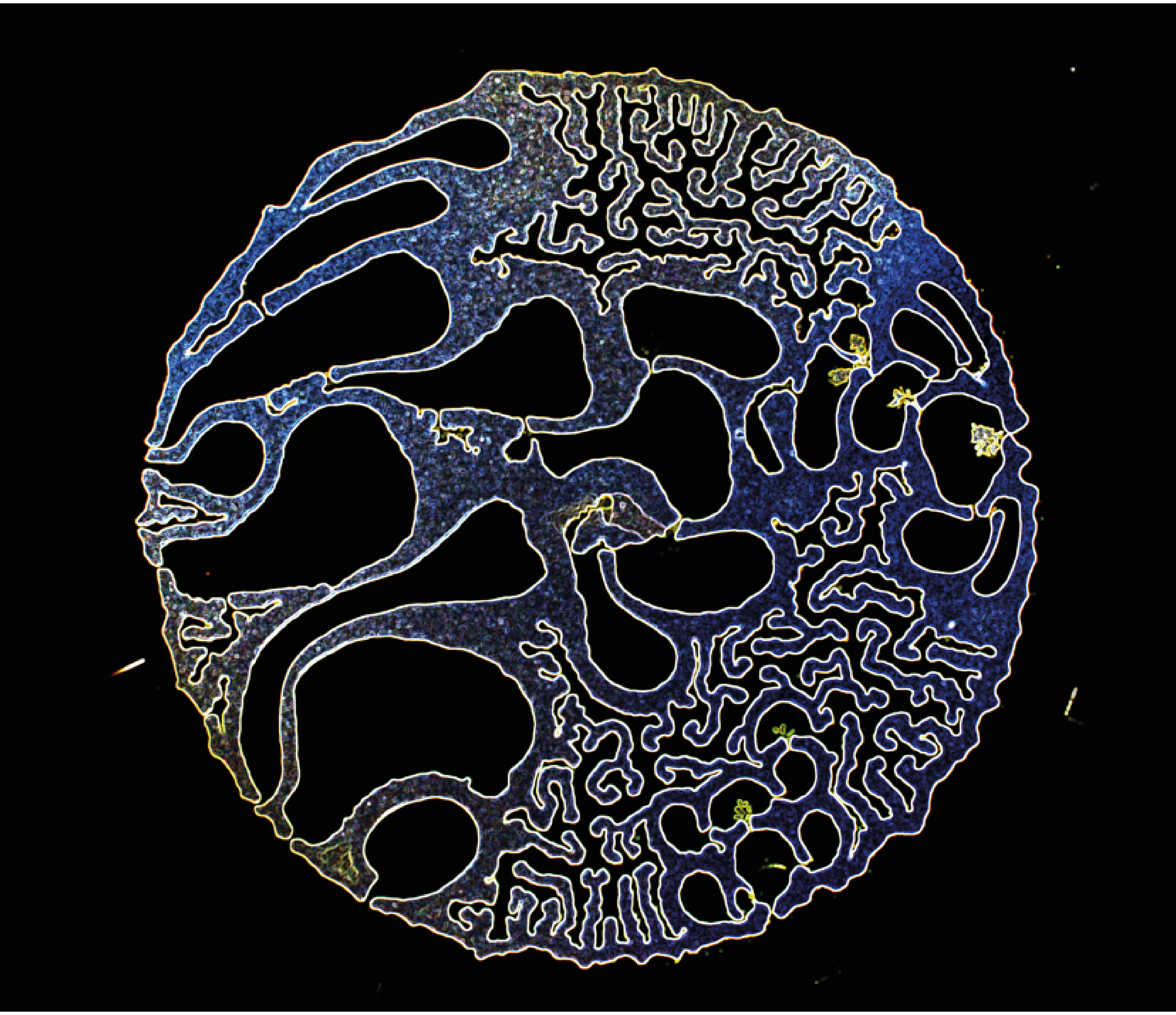
PoreLab
NTNU-UiO Porous Media Laboratory

