a calcite surface. a) Formation of nanoparticles. b) Growth of calcite hillocks where two of the sides are prevented from normal growth due to incorporation of chromate ions.

A different technique to study nanoscale mineral-fluid interfaces is molecular dynamics simulations, which provides a deeper understanding of atom-scale processes that is not visible in experiments. For example, by quantifying the behavior of water molecules between two mineral surfaces under pressure, we aim to provide insight about whether reactions, or mineral transformations, requiring water can proceed or not under large stresses.

Publications:

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

Funding:
The Rearch Council of Norway

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

The overall strength of rocks and granular materials is often associated with processes that take place in contacts between individual solid grains. The solid contacts are the most reactive regions, in which minerals can grow or dissolve in the presence of out-of-equilibrium fluids. The growth and dissolution frequently determine if contact will be strong or weak, as they may cement solid grains together or push them away from each other. The overarching goal of this project is to recognize which processes make the solid-solid interfaces weak, and how to convert the weak interfaces into strong ones. Although we see the destructive effects of weak interfaces at a macroscopic scale (earthquakes, rock subsidence, material failure), the very mechanisms governing the interfacial strength are frequently operating at much smaller scales.

To recognize these mechanisms and modify them, we need analytical methods that investigate the relevant nano-processes. In this experimental project, we study the interfaces with the Surface Forces Apparatus (SFA). Within the first 5 months of the project, we tested and improved two methodologies to study dynamic mineral interfaces: electrochemical SFA setup (EC-SFA) and the synchrotron X-ray source SFA setup (X-SFA). EC-SFA setup enables to control the surface charge of one of two confining surfaces by applying electrical potential. Our goal is to study mineral corrosion reactions in confinement, which are induced by dissimilar surface charge of the two contacting surfaces. Such corrosion of mineral surfaces has challenged the understanding of one of the most important deformation processes in rocks – pressure solution.

X-SFA is a version of the SFA adapted to the SAXS/WAXS X-ray synchrotron experiment. A 1 µm-wide beam of high energy X-ray can be precisely directed along the confinement region between two surfaces mounted in the SFA. The SFA geometry consists of one flat surface and one cylindrical surface, yielding a 200 µm-wide and 4 mm-long confined region, in which the separation between two surfaces is as small as few nm Our preliminary results from these experiments show that mineral replacement reactions can be induced by friction.

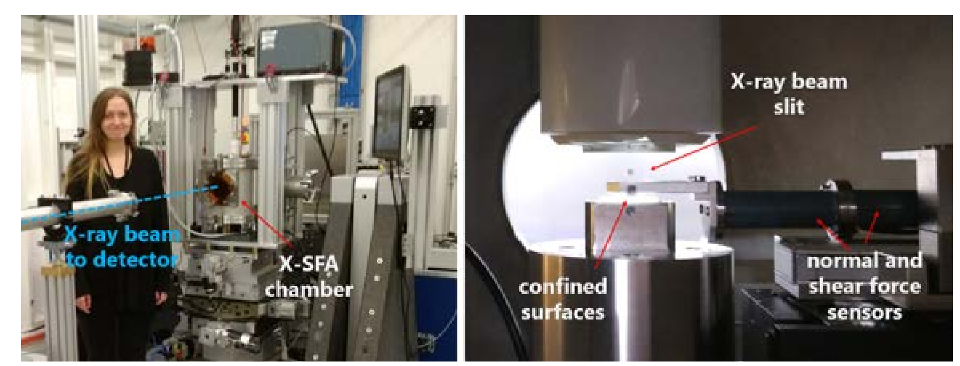

Fig. 1: X-SFA set-up at DESY (Deutsches Elektronen-Synchrotron) Petra III P21.2 Beamline in Hamburg.

Funding:
The Research Council of Norway; Centre for Digital Life Norway

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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

By volume, concrete is the most important material in the world – more than twice as much concrete is produced every year as every other material combined. At the same time, the production of cement, which is the most important component of concrete, accounts for somewhere between 5 and 10 % of global, anthropogenic CO_2 emissions.

The goal of BioZEment 2.0 is to develop the fundamental knowledge that is required for being able to produce concrete materials based on biotechnology. Biotechnology can allow us to produce materials with considerably lower energy use and CO_2 emissions than what we make today. In order to reach this goal, we have established a multidisciplinary consortium with expertise in microbiology, life cycle assessment, techno-economic analysis and research on consumers. Preliminary results confirm that this type of material has the potential to make a significant difference in global CO_2-emissions, and that the attitudes of consumers in general are positive. We are now working on developing and coupling the different experimental and mathematical/numerical models we are using for the material and bacteria on the microscale, while also developing prototypes that will be used to understand how the different processes contribute to the material properties on the larger scale.

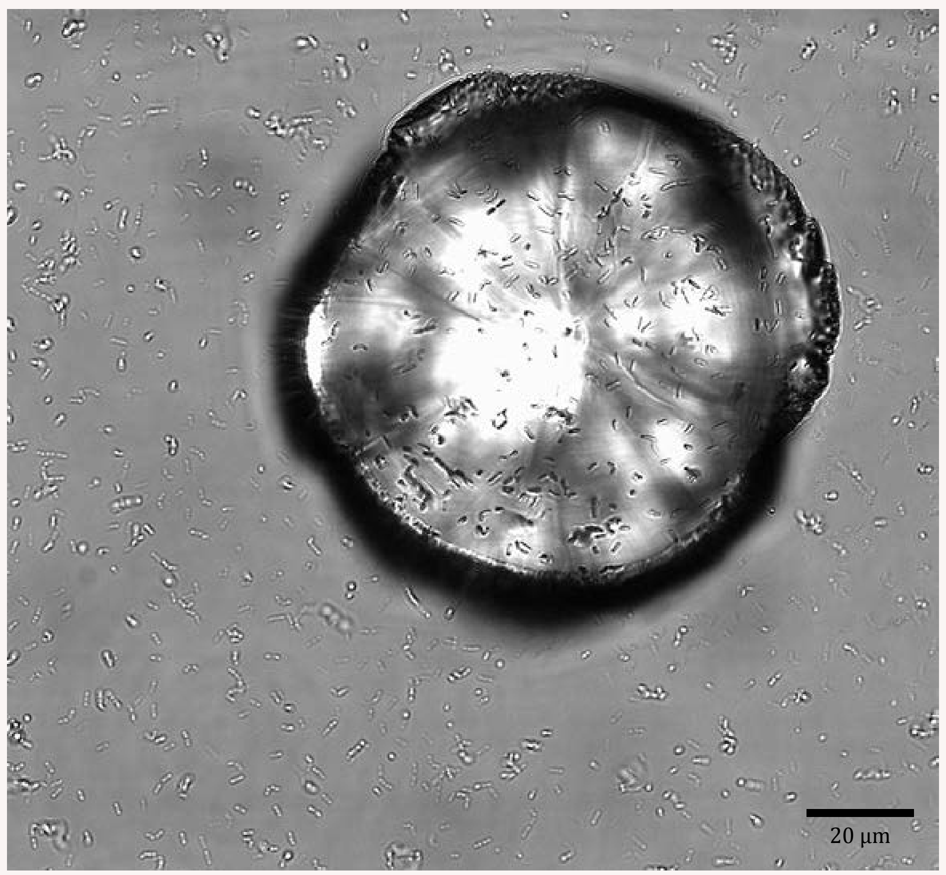

Fig. 1: Optical microscope image of calcium carbonate crystal grown in the presence of urease active bacteria. Some of the bacteria can be seen encapsulated in the crystal.

Publications:

Røyne, A., Phua, Y.J., Balzer, Le S., Eikjeland, I.G., Josefsen, K.D., Markussen, S., et al. (2019) *Towards a low CO_2 emission building material employing bacterial metabolism (1/2): The bacterial system and prototype production.* PLoS ONE 14(4): doi: 10.1371/journal.pone.0212990

Myhr, A., Røyne, F., Brandtsegg, A.S., Bjerkseter, C., Throne-Holst, H., Borch, A., et al. (2019) *Towards a low CO_2 emission building material employing bacterial metabolism (2/2): Prospects for global warming potential reduction in the concrete industry.* PLoS ONE 14(4), doi: 10.1371/journal.pone.0208643

Karlsen, E., Schulz, C., Almaas, E. *Automated generation of genome-scale metabolic draft reconstructions based on KEGG.* BMC Bioinformatics 2018; Volum 19(467) s. 1-11

Funding:
ERC Advanced grant; Alexander von Humboldt Foundation; Swiss Research Council; Natural Science and Engineering Research Council (NSERC) of Canada; UK Natural Environment Research Council (NERC)