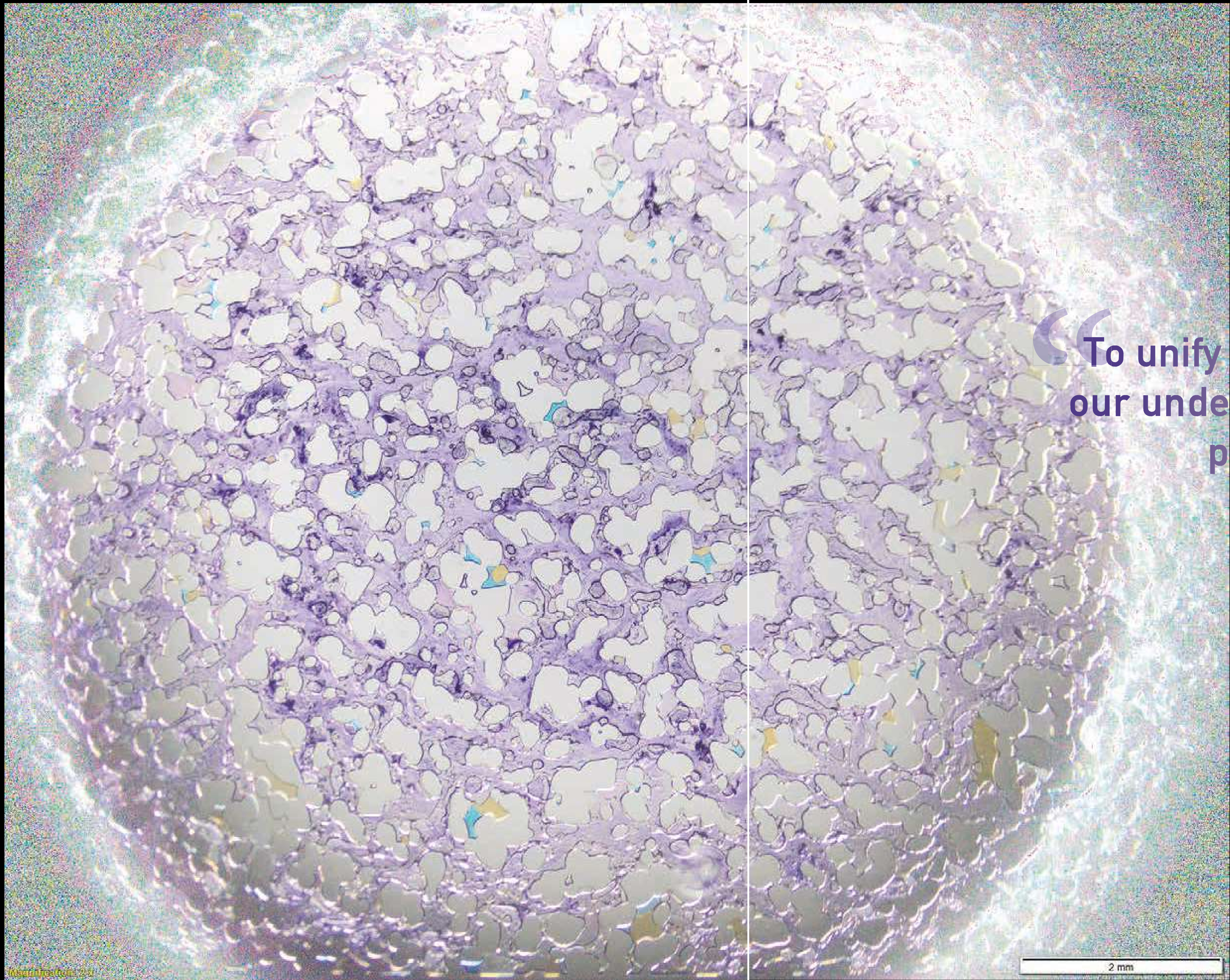
# Annual Report 2018



NTNU
Norwegian University of Science and Technology

UiO : University of Oslo

Norwegian Centre of Excellence
The Research Council of Norway




Our Mission

## “To unify and advance our understanding of porous media

# WHAT IS PORELAB?

Our internationally recognized work was awarded Norwegian Center of Excellence (CoE) in August 2017 from the Norwegian Research Council. PoreLab, acronym for Porous Media Laboratory, was born!

A CoE is a funding scheme administered by the Norwegian Research Council. The goal of the CoE program is to give Norway's best scientists the opportunity to establish larger units focusing on frontier research at a high international level and to contribute to raising the quality of Norwegian research.

PoreLab has two nodes, at the Norwegian University of Science and Technology (NTNU) in Trondheim and at the University of Oslo (UiO). It is led by five principal scientists from physics, chemistry and reservoir engineering. At UiO, PoreLab is organized under the auspices of the Njord Center which is a newly established cross-disciplinary geoscience-physics center.

The mission of PoreLab is to advance the understanding of flow in porous media. Starting from a sound basis in physics we aim for a better description of flows that range from geology to biology and technology. Our objective is to develop a generalized statistical mechanics for porous media flow at the pore level which will give us an effective media description on the larger continuum scales – a generalized non-equilibrium thermodynamics for porous media flow. We work to link the physics at the pore scale to the large-scale differential equations. We address the upscaling problem using methods adapted from non-equilibrium thermodynamics and statistical mechanics.