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

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

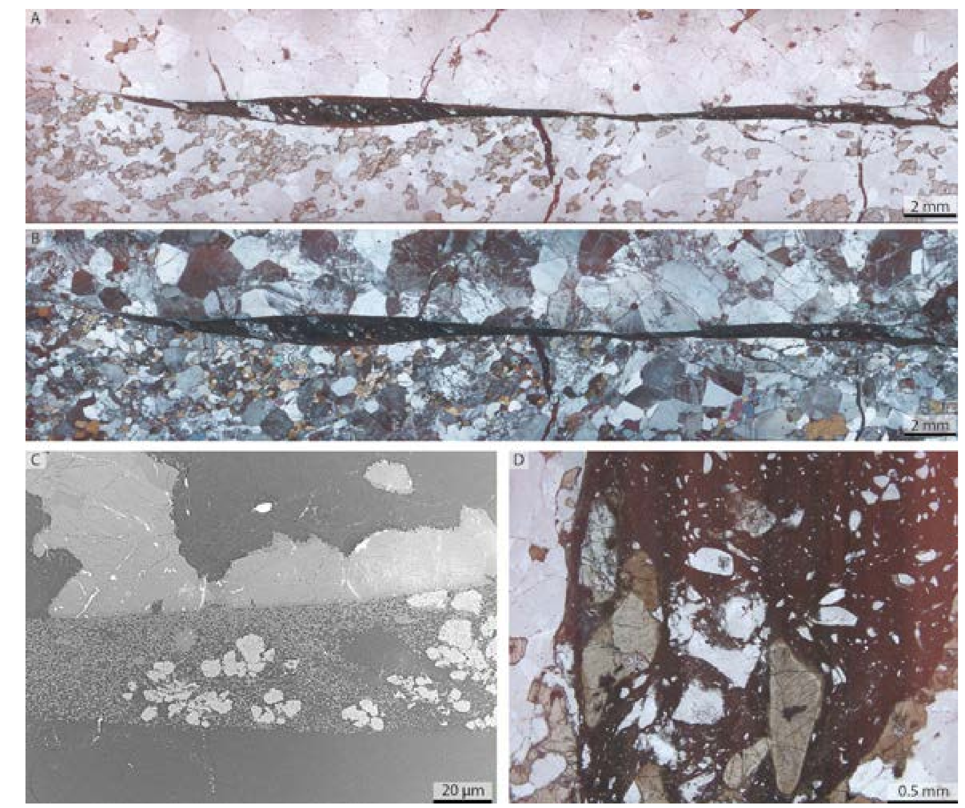

Fig. 1: Dry Pseudotachylyte in amphibole-bearing paragneiss. Optical micrographs in plane polarized (a) and cross polarized (b) light showing a pseudotachylyte that juxtaposes pyroxene and amphibole-rich (bottom) and poor (top) host rock. There is no alteration zone around the pseudotachylyte. c) Backscatter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

Publications:

Campbell, L.R., Menegon, L., 2019. *Transient high strain rate during localised viscous creep in the dry lower continental crust (Lofoten, Norway).* Journal of Geophysical Research – Solid Earth, 124, doi: 10.1029/2019JB018052.

Dunkel, K.G., Jamtveit, B, Austrheim, H., 2019, *Ophicarbonates of the Feragen Ultramafic Body (Norway).* Norwegian Journal of Geology, 99, 1-18.

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, 47, 235-238.

Funding:
ERC Advanced grant; Alexander von Humboldt Foundation; Swiss Research Council; Natural Science and Engineering Research Council (NSERC) of Canada; UK Natural Environment Research Council (NERC)

Participants
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The structural transformations that the lower crust experiences during earthquake cycles are preserved in the geological record in the in the form of pristine pseudotachylytes (solidified quenched frictional melt produced during coseismic slip, Figure 1) and mylonitised pseudotachylytes, which form by solid-state viscous creep during the postsesimic and interseismic periods (Figure 2). By examining the grain-scale deformation microstructures of mylonites with electron backscatter diffraction (EBSD, Figure 2), we can derive the stress history, the creep rate and the viscosity of these mylonites. Our results are consistent with geodetic measurements of lower crustal viscosity variations during the postseismic and interseismic stages, thus bridging the gap between the geological record and the direct observation of earthquake cycle deformation.

Our studies of wall rock microstrutures demonstrate that earthquakes in the lower crust form by dynamic rupture, i.e. brittle deformation. This is in contrast to most models of lower crustal deformation, which assume that the lower crust is weak and only deforms in ductil manners. Brittle deformation at lower crustal depths require very high stresses and may be linked to stress pulses generated by large earthquakes at shallower levels in the crust.

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

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

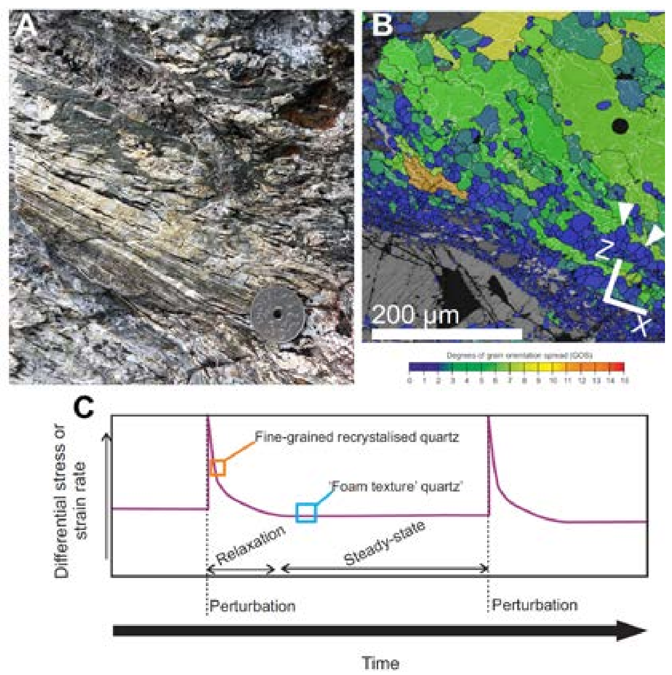

Fig. 2: (A) Mylonitised pseudotachylytes from Nusfjord, Lofoten. (B) Electron backscatter diffraction map of quartz from the sample shown in (A). The map is colour-coded according to the Grain Orientation Spread (GOS) of the quartz grains, which indicates the internal distortion of the crystal lattice as a consequence of viscous creep. The white arrows indicate larger quartz grains that formed at decreasing stress conditions during the interseismic stage, which followed the transient high stress deformation in the postseismic stage. (C) Conceptual model of the evolution of the evolution of grain size of quartz and of the creep rate of mylonitised pseudotachylytes from Nusfjord active during the postseismic and interseismic stages.

Publications in Highlights:

Incel, S., Schubnel. A., John, T., Freeman, H., Wang, Y., Renard, F., Jamtveit, B., 2019, *Experimental evidence for wall rock pulverization during dynamic rupture at ultra-high pressure conditions.* Earth and Planetary Science Letters, 528, 115832

Jamtveit, B., Petley-Ragan, A., Dunkel, K.G., Incel, S., Aupart, C., Austrheim, H., Corfu, F., Menegon, L., and Renard, F., 2019, *Earthquakes and fluid-induced metamorphism of stressed lithosphere.* Journal of Geophys. Research (Feature article), 124, 7725-7755.

Petley-Ragan, A., Ben-Zion, Y., Renard, F., Austrheim, H., Ildefonse, B., and Jamtveit,B., 2019, *Dynamic earthquake rupture in the lower crust.* Science Advances, 5, eaaw0913

Zheng, X., Cordonnier, B., McBeck, Jamtveit, B., Zhu, W., and Renard, F., 2019, *Mixed-mode strain localization generated by hydration reaction at crustal condition.* Journal of Geophys. Research, 124, 4507-4522.

Zhong, X., Andersen, N.H., Dabrowski, M., and J amtveit, B., 2019, *Zircon and quartz inclusions in garnet used for complementary Raman-thermobarometry: application to the Holsnøy eclogite, Bergen arcs, Western Norway.* Contrib. Mineralogy & Petrology, 174, doi: 10.1007/s00410-019-1584-4

Funding:
The Research Council of Norway

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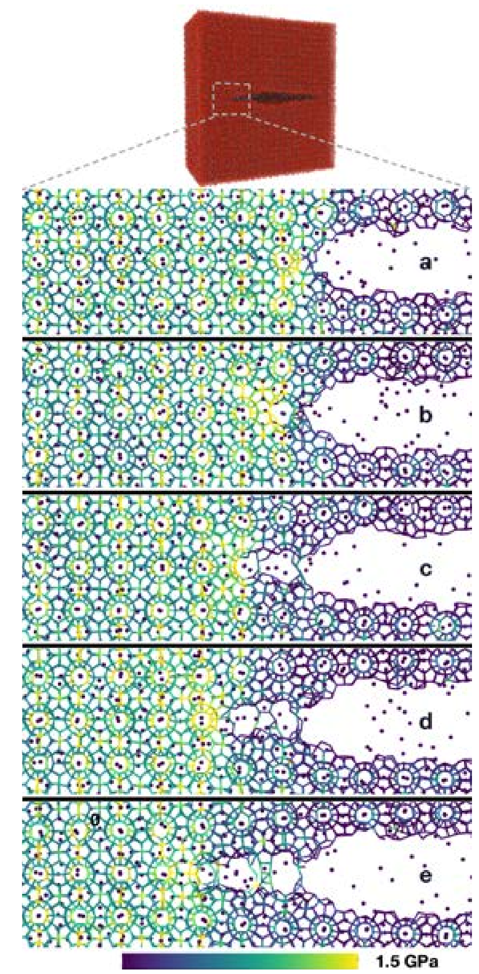
Thermally activated fractures in methane hydrates



Gas hydrates are ice-like crystalline substances where a lattice of water molecules form cages that trap individual gas molecules. Gas hydrates form at high pressure and moderate temperature conditions when a hydrate-forming gas comes in contact with water, which is the case under the seabed on continental slopes, and under the arctic tundra. Therefore, vast amounts of hydrates are stored in nature, in the form of gas hydrate bearing sediments, with methane being the most common hydrate forming gas. Gas hydrates make up a significant part of the mechanical stability of such sediments, which makes the mechanical properties of pure hydrates important for permafrost and marine slope stability, and to assess associated risk scenarios such as underwater landslides and sediment collapse. Since methane hydrates contain large amounts of methane, they are both viewed as attractive as a possible future energy resource and a major risk to the climate system. Therefore, it is important to establish how methane hydrates respond to perturbations of stress and temperature. In this project, we have focused on fracture on the small scale.

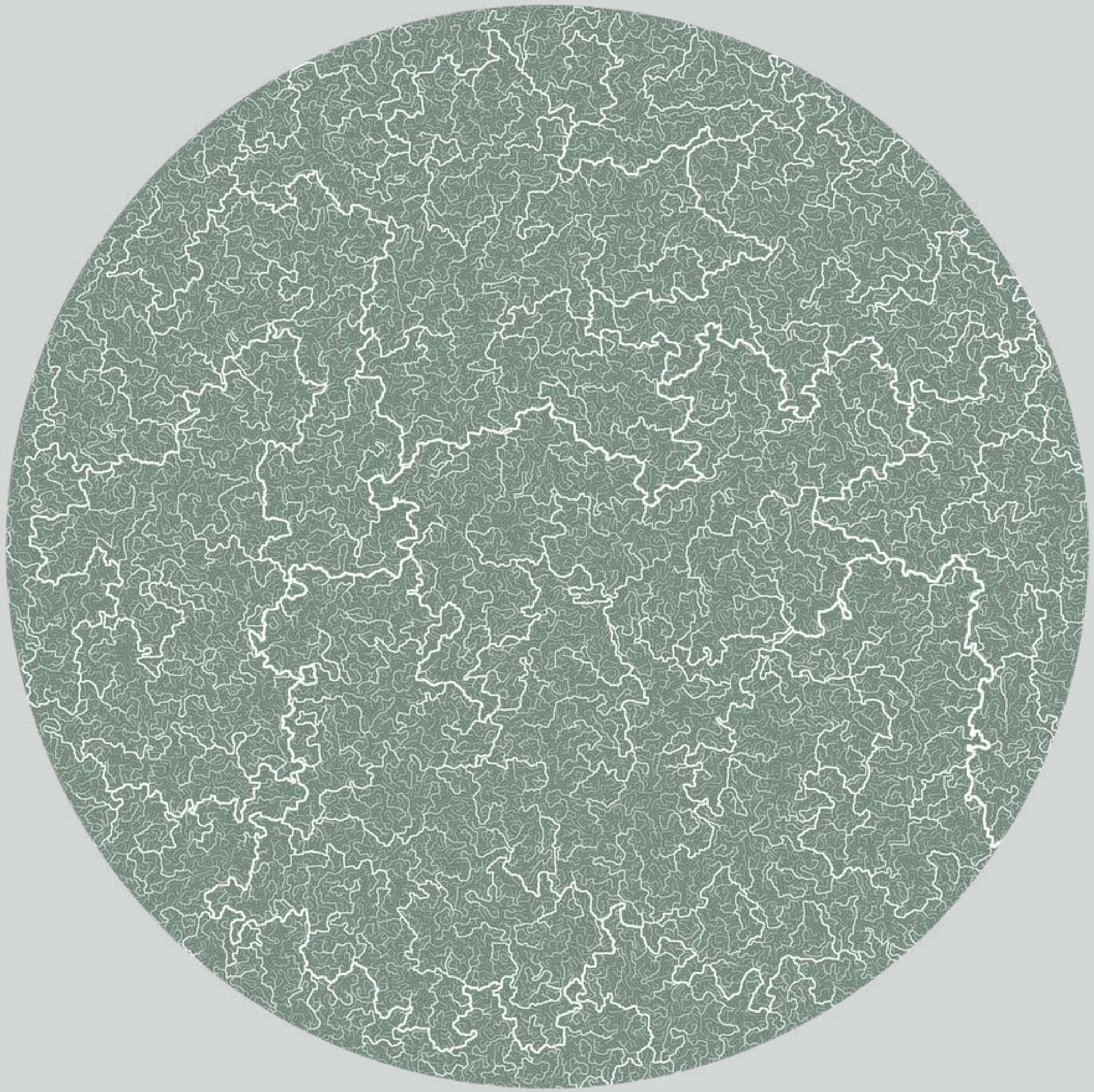
Fig. 1: Molecular mechanism during fracture along the (001) plane of monocrystalline methane hydrate. Colors indicate the viral stress normal to the crack plane. The crack propagates by building stresses on the cage scale of the hydrate, resulting in the opening of successive hydrate cages. There are no dislocations forming away from the crack tip, thus the fracture is brittle.

To investigate what processes may be present on the molecular scale, we ran molecular dynamics simulations where we subjected methane hydrates to tension. Molecular dynamics is in the unique position of both being able to produce a realistic stress field and explicitly including the fundamental mechanism of fracture: breaking of molecular bonds.

We strained our computer simulated systems to levels where they cracked, but sufficiently gently for the onset of fracture to be a bit delayed with respect to the applied strain. In that way, we can observe the relationship between how much we strained and how long it takes before the methane hydrate cracks. We find that the hydrate breaks cage by cage in a way that is quantitatively consistent with a thermal activation model.

Publications:

Sveinsson, H. A. & Malthe-Sørenssen, A. 2019. *Molecular-scale thermally activated fractures in methane hydrates: a molecular dynamics study.* Physical Chemistry Chemical Physics, 21, 13539–13544.



04

Appendices

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PhD and Postdoc projects

PhD projects

Candidate	Title/Topic	Supervisor
Aupart, Claire Olga Maryse	*Mechanochemical feedbacks during hydration of ultramafic rocks*	Bjørn Jamtveit, Håkon Austrheim, Anders Malthe-Sørenssen
Baldelli, Beatrice	*Gravity-stabilized flow on self-affine surfaces*	Eirik Grude Flekkøy, Knut Jørgen Måløy, Gaute Linga
Bouchayer, Coline Lili Mathy	*Modelling transient velocity variations in glaciers*	Thomas Schuler, François Renard, Kjetil Thøgersen, Andreas Kääb
Brodin, Joachim Falck	*Experimental studies on flow in porous media in 3D*	Knut Jørgen Måløy, Eirik Grude Flekkøy, Marcel Moura
Guren, Marthe Grønlie	*Nanoscale imaging and modelling of mineral surfaces during mechano-chemical transformations*	François Renard, Anja Røyne, Anders Malthe-Sørenssen
Johnson, James Ronald	*Microfractures in Organic Shales and their transport properties*	François Renard, Nazmul Mondol
Kandula, Neelima	*X-ray micro tomographic studies on the precursors to failure in rocks at conditions relevant for earthquake nucleation*	François Renard, Dag Kristian Dysthe, Jerome Weiss
Laberg Hejlesen, Zakarias	*Quantum turbulence and finite temperature effects in Bose-Einstein Condensates*	Luiza Angheluta, Joachim Bergli
Olsen, Kristian Stølevik	*Statistical physics for two-dimensional complex flow*	Knut Jørgen Måløy, Eirik Grude Flekkøy
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
Skogvoll, Vidar	*Multiple scales modelling of crystal plasticity*	Luiza Angheluta, François Renard, Luca Menegon
Thorens, Louison	*Tunable interactions inside deformable porous media*	Knut Jørgen Måløy, Mickaël Bourgoin, Eirik Grude Flekkøy, Stéphane Santucci

PhD and Postdoc projects

Finished PhDs in 2019

Candidate	Title/Topic	Supervisor
Ayaz, Monem	*Experimental and numerical investigation of cluster morphologies and dynamic during biphasic flow in porous media*	Renaud Toussaint, Gerhard Schafer, Knut Jørgen Måløy
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
Gløersen, Øyvind Nøstdahl	*On the bioenergetics of cross-country skiing*	Anders Malthe-Sørenssen, Dag Kristian Dysthe, Thomas Losnegard, Matthias Felix Gilgien
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
Li, Lei	*Nanoconfined calcite growth.*	Dag Kristian Dysthe, Anja Røyne
Petley-Ragan, Arianne Juliette	*The coupling between fluid driven metamorphism and tectonic stress.*	Bjørn Jamtveit, Håkon Austrheim
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
Xu, Le	*Experimental Observations of Dissolution in Fractures in Circular Geometry*	Knut Jørgen Måløy, Eirik Grude Flekkøy
Zheng, Xiaojiao	*Reaction-induced Fracturing in Confined Systems.*	Bjørn Jamtveit, Håkon Austrheim, François Renard

PhD and Postdoc projects

Postdoc projects

Fellow	Title/Topic	Supervisor
Barras, Fabian	*Modelling the interplay between earthquake rupture and fluid migration in the Earth's crust*	François Renard, Bjørn Jamtveit
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)*	François Renard
Cordonnier, Benoît	*Neutron imaging of pollutant flow within geological samples*	François Renard
Demurtas, Matteo	*Granular flow and mineral anisotropy*	Karen Mair
Dumazer, Guillaume	*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
Dziadkowiec, Joanna	*Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity*	Markus Valtiner, Anja Røyne, Dag Kristian Dysthe
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
Linga, Gaute	*Numerical modelling of the complexity of fluid flow in deforming porous media*	François Renard, Eirik Grude Flekkøy
McBeck, Jessica Ann	*Predicting strain localization and fault development with X-ray tomography deformation experiments, digital volume correlation, discrete element method modeling, and machine learning*	François Renard and 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, workshops and seminars

January 18th. **Giulio di Toro, University of Padova**. *"Pseudotachylytes: promise a lot, keep little!"*.