PoreLab receives an annual funding from the Norwegian Research Council of about 15 MNOK for an initial five years period. NTNU and UiO contribute with the same financial support. Conditional to a positive outcome of a mid-term evaluation, an additional five years will be granted. If so, the date of completion will be August 2027.

*From left: Knut Jørgen Måløy, Signe Kjelstrup, Eirik Flekkøy, Alex Hansen, Ole Torsæter, Liv Furuberg (Photo: Marie-Laure Olivier)*

COVER PAGE: *Drying pattern: Pattern formed in a drying process where a mixture of grains and fluid (blue area) between two glass plates is invaded by air (black area.) Picture courtesy: Department of Physics, UiO*

PAGES 2 AND 3: *Microfluidics flow experiment with lab-on-chip technology. Picture courtesy: Georg J. B. Voss, Department of Geoscience and Petroleum, NTNU*



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# DIRECTOR'S COMMENTS

The Porous Media Laboratory – PoreLab – has now existed for 18 months. It is time to pause for a minute and reflect on where we are and where we are going. But, perhaps we should start with "why we are" before attempting to answer the first and outline a plan as answer to the second question.


*Alex Hansen, Director for PoreLab.*
*Photo: Marie-Laure Olivier*





## WHY POROUS MEDIA?

It is only a decade and a half ago that Paul Roberts in his book The End of Oil: *On the Edge of a Perilous New World* stated that the dwindling oil reserves constituted "arguably the most serious crisis our industrial society has ever faced." This view was widely spread at the time. The development of alternative energy sources has in the meantime come to a point where optimism has set in and it makes sense to loosen up somewhat over this.

Six years ago, however, the UN declared 2013 as the International Year of Water. They declared, "By 2025, 1.8 billion people will be living in regions with absolute water scarcity, and two-thirds of the world population could be under stress conditions." This is a growing crisis.

Lack of oil and lack of water – are they related problems? Yes, they are. Drilling for oil and drilling for water, i.e. the exploitation of sub terrain reservoirs are very much alike. Perhaps the two gushers side by side illustrate this well. The one on the left shows the first Texas oil gusher, Spindletop, drilled in 1901, and the photo on the right shows a water gusher on the border to Darfur, Sudan, drilled in 2010. Fridtjov Ruden whose company did the drilling, commented to me that he regards his business, water exploration, as "the poor cousin of the oil industry." They are indeed related.

At the heart of the oil industry, and the budding water industry, an industry that will eclipse the present importance of the oil industry, one finds porous media. This is where the oil or water sit.

We also find porous media in biological systems: In any multicellular organism - that being trees or people - fluids need to be transported. In geology and/or geophysics, water moves in soils, with the risk of polluting aquifers. In cold areas, frost heave is the result of water transport through soil. On the opposite side of the temperature scale, geothermal systems rely on hot water transport in fractures – here seen as a porous medium at large scale. Industrial filters and fluidized bed reactors belong to the realm of chemical engineering and constitute examples of porous media. Hydrogen fuel cells rely on the simultaneous transport of water and hydrogen and oxygen through porous electrodes and electrolytes to work. In materials science, impregnation processes, e.g. wood impregnation, rely on the transport of fluids into porous media.

The fact that porous media are central to such a variety of fields does not mean that they are ill defined; porous media are porous media. What this diversity means is that many different fields with many different viewpoints have separately pondered them. Hence, the knowledge is fragmented. An interdisciplinary center focused on porous media that can bring these fields together would be in the position to sew together these fragments. Done wrongly, we would end up with a patchwork quilt of knowledge that does not bring anything new. Done correctly, we would be demonstrating that the whole is more – even much more – than the sum of the parts. PoreLab has this role as an interdisciplinary hub as a central goal.

Perhaps the most important outstanding problem in fundamental porous media research is the *upscaling problem*. In most practical applications of porous media, the length scale of interest is much larger than the scale at which the relevant physics is going on. The pores, where the physics is, are typically ten to a hundred micrometer in size – are some 7 orders of magnitude smaller than the scales of interest for practical purposes which are in the meter range or larger. Porous media look dramatically different on the pore scale from the meter scale where they look like continuous media. Here we have arrived at the core problem: *How to connect the physics at the pore scale with the behavior seen at large scale*. This is the central problem we try to solve in PoreLab.