February 8th. **Danny Caballero, Michigan State University**. *"The integration of numerical computation in physics education"*.

February 13th. **Fabian Barras, Ecole Polytechnique Fédérale de Lausanne (EPFL)**. *"Onset of sliding along frictional interfaces: From microcontacts rejuvenation to the energetics of earthquake rupture"*.

February 15th. **Luiz Morales, Department of Earth Sciences, ETH Zürich**. *"Interphase boundary misorientation in serpentinized mantle rocks"*.

March 20th. **Patrick Huber, Hamburg University of Technology**, *"Soft Matter in Nanoporous Media: From Nanoscale Physics to Metamaterials' Science"*.

June 5-7th. *The 2019 Njord seminar: "Earthquakes in the Lower Crust"*. **Organizer: Bjørn Jamtveit.** Location: Alver Hotel & Holsnøy, Norway.

June 17th. **Ian Bourg, Princeton University.** *"Clay, water, and salt: Controls on the hydrology and mechanics of fine-grained soils and sedimentary rocks"*.

June 19-20th. *EarthFlows meeting 2019: "Complexity in Solid Earth and Geophysical Flows"*. **Organizer: Luiza Angheluta and Bjørn Jamtveit.**

June 25-28th. *Workshop: "Complexity in Solid Earth Flows"*. **Organizer: François Renard.** Location: Blesle, France.

August 23rd. **Einat Aharonov, the Fredy & Nadine Institute of Earth Sciences, The Hebrew University of Jerusalem.** *"Understanding the physics of liquefaction from a coupled grain fluid model"*.

August 20th. **Benoît Coasne, Laboratoire Interdisciplinaire de Physique, University Grenoble Alpes.** *"Adsorption and Transport in Multiscale Porous Materials"*.
September 5th. *Whole day workshop: "Oman"*. **Organizer: Bjørn Jamtveit.**

September 10th. **David Grégoire, Laboratory of Complex Fluids and Their Reservoirs, Université de Pau et des Pays de l'Adour.** *"Multiphysics couplings appearing in micro-to-macro porous media encompassing damage, transport and adsorption-induced strain"*.

September 13th. **Björn Birnir, Centre for Complex and Nonlinear Science, UCSB.** *"The Timing of Global Change"*.

October 15th. **Aagje Eijsink, MARUM Research Faculty, Universität Bremen.** *"Frictional behavior at plate rate and its relationship with fault surface roughness"*.

October 17th. **Quirine Eibhilin Krol, Eidgenössische Technische Hochschule Zürich.** *"Evolution of snow microstructure"*.

November 1st. *Njord poster session.*

November 5th. **David Wallis, Department of Earth Sciences, Utrecht University.** *"Dislocations and their stress fields measured by HR-EBSD: A new model for transient creep of olivine"*.

November 25-29th. *LASI VI workshop: "The physical geology of subvolcanic systems: laccoliths, sills and dykes"*. **Organizer: Olivier Galland. Location: Malargüe, Mendoza Province, Argentina.**

November 29th. *Prometheus workshop.* **Organizer: François Renard.**

December 6th. *EarthFlows Winter seminar.* **Organizer: Luiza Angheluta.**

December 9-10th. *BioZEment 2.0 project workshop.* **Organizer: Anja Røyne.**

Production list 2019:

Publications

1. Adamuszek M., **Dabrowski M.** 2019. *Sinking of a fragmented anhydrite layer in rock salt*, Tectonophysics, 766: 40-59

2. Aslan, G., Lasserre, C., Cakir, Z., Ergintav, S., Cetin, S., Dogan, U., Bilham, R., and **Renard, F.** 2019. *Shallow creep along the 1999 Izmit earthquake rupture (Turkey) from GPS and high temporal resolution interferometric synthetic-aperture radar data (2011–2017)*, Journal of Geophysical Research, doi: 10.1029/2018JB017022. Editor Highlight in Eos.org

3. Aslan, G., Cakir, Z., Lasserre, C., and **Renard, F.** 2019. *Investigating Subsidence in the Bursa Plain, Turkey, Using Ascending and Descending Sentinel-1 Satellite Data, Remote Sensing*, 11(1), 85, doi: 10.3390/rs11010085.

4. Burchardt, S., Mattson, T., Palma, J. O., **Galland, O.**, Almqvist, B., **Mair, K.**, Jerram, D., Hammer, Ø., Sun, Y. 2019. *Progressive growth of the Cerro Bayo cryptodome, Chachahuén volcano, Argentina – implications for viscous magma emplacement.* Journal of Geophysical Research-Solid Earth, 124, doi: 10.1029/2019JB017543.pdf

5. Campbell, L.R., **Menegon, L.** 2019. *Transient high strain rate during localised viscous creep in the dry lower continental crust (Lofoten, Norway).* Journal of Geophysical Research – Solid Earth, 124, doi: 10.1029/2019JB018052.

6. Cochard, A., Lengliné, O., **Måløy, K.J.**, **Toussaint, R.** 2019. *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, 377 (2136), art. no. 20170399, doi: 10.1098/rsta.2017.0399

7. **Cordonnier, B.**, Pluymakers, A., Tengattini, A., Marti, S., Kaestner, A., Fusseis, F., **Renard, F.** 2019. *Neutron imaging of cadmium sorption and transport in porous rocks*, Frontiers in Earth Sciences, doi: 10.3389/feart.2019.00306.

8. **Dabrowski, M.**, Grasemann, B. 2019. *Numerical modelling of boudinage under pure shear: implications for estimating viscosity ratios and finite strain from natural examples*, Journal of Structural Geology 126: 109-128

9. **Demurtas, M.**, Smith, S.A.F., Prior, D.J., Spagnuolo, E., Di Toro, G. 2019. *Development of crystallographic preferred orientation during cataclasis in low-temperature carbonate fault gouge.* Journal of Structural Geology 126, 37–50, doi: 10.1016/j.jsg.2019.04.015

10. **Demurtas, M.**, Smith, S.A.F., Prior, D.J., Brenker, F.E., Di Toro, G. 2019. *Grain size sensitive creep during simulated seismic slip in nanogranular fault gouges: constraints from Transmission Kikuchi Diffraction (TKD)*, Journal of Geophysical Research: Solid Earth. Doi: 10.1029/2019JB018071

11. **De Ruiter, L.**, Putnis, C.V., Hövelmann, J., King, H. and **Austrheim, H.** 2019. *Direct observations of the coupling between quartz dissolution and Mg-silicate formation.* ACS Earth and Space Chemistry. 3, 617-625

12. **Dziadkowiec, J.**, Zareeipolgardani, B., **Dysthe, D.K.**, **& Røyne, A.** 2019. *Nucleation in confinement generates long-range repulsion between rough calcite surfaces.* Scientific Reports. ISSN 2045-2322. 9. doi: 10.1038/s41598-019-45163-6

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Papers accepted or under review:
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1. **Barras, F.**, Aghababaei, R., and Molinari, J-F. Under review 2019. *Onset of sliding across scales: How the contact topography impacts frictional strength.* Submitted to Physical Review Letters on October 17.

2. **Bertelsen, H.S., Guldstrand, F., Galland, O.**, Sigmundsson, F., Pedersen, R., **Mair K.** Under review 2019. *Beyond elasticity: Are Coulomb properties of the Earth's crust important for volcano geodesy?* Submitted to Journal of Volcanology and Geothermal Research.

3. Campbell, L.R., **Menegon, L.**, Fagereng, Å., Pennacchioni, G. Under review 2019. *Earthquake nucleation in the lower crust by local stress amplification.* Nature Communications.

4. Di Chiara, A., Morris, A., Anderson, M.W., **Menegon, L.**, Tremblay, A. Under review 2019. *Magnetic anisotropy reveals Acadian transpressional fabrics in an Appalachian ophiolite (Thetford Mines, Canada).* Geophysical Journal International.

5. **Dumazer, G.**, Sandnes, B., **Måløy, K.J.**, and **Flekkøy, E.G.** Under review 2019. *Capillary bulldozing of sedimented granular material confined in a millifluidic tube.* Submitted to Physical Review Fluids.

6. Giuntoli, F., **Menegon, L.**, Warren, C.J., Darling, J., Anderson, M. Under review 2019. *Protracted shearing at mid crustal conditions during large-scale thrusting in the Scandinavian Caledonides*. Tectonics.

7. Graziani, R., Monomoli, C., Iaccarino, S., **Menegon, L.**, Nania, L., Carosi, R. Under review 2019. *Structural setting of a transpressive shear zone: insights from geological mapping, quartz petrofabric and kinematic vorticity analysis in NE Sardinia (Italy).* Geological Magazine

8. **Guren, M.G.**, Putnis, C.V., Montes-Hernandez, G., King, H., **Renard, F.** Under review 2019. *Direct imaging of coupled dissolution-precipitation and growth processes on calcite exposed to chromium-rich fluids.* Submitted to Chemical Geology.

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11. **McBeck, J.**, Ben-Zion, Y., **Renard, F.** Under review 2019. *The mixology of precursory strain partitioning approaching brittle failure in rocks*, Geophysical Journal International.

12. **McBeck, J.**, Cooke, M., **Renard, F.** Under review 2019. *How the energy budget scales from the laboratory to the crust in accretionary wedges*, Earth and Planetary Science.

13. Montes-Hernandez, G., **Renard, F.**, Auzende, A.-L., Findling, N. Under review 2019. *Amorphous calcium-magnesium carbonate (ACMC) accelerates dolomitization at room temperature under abiotic conditions*, Crystal Growth and Design.

14. Nielsen, B.F., **Linga, G.**, Christensen, A., and **Mathiesen, J.** Under review 2019. *Substrate curvature governs texture orientation in thin films of smectic block copolymers.* Submitted to Soft Matter.

15. Papa, S., Pennacchioni, G., **Menegon, L.**, Thielmann, M. Under review 2019. *High-stress creep preceding coseismic rupturing in amphibolite-facies ultramylonites.* Earth and Planetary Science Letters.

16. Pierdominici, S., Kück, J., Millet, J., Thomas, D. Jerram, D., Planke, S., Haskins, E. Lautze, N., **Galland, O.** Under review 2019. *Stress field interactions between large overlapping shield volcanoes: borehole breakout evidence from the Big Island of Hawaii, USA.* Journal of Geophysical Research – Solid Earth.

17. Poppe, S., **Galland, O.**, de Winter, N., Goderis, S., Claeys, P., Debaille, V., Boulvais, P., Kervyn, M. Under review 2019. *Structural and geochemical interactions between magma and sedimentary host rock: the Hovedøya case, Oslo Rift, Norway.* Geochemistry, Geophysics, Geosystems.

18. Prando, F., **Menegon, L.**, Anderson, M.W., Marchesini, B., Mattila, J., Viola, G. Under review 2019. *Fluid-mediated, brittle ductile deformation at seismogenic depth – Part 2: Stress history and fluid pressure variations in a shear zone in a nuclear waste repository (Olkiluoto Island, Finland).* Solid Earth.

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20. Sleveland, A., Midtkandal, I., **Galland, O.**, Leanza, H.E. In revision 2019. *Sedimentary architecture of mixed-process mouth bar complexes in the Mulichinco Formation, Neuquén Basin, Argentina.* Frontiers in Earth Sciences: Stratigraphy, sedimentology and diagenesis.

21. Spacapan, J.B., D'Odorico, A., Palma, O., Leanza, H.A., Rojas Vera E., Rocha, E., Ruiz, R., **Galland, O.**, Medialdea, A. In revision 2019. *Chapter 21 – Los Cavaos oil field, an example of Igneous Petroleum System.* Vaca Muerta AAPG Memoir

22. **Zhong, X.**, Moulas, E., Tajčmanova, L. Under review and published for open discussion in 2019. *The relaxation of residual inclusion pressure and implications to Raman-thermobarometry.* Solid Earth (SE).

Invited talks:
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1. Dysthe, D.K. 2019. *Crystal growth in nanoconfinement.* SIMAP, February 12.

2. Dysthe, D.K. 2019. *Molecular layer resolution of crystal growth in nanoconfinement.* Institut Lumiere Matiere, October 11.

3. Dysthe, D.K. 2019. *Simultaneous measurement of intracellular actin dynamics and strain field of the extracellular matrix.* Dysco, March 18-19.

4. Dysthe, D.K. 2019. *Crystal growth in nanoconfinement.* Liphy, May 23.

5. Dziadkowiec, J., Zareeipolgardani, B., Bratvold, J.E., Nilsen, O., Dysthe, D.K., Røyne, A. 2019. *Long-range repulsive forces between reactive calcite surfaces are generated due to nucleation in a confined solution. Cecam Wokshop: Current Challenges in transport, growth and dissolution at mineral-fluid interfaces.* Lyon, France. April 3-5

6. Flekkøy, E.G. 2019. *Anomalous diffusion in labyrinthine structures. Patterns in geomechanics conference*, Sydney. February 2019.

7. Flekkøy, E.G. 2019. *Anomalous diffusion in labyrinthine structures.* US Department seminar, Lawrence Berkley labs, January.

8. Flekkøy, E.G. 2019. *River networks and labyrinths.* IS Rothman Group seminar, MIT. January.

9. Guldstrand, F. 2019. *Viscous Laboratory Dykes and the Associated Quasi-2D Deformation due to Intrusion, Propagation and Emplacement in Cohesive Mohr-Coulomb Hosts.* Uppsala University. April 8-12.

10. Guldstrand, F., Galland, O., Mair, K. 2019. *Learning by doing in the laboratory.* Workshop at iEarth geolearning forum.

11. Jamtveit, B. 2019. *Dynamic Earthquake rupture in strong lower crust.* AGU Fall meeting, San Francisco, December 11.

12. Jamtveit, B. et al. 2019. *High-P metamorphism caused by fluid induced weakening of deep continental crust.* AGU Fall meeting, San Francisco, December 13.

13. Linga, G. 2019. *Influence of roughness, inertia and surface charge on fluid transport in fractures and pores: Insights from direct numerical simulations.* InterPore Norwegian chapter, 3rd National Workshop on Porous Media, Stavanger, October 16.

14. McBeck, J., Aiken, J. M., Ben-Zion Y., Cordonnier, B., Renard, F. 2019. *Predicting the distance to system-scale failure throughout dynamic in situ X-ray tomography experiments,* AGU Fall Meeting 2019.

15. McBeck, J., Cordonnier, B., Mair, K., Renard, F. 2019. Oral. *In situ dynamic X-ray microtomography reveals the evolving energy budget of faults within continental crust*, EGU General Assembly Conference Abstracts, 5058.

16. Menegon, L. 2019. *Mylonitised pseudotachylytes: a record of postseismic creep in the lower crust?* The 2019 Njord seminar at Holsnøy, Norway, June 5-6.

17. Menegon, L. 2019. *The geological record of the earthquake cycle in the lower crust.* University of Milan-Bicocca, Italy, January.

18. Menegon, L. 2019. AGU Fall Meeting, session: *Ductile deformation in the middle and lower crust*: Integrating experimental and geologic observations to constrain crustal rheology, talk: *Brittle-viscous deformation and the earthquake cycle in the lower crust.* December.

19. Menegon, L. 2019. EGU Summer School. *Structural Analysis of Crystalline Rocks, From deformation mechanisms and microstructures to shear zone rheology, Brittle-ductile deformation cycles in the dry lower crust and in the wet middle crust.*

20. Moura, M., Måløy, K.J., Flekkøy, E.G., Schäfer G., and Toussaint, R. 2019. *Unconventional transport mechanisms in porous media: connectivity enhancement due to thin film flow",* InterPore 11th International Conference on Porous Media & Annual Meeting, Valencia, Spain.

21. Moura, M., Måløy, K.J., Flekkøy, E.G., Schäfer, G., and Toussaint, R. 2019. *Unconventional transport mechanisms in porous media: connectivity enhancement due to thin film flow*, Nordforsk School on Computational Mathematical Modeling, Geilo, Norway.

22. Måløy, K.J, Eriksen, J.A., Toussaint, R., Flekkøy, E.G., Galland, O., Sandnes, B. 2019. *Pattern formation of frictional fingers in a gravitational field* APS meeting Boston, USA, March 7.

23. Måløy, K.J., Eriksen, J.A., Toussaint, R., Flekkøy, E.G., Galland, O., Sandnes, B. 2019. *Pattern formation of frictional fingers in a gravitational potential",* In Patterns in Geomechanics, Sydney Australia, January 30.

24. Renard, F. 2019. Invited keynote lecture. *Dynamics of microfracture precursors during the nucleation of faulting in rocks*, GeoProc2019, The 7th International Conference on Coupled THMC Processes. Utrecht, the Netherlands. July 3-5.

25. Renard, F. 2019. Invited keynote lecture. *Imaging the precursors to rupture in rocks and their role in failure nucleation,* CECAM workshop. Modeling tribology: friction and fracture across scales". Lausanne, Switzerland. January 28-30.

26. Renard, F. 2019. *Advanced 4D imaging of geological processes using synchrotron and neutron microtomography.* NTNU, Trondheim, Norway. October.

27. Renard, F. 2019. *Evolution of precursors when approaching failure in rocks, Conference Avalanche Dynamics and Precursors of Catastrophic Events.* Les Houches, France. February 4-8.

28. Rikvold, P.A., Gurfinkel, A. 2019. *Interpolating between centrality measures on complex networks using absorbing Markov chains.* Aalto Univeristy Complexity Summer Camp. Aalto University, Otaniemi, Finland. July 31.

29. Toussaint, R., Ben Zeev, S., Clément, C., Aharonov, E., Goren L., and Parez, S. 2019. *Physics of liquefaction during earthquakes.* University of Tokyo, Japan.

30. Toussaint, R., Ben Zeev, S., Clément, C., Aharonov, E., Goren L., and Parez, S. 2019. *Physics of liquefaction: impact of viscous forces.* University of Okayama, Japan.

Other talks:

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1. Angheluta, L. 2019. *How different are superfluid flows from classical flows?"* Fysikk i Origo, UiO, May 9.

2. Angheluta, L. 2019. *How different are superfluid flows from classical flows?"* Institute of Marine Research, Bergen, May 7.

3. Angheluta, L. 2019. *Hurricanes in stirred Bose Einstein condensates.* School of Computational Mathematical Modelling, March 25-29, Geilo.

4. Aupart, C., Schlindwein, V., Ben-Zion, Y., Renard, F., Jamtveit, B. 2019. *Earthquake-controlled serpentinization at ultraslow spreading ridges.* The Njord Seminar, Holsnøy. June 6.

5. Barras, F. and Brantut, N. 2019. *Earthquake Rupture Driven by Shear Localisation within the Fault Gouge.* AGU Fall meeting, San Francisco. December 12.

6. Baud, P., Huang, L., Cordonnier, B., Renard, F., Liu, L., Wong, F.-F. 2019. Talk. *Compaction localization in porous limestone studied by 4D synchrotron X-ray imaging,* EGU General Assembly Conference Abstracts, 4265.

7. Bouchayer, C.L.M. 2019. *A year on ice.* GeoHyd Lunch Seminar. November 1.

8. Bouchayer, C.L.M. 2019. *Modeling transient velocity variations in glaciers.* EarthFlows winter meeting. December 6.

9. Campbell, J. 2019. *Ice growth in Pores.* Conference InterPore UK. September 3.

10. Demurtas, M., Mair, K., Abe, S., 2019. *Fracturing and force chain evolution during granular flow in bimaterial gouges*, EarthFlows workshop, Oslo. June 19-20.

11. Dunkel, K.G., Morales, L.F.G., Jamtveit, B.: *Wall-rock damage and alteration in orthogneisses from Lofoten as revealed by CL imaging, EBSD, and TEM analyses.* Talk at the GeoMünster 2019 (the Annual Conference of the German Geological Society and the German Mineralogical Society). Münster, Germany. September 22-25.

12. Dunkel, K.G., Renard, F., Valen, L.V., Jamtveit, B. 2019. *Earthquakes in the lower continental crust.* Talk at the EarthFLows seminar. June 6.

13. Dunkel, K.G., Valen, L.V., Renard, F., Jamtveit, B. 2019. *Microstructures of dry pseudotahylytes from Lofoten, Norway."* The Njord Seminar, Holsnøy. June 6.

14. Dysthe, D.K. 2019. *Atomic scale view of crystallization in confinement Nucleation, step flow and transport limitation. Current Challenges in transport, growth and dissolution at mineral-fluid interfaces,* April 3-5.

15. Dysthe, D.K. 2019. *Calcium carbonate (re-) crystallization questions. Current Challenges in transport, growth and dissolution at mineral-fluid interfaces,* April 3-5.

16. Dysthe, D.K. 2019. *Molecular layer resolution of crystal growth in nanoconfinement.* Fysikermøtet, August 7-9.

17. Dysthe, D.K. 2019. *Simultaneous measurement of intracellular actin dynamics and strain field of the extracellular matrix.* TOPIM. January 13-18.

18. Dziadkowiec J. (CaCO3) *Nucleation in confinement.* Joint seminar of CEST (Austrian competence centre for electrochemical surface technology) and Applied Interface Physics Group TU Vienna; Vienna, Austria. September 21.

19. Eriksen, F. 2019. *Impact of gravity on pore-scale steady-state flow patterns,* SK70 workshop, Trondheim, August.

20. Eriksen, F. 2019. *Steady-state two-phase flow in porous media,* Geilo winter school on Computational Mathematical Modeling, Geilo. March.

21. Fondriest, M., Bistacchi, A., Demurtas, M., Balsamo, F., Storti, F., Valoroso, L., Di Toro, G., 2019. *Three-dimensional anatomy of an active seismic source: kinematic complexity and structural inheritance constrained by field observations and present-day seismic activity (Central Apennines, Italy),* CRUST workshop, Perugia. July.

22. Galland, O., de la Cal, H., and Rabbel, O. 2019. *Laccolith-induced deformation – A case study integrating field mapping, 3D seismic and well data at Pampa Amarilla, Neuquén Basin, Argentina.* LASI6 conference, Malargüe, Argentina. November.

23. Guren, M.G., Zheng, X., Jamtveit, B., Hafreager, A., Sveinsson, H., Malthe-Sørenssen, A., Renard, F. *Molecular dynamics simulations of the hydration force and transport properties of a water film during reaction-induced fracturing.* Goldschmidt. August 19-23.

24. Incel, S., Schubnel, A., John, T., Labrousse, L., Hilairet, N., Freeman, H., Wang, Y., Renard, F., Jamtveit, B. 2019. Talk. *Experimental evidence for wall rock pulverization during dynamic rupture at ultra-high pressure conditions,* EGU General Assembly Conference Abstracts, 3897.

25. Jamtveit, B. et al. 2019. *High-P metamorphism caused by fluid induced weakening of deep continental crust.* EGU Vienna. April 10.

26. Johnson, J., Hansen, J., Renard, F., Mondol, N. 2019. *Geomechanical Analysis of Maturation for the Draupne Shale, Offshore Norway,* Sixth EAGE Shale Workshop, doi: 10.3997/2214-4609.201900272.

27. Johnson, J., Hansen, J., Renard, F., Mondol, N. 2019. *Modeling maturation, elastic, and geomechanical properties of the Draupne Formation, offshore Norway,* SEG Technical Program Expanded Abstracts 2019, doi: 10.1190/segam2019-3215340.1.

28. Kjøll, H.J., Andersen, T.B., Galland, O., Corfu, F., Labrousse, L., Tegner, C., Planke, S. 2019. *Deep section of a Neoproterozoic fossil magma rich rifted margin exposed.* EGU General Assembly 2019, April 7-12.

29. Kjøll, H.J., Andersen, T.B., Labrousse, L., Galland, O. 2019. *From rift to drift – Construction of the magma-rich pre-Caledonian Iapetus margin of Baltica.* GSA annual meeting 32019. September 22-25.

30. Kjøll, H.J., Galland, O., Labrousse, L., Andersen, T.B. 2019. *Dyke emplacement mechanisms across the brittle-ductile transition.* Norwegian Geological Society Wintermeeting. January 7-9.

31. Linga, G. 2019. *Two-phase electrohydrodynamics in complex geometries – modelling and simulation.* InterPore2019 Valencia. May 6-10.

32. McBeck, J., Kandula, N. Aiken, J., Renard, F. 2019. *Predicting fracture growth with machine learning.* Earthflows Workshop, Oslo, Norway. June 19-20.

33. Menegon, L., Fagereng, Å, 2019. *Viscous creep drives brittle failure at the base of the seismogenic zone.* Oral presentation at the EGU General Assembly2019, Vienna. April 7-12.

34. Olsen, K. 2019. *Thermodynamics of state-dependent diffusion,* EarthFlows meeting 2019, Complexity in Solid Earth and Geophysical Flows. June 19-20.

35. Petley-Ragan, A., Ben-Zion, Y., Austrheim, H., Ildefonse, B., Renard, F. and Jamtveit, B. 2019. *Dynamic earthquake rupture in the lower crust.* The Njord Seminar: Earthquakes in the Lower Crust. June 5-7.

36. Petley-Ragan, A., Ben-Zion, Y., Renard, F., Austrheim, H. and Jamtveit, B.* 2019. *Dynamic earthquake rupture in the lower crust.* EGU Conference 2019.

37. Petley-Ragan, A., Ben-Zion, Y., Renard, F., Austrheim, H., Jamtveit, B. 2019. Talk. *Dynamic earthquake rupture in the lower crust,* EGU General Assembly Conference Abstracts, 3304.

38. Petley-Ragan, A., Jamtveit, B., et al 2019. *Dynamic Earthquake rupture in strong lower crust.* EGU Vienna. April 8.

39. Rabbel O., Galland O., Palma, O., Spacapan, J.B., Senger, K. Lecomte, I., and Mair, K. 2019. *From field observations to seismic modeling: The El Manzano Sill Complex (Argentina) as a showcase of the influence of igneous intrusions on petroleum systems.* LASI6 conference, Malargüe, Argentina. December.

40. Razbani, M.A., Zehner, J.S., Jettestuen, E., Røyne, A., Sikorski, P., Malthe-Sørenssen, A. 2019. *A pore-scale model of microbially induced calcium carbonate precipitation.* InterPore2019. May 6-10.

41. Renard, F. 2019. Talk. *Extracting damage within fault zones from 3D X-ray microtomography data.* 2nd Machine Learning in Solid Earth Geoscience conference. Santa Fe, New Mexico, USA. March 18-22, 2019

42. Renard, F., Zheng, X., Cordonnier, B., McBeck, J., Jamtveit, B., Zhu, W. (2019). Poster. *Mixed-mode strain localization generated by hydration reaction at crustal conditions*, EGU General Assembly Conference Abstracts, 3310.

43. Rikvold, P.A., Gurfinkel, A. 2019. *Random-walk based interpolations between centrality measures on complex networks"* NORDITA-EPS conference on Statistical Physics of Complex Systems.

44. NORDITA, University of Stockholm, Sweden. May 10.

45. Senger K., Betlem P., Rabbel O., Galland O. and Lecomte I. 2019. *Early Cretaceous igneous intrusions in Svalbard: seismic modelling as a link between boreholes, outcrops and seismic data.* LASI6 conference, Malargüe, Argentina. December.

46. Skogvoll, V. 2019. *Modelling microplasticity with the Phase-Field Crystal.* EarthFlows Winter Seminar, December 6.

47. Sleveland, A., Midtkandal, I., Galland, O., Leanza, H.A. 2019. *Compensational stacking and architecture of mouth-bar deposits in a mixed-process deltaic environment; Mulichinco Formation, Neuquén Basin, Argentina.* AAPG ACE 2019. May 20-22.

48. Sleveland, A., Midtkandal, I., Galland, O., Leanza, H.A. 2019. *Sedimentary architecture of mixed-process mouth bar deposits in the Mulichinco Formation, Neuquén Basin, Argentina.* 34th International Meeting of Sedimentology; September 10-13.

49. Szczepański J., Zhong X., Dąbrowski M., Goleń M., Wang H. 2019. *Petrology of high pressure metapelite from the Kamieniec Metamorphic Belt (Sudetes, NE Bohemian Massif): combined Raman spectroscopy of quartz inclusions in garnet and PT pseudosections approach.* EGU General Assembly Conference, Vienna. April.

50. Sørdal, V. 2019. *Deep Reinforcement learning for quantum optimization.* The Njord Centre. April 11.

51. Thøgersen, K. 2019. *Rate-and-state friction elucidates glacier-flow instabilities.* 50 years anniversary seminar for Anders Malthe-Sørenssen

52. Thøgersen, K. 2019. *Rate-and-state friction elucidates glacier-flow instabilities. GeoHyd lunch seminar*, Department of Geosciences.

53. Thøgersen, K. 2019. *Seismic moment and earthquake duration. What can we learn from simple models?"* The 2019 Njord seminar at Holsnøy, Norway. June 5-6.

54. Toussaint, R. 2019. *Hot cracks or cool cracks? A model for the brittle-ductile transition of solids*, EGU General Assembly.

55. Van Stappen, J., McBeck, J., Cordonnier, B., Pijnenburg, R., Renard, F., Spiers, C., Hangx, S. 2019. *Understanding strain-accommodating processes in depleted sandstone gas reservoirs through in-situ triaxial testing and X-ray CT imaging*, EGU General Assembly Conference Abstracts, 13586.

56. Zhong X., Petley-Ragan A., Incel S., Dabrowski M., Austrheim H., Andersen N. Jamtveit, B. 2019. *Overpressure recorded in pseudotachylyte caused by frictional melting during earthquakes.* AGU Fall meeting, San Francisco. December 13.

57. Zhong, X., Dabrowski, M., Andersen N., Jamtveit, B. 2019. *Raman thermobarometry based on quartz and zircon inclusions in garnet host: application to Holsnøy eclogite, Bergen arc, Norway.* EGU General Assembly Conference, Vienna. April.

58. Zhong, X., Dabrowski, M., Andersen N., Jamtveit, B. 2019. *Raman thermobarometry based on quartz and zircon inclusions in garnet host: application to Holsnøy eclogite, Bergen arc, Norway.* SIMP, Parma, Italy.

Posters and PICOs:

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1. Arran, M., Mangeney, A., de Rosny, J., Farin, M., Toussaint, R. 2019. Poster. *High-frequency Seismic Signals from Landslides: Insight from Laboratory Flows and DEM Simulations*, AGU Fall Meeting 2019

2. Aslan, G., Lasserre, C., Cakir, Z., Ergintav, S., Ozarpaci, S., Dogan, U., Bilham, R., Renard, F. 2019. Poster. *Characterizing interseismic aseismic slip along the 1999 Izmit earthquake rupture (Turkey) from GPS, InSAR and creepmeter measurements*, EGU General Assembly Conference Abstracts, 5788.

3. Aspaas, A., Krautblatter, M., Renard, F., Etzelmüller, B. 2019. Poster. *Effects of glimmer rich rocks on the failure criterion of ice-filled permafrost rock joints*, EGU General Assembly Conference Abstracts, 14551.

4. Aupart, C., Dunkel, K., Morales, L., Godard, M., Jamtveit, B., The Oman Drilling Project Science Party. 2019. Poster. *Early cataclasis in serpentinites from the Oman ophiolite.* Njord Poster Session. November 1.

5. Aupart, C., Schlindwein, V., Ben-Zion, Y., Renard, F., the Oman Drilling Project Phase 2 Science Party, Jamtveit, B. 2019. Poster. *Fracture network and serpentinization at oceanic spreading ridges: in-situ observations and comparison with a fossilized system.* EGU General Assembly Conference Abstracts, 5292.

6. Bouchayer, C.L.M. 2019. Poster. *Past, present and future evolution of Mer de Glace glacier Mont-Blanc massif (France).* PhD Day, Mathematical and Natural Sciences Faculty, UiO. October 18.

7. Chauve, T., Scholtès, L., Donzé, F., Mondol, N. H., Renard, F. 2019. Poster. *Microfracture propagation in layered shale rocks during primary migration.* EGU General Assembly Conference Abstracts, 8126.

8. Dabrowski, M., and Grasemann, B. 2019. Poster. *Numerical modeling of torn boudinage under pure shear: implications for estimating viscosity ratios and finite strain from natural examples.* EGU General Assembly Conference.

9. Demurtas, M., Mair, K., Abe, S., 2019. Poster. *Does cleavage matter? Investigating the influence of cleavage planes during granular flow*, Tectonic Studies Group Annual Meeting, Bergen, Norway. January.

10. Demurtas, M., Mair, K., Abe, S. 2019. PICO presentation. *Granular flow and mineral anisotropy: exploring the influence of cleavage planes during brittle deformation using experiments and numerical models*, European Geosciences Union General Assembly, Conference Abstracts, v. 19, p. 18045, Vienna. April.

11. Dziadkowiec, J., Javadi, S., Røyne, A. 2019. *Contacts between reactive surfaces.* Fysikermøtet. August 7-9.

12. Fattaruso, L., Cooke, M. L., McBeck, J., Kandula, N., Renard, F. 2019. Poster. *How do strength anisotropy and heterogeneity control fracture propagation, and corresponding energy budgets and stress-strain evolution?* AGU Fall Meeting 2019.

13. Guldstrand, F., Bertelsen, H.S., Souche, A., Galland, O. & Zanella, A. 2019. Poster. *Intrusion of Viscous Magma in a Cohesive Crust – Visualized and Quantified from Quasi-2D Laboratory Experiments, LASI6 Malargüe Argentina.* November 25-29.

14. Guren, M.G., Putnis, C., Montes-Hernandez, G., Renard, F. *Atomic force microscopy imaging of coupled dissolution-precipitation on a calcite surface when exposed to a chromium-rich fluid.* EGU; April 8-12.

15. Guren, M.G., Zheng, X., Jamtveit, B., Hafreager, A., Sveinsson, H., Malthe-Sørenssen, A., Renard, F. *Molecular dynamics simulations of the hydration force and transport properties of a water film during reaction-induced fracturing.* Goldschmidt. August 19-23.

16. Guren, M.G., Zheng, X., Jamtveit, B., Hafreager, A., Sveinsson, H., Malthe-Sørenssen, A., Renard, F. *Molecular dynamics simulations of the hydration force and transport properties of a water film during reaction-induced fracturing.* MolSim-2019: Understanding Molecular Simulation. January 7-18.

17. Joudeh, N., Røyne, A., Mikheenko, P., Linke, D. *Bio-Engineered Palladium Nanoparticles (BEDPAN).* Digital Life Conference 2019. September 5-6.

18. Kariche, J., Meghraoui, M., Toussaint, R. 2019. Poster. *Stress transfer and poroelasticity associated to the 2019 Ridgecrest (California) earthquake sequences.* AGU Fall Meeting 2019.

19. McBeck, J., Cordonnier, B., Vinciguerra, S., & Renard, F. 2019. Poster. *Transient volumetric and shear strain localization in Etna basalt.* Poster presentation at 2019 Avalanche Dynamics and Precursors of Catastrophic Events, Les Houches, France.

20. McBeck, J., Kandula, N. Aiken, J., Renard, F. 2019. Poster. *Using machine learning to predict fracture growth.* The 2nd Annual Conference on Machine Learning, Santa Fe, NM, US.

21. McBeck, J., Mair, K., Renard, F. 2019. Poster. *The impact of porosity on the spatiotemporal localization of force chains and fractures.* 2019 Tectonic Studies Group Meeting, Bergen, Norway.

22. Renard, F., Cordonnier, B., McBeck, J. 2019. Poster. *Competition between creep and brittle deformation on mature faults: Insights from in situ dynamic X-ray microtomography*, AGU Fall Meeting.

23. Rikvold, P.A., Gurfinkel, A. 2019. *Random-walk based interpolations between centrality measures on complex networks. Biannual Meeting of The Norwegian Physical Society.* University of Oslo, Norway. 7-9 August, 2019. August 7.

24. Skogvoll, V. 2019. Poster. *The Phase-field Crystal.* PhD Day. October 18.

25. Thorens, L. 2019. Poster. *Taming the bulldozing instability during the drainage of a ferromagnetic frictional fluid.* InterPore Valencia 2019. May 6-10.

26. Zehner, J.S., Karlsen, E., Razbani, M.A., Jettestuen, E., Malthe-Sørensen, A., Wentzel, A., Sikorski, P., Almaas, E., Røyne, A. *The quest for bio-concrete: crossing disciplinary boundaries and wrangling bacteria to enable cleaner construction.* DigitalLife 2019. September 5-6

Outreach:

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1. Flekkøy, E.G. 2019. *SFF PoreLab, Instituttseminar Fysisk institutt*, November 18.

2. Guldstrand, F. 2019. *Visit from French School Oslo in lab during Spring 2019*

3. Guldstrand, F. 2019. *Visit from Wang School Oslo in lab during Spring 2019*

4. Jamtveit, B., Uhrenholdt-Jacobsen, A., og Wyller, T.B. 2019. *Opinion piece.* Foretaksproblemet. Klassekampen, February 18.

5. Røyne, A. 2019. *Fysikkshow for barn.* Fysikkshow. May 7.

6. Røyne, A. 2019. *Grunnstoffer: Verdens framtid og deg.* Foredrag. March 9.

7. Røyne, A. 2019. *Historien om verden og grunnstoffene på syv dager.* Naturfag 2019

8. Røyne, A. 2019. *Hva alt er laget av og hvor det kommer fra.* Programseminar for fysikkstudenter. March 9.

9. Røyne, A. 2019. *Hva er egentlig verden bygd opp av?* Lokallagssamling. March 23.

10. Røyne, A. 2019. *Jorda før livet.* Biokonferansen 2019. November 8.

11. Røyne, A. 2019. *Klima for dummies.* Oversetterseminaret 2019. November 10.

12. Røyne, A. 2019. *Mennesket grunnstoffer.* Vitenkafé: *God kjemi – for alle!* February 2.

13. Røyne, A. 2019. *Menneskets grunnstoffer.* Åpen dag ved UiO. March 7.

14. Røyne, A. 2019. *Menneskets grunnstoffer.* Foredrag; March 11, 13 and 15, April 4, 11 and 25, September 6, September 17, October 18.

15. Toussaint, R. 2019. *Exhibition at Science Fair "Fete de la Science 2019"*, Strasbourg, France, *about the history and mechanism of migration of hydrocarbons*. 3 days exhibition, October.

16. Toussaint, R. 2019. *Popular lecture: participation to conception and animation of "Escape80", an Escape Game for large audience about the history of Science in Alsace*. 2 days in October.

In media:

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1. Cook T. 2019. *Variations in creep along one of Earth's most active faults*, featuring in Eos.org the article Aslan et al., Journal of Geophysical Research.

2. Dunkel, K.G. 2019. *Mineralforvandlinger under lupen*. In geoforskning.no. December 11.

3. Flekkøy, E.G. 2019. *UiO-forskere kan ha påvist en hybelkanin i verdensrommet*. Titan.uio.no. October 18.

4. Flekkøy, E.G. 2019. *Det flyvende kjedet*. Fra Fysikkens Verden. 2/2019.

5. Flekkøy, E.G. 2019. *Hvorfor elefanter og skiløpere noen ganger kan høres så langt*. Fra Fysikkens Verden. 3/2019.

6. Flekkøy. E.G., Grøn, Ø.G. 2019. *Det interstellare objektet 'Oumuamua som en fraktal masseansamling*. Fra Fysikkens verden 4/2019.

7. Lynnebakken, H. 2018. *Interview with Marcel Moura on the flying chain, YouTube-hit om metallkjeder ble forskning på toppnivå*. Titan.uio.no. December 13.

8. Mair, K., Bertelsen, H.S., Guldstrand, F., Galland, O. Submitted 2019. *Learning by doing: Use of research-based methods and novel laboratory experiments in teaching Earthquake and Volcanic Processes*. EOS, American Geophysical Union, Opinion article.

9. Menegon, L. 2019. *Contribution to 'Pseudotachylyte'* directed by Heidi Morstang (University of Plymouth, UK). Premiere screening at the Norwegian Documentaries competition (Competition).

10. Moura, M. 2019. Radio. *Clean-up operation of the Brazilian beaches affected by the 2019 oil spill: how scientific knowledge derived from previous environmental disasters can help in defining a plan of action"* Special guest at The Brazilian Radio "Cultura" on the topic of oil spills. October 29.

11. Panahi, H., Meakin, P., and Renard, F. 2019. *Fluid expulsion and microfracturing during the pyrolysis of an organic rich shale*. Advances in Engineering.

12. Renard, F., Røyne, A., Putnis, C. V. 2019. *Boundary layer control on mineral reactivity in soils and rocks*. Science Trends.

13. Røyne, A. 2019. *Ekko: Abels Tårn*. NRK P2 [Radio]. September 13.

14. Røyne, A., Einevoll, G. 2019. *Vett og vitenskap: Om grunnstoffer*. Podcast [Internet]. November 17.

15. Røyne, A., Torgersen, E., Tarjem, G. 2019. *Ekko – Grunnstoffer 3:6 titan kan gjøre oss til kyborger*. NRK P2 [Radio]. January 14.

16. Røyne, A., Torgersen, E., Tarjem, G. *Ekko – Grunnstoffer 4:6 Aluminium kan forandre verden*. NRK P2 [Radio]. January 21.

17. Røyne, A., Torgersen, E., Tarjem, G. *Ekko – Grunnstoffer 5:6 Det livsviktige fosforet*. NRK P2 [Radio]. February 28.

18. Skaugen, A. 2019. *Hva har krystaller og superfluider til felles?"* Titan.uio.no, August 29.

19. Thøgersen, K., and Malthe-Sørenssen, A. 2019. *Nå er isbreene fravristet noen av sine dypeste hemmeligheter*. titan.uio.no/Teknisk ukeblad. July 29.

20. Toussaint, R., Flekkøy, E.G., and Luu, J. 2019. *Des scientifiques ont-ils détecté un mouton dans l'espace?*, INSU-CNRS.

21. Toussaint, R., Flekkøy, E.G., and Luu, J. 2019. *Et maintenant… les moutons* dans l'espace! …* (de poussière)*, News of Earth Science Department in Strasbourg.

22. Turquet, A. 2019. *Location Estimation Of Air/Fluid Pressure-Induced Microseismic Events*. Science Trends. October 10.

23. Vollsnes, A.V, Røyne, A., Leira, T., Torgersen, E. 2019. *Regnskogene er ikke jordas lunger – så hvor kommer oksygenet vi puster fra?*. titan.uio.no [Tidsskrift] August 30.

Project portfolio

Project leader	Project title	Host	Source	Accounting 2019 (NOK in 1000)	Project Start dato	Project End date	Total external financing (NOK in 1000)
Angheluta, Luiza; Jamtveit, Bjørn	EarthFlows 2	The Njord centre	UiO	164	01.01.2019	31.12.2023	N/A
Dysthe, Dag Kristian	NanoHeal	Dept. of Physics	RCN	417	01.01.2015	31.12.2018	9 380
Dziadkowiec, Joanna	Solid-solid interfaces as critical regions in rocks and materials: probing forces, electrochemical reactions, friction and reactivity.	The Njord centre	RCN	699	01.04.2019	31.03.2022	3 234
Galland, Olivier	Dynamics of Igneous Plumbing Systems in Sedimentary Basins	Dept. of Geosciences	RCN	53	01.09.2015	30.03.2019	8 493
Galland, Olivier	Natural Fracture Characterization in the Intrusive Systems	Dept. of Geosciences	YPF S.A.	10	19.02.2016	31.02.2019	260
Jamtveit, Bjørn	Disequilibirum metamorphism of stressed litosphere	Dept. of Geosciences	ERC	5 205	01.09.2015	31.08.2020	21 200
Malthe-Sørenssen, Anders	US-Norwegian collaboration on fluid-consuming transformation processes	Dept. of Physics	RCN	668	01.01.2016	31.12.2019	3 915
Malthe-Sørenssen, Anders	History-dependent friction	The Njord centre	RCN	65	01.07.2019	31.06.2023	9 229
Malthe-Sørenssen, Anders.	Coupled processes in gas hydrate disassocation	Dept. of Physics	RCN	73	01.07.2014	31.09.2018	6 725
Måløy, Knut Jørgen	Porous Media Laboratory	Dept. of Physics	RCN	7 750	01.07.2017	30.06.2027	66 400
Renard, François	Advanced X-ray and neutron imaging of fractures and porous rocks	Dept. of Geosciences	RCN	1 550	01.01.2018	31.12.2020	3 093
Renard, François	Microfractures in black shales and their transport properties	Dept. of Geosciences	RCN	3 207	01.04.2017	30.09.2021	11 201
Renard, François	Unravelling the spatio-temporal nature of rock deformation using 4D X-ray tomography	Dept. of Geosciences	RCN	2 081	01.05.2016	31.10.2020	8 989
Renard, François; Jamtveit, Bjørn	MODIFLOW: Modelling Flow across scales	The Njord centre	Equinor	812	01.01.2019	31.12.2023	9 048
Røyne, Anja	Systems analysis & fundamental control of bacterial processes in the production of bio-concrete for construction purposes (BioZEment 2.0)	Dept. of Physics	RCN	1 288	01.05.2017	30.09.2020	4 726

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PoreLab
NTNU-UiO Porous Media Laboratory

PGP PHYSICS OF GEOLOGICAL PROCESSES