## PREHISTORY AND FIRST YEAR

We started working on the proposal that would eventually result in the creation of PoreLab in the early fall of 2015. I was extremely reluctant at first. The competition would be fierce. The best research groups in the country would all put everything they got into this. We would have to do the same. We knew that what we had as a core idea was solid, bold and ready to fly. Some of us, the Oslo team and myself, had worked together for more than a couple of decades on fundamental problems concerning porous media flow. Over at the NTNU Department of Chemistry, the physical chemistry group had decades of experience to point of being among the world leaders in non-equilibrium thermodynamics, and we had started talking about combining their field with ours already some five years earlier. What was lacking at this point was a strong connection to engineering. The NTNU Department of Geoscience and Petroleum would provide the necessary (and beyond) expertise, completing the team. Having survived the first application round, we then spent the spring of 2016 writing the detailed proposal, which would make or break us. Any reluctance was now completely gone. With a typical Center of Excellence budget for ten years of around 250 000 000 kroner and the typical proposal containing some 60 000 characters, the value of each character would be some 4000 kroner (around 400 Euro) if successful. No wonder every single word – no, character - appearing in the proposal would be treated with the uttermost care; nurtured like a rare plant. In January of 2017, I was invited for an interview with the expert panel. I wrote some eight versions of the presentation I would give from scratch. When students passed my office door, I would haul them into my office, place them on a chair and force upon them the current version of the presentation. And it worked. In March, I received the call from NFR that informed us that PoreLab would become a reality.

The victory celebrations would within short be replaced by a grave sense of responsibility. Our NTNU colleague Martin Ystenes once made a remark in a different context that transcribed into the present situation would be something like this: After ten years, you will need to be able to look into the eyes of some 125 average taxpayers and tell them that PoreLab deserved everything they paid in taxes over those ten years. What a level of trust society has put in us.

Since its formal inception on August 15, 2017, PoreLab has grown rapidly. Very soon, we started a close collaboration with the NTNU Department of Civil and Environmental Engineering with a focus on frost heave; a problem of great fundamental interest where flow in porous media meets non-equilibrium thermodynamics but also of great importance for our societies in the temperate and arctic regions. In Norway where we do not have permafrost, frost heave is a destructive and costly factor. Farther north or east, where there is permafrost, it is the opposite. With the ongoing warming of the climate, there is trouble ahead and the fundamentals of ice formation and water transport in soils sit at its core. More recent is the incipient collaboration with the NTNU Department of Structural Engineering on transport processes in concrete, which is a (nano-) porous material. The Romans invented cement-based building materials so it is natural to believe that everything there is to know about such materials must have been uncovered since long. The situation is different. The techniques used to analyze these materials have improved so much over the last few years that they are now delivering open questions at a rate outpacing that at which answers may be given. In other words, cement-based materials are becoming increasingly mysterious.

These two examples, one thriving, one incipient, demonstrate how PoreLab is establishing itself as an interdisciplinary hub for fundamental porous media research.

We are in the process of expanding our international relations through strengthening existing contacts and creating new. Several well-known and not so well known or more precisely up and coming, scientists will stay with us for longer periods ranging from a few weeks to up to a year.

## INTERDISCIPLINARITY

There are two possible ways to be interdisciplinary. The first way is to gather a homogeneous group of researchers, which then attacks a wide number of problems arising from different disciplines. This approach is flawed. It is the embodiment of the Maslow law: "if all you have is a hammer, everything looks like a nail." The second way is to gather a diverse group of scientists around a well-defined problem. This is true interdisciplinarity; interdisciplinarity that in this case encompassing different universities, faculties and departments, and this is at the core of PoreLab. Interdisciplinarity at this scale is rather untried in Norway and we are seeing ourselves as not only a laboratory for porous media, but also for interdisciplinary research. A component necessary to succeed with this kind of interdisciplinarity is that we sit together on a daily basis. This was solved by the wonderful location that was found for us at the NTNU and the location that we are still waiting to move to at the University of Oslo. I thank the involved Deans, Olav Bolland and Øyvind W. Gregersen for making this possible. I also thank the Vice President of the Norwegian Academy of Science and Letters Anders Elverhøi for invaluable help in driving home to our leaders what the necessary conditions are for succeeding in interdisciplinary research.

When I was in high school in the early seventies, I traveled to Trondheim to seek advice from Harald Wergeland, the legendary professor of theoretical physics at the Norwegian Institute of Technology (now NTNU). He told the young teenager that the verb "to research" does not exist in imperative. He meant by this that research, like art, cannot be forced. All one can do is to make sure that the conditions to do research are as optimal as possible. PoreLab now has such conditions. It is now all up to us.

## AMBITIONS FOR 2019

The initial period of finding our traction is now over and we foresee that 2019 will be a period of consolidation.

We have reached the stage where the scientific discussions within the center, both locally in Trondheim and Oslo, but also between the nodes flow freely. The communication between the two nodes hinges on communication technology which has proven to be somewhat challenging. We will continue to improve on our skill on this.

Our junior center members, doctoral students and postdocs, are collaborating at an increasing rate. Our approach to this has been through creating the PoreLab Junior Forum, which has proven to be very successful. We will continue to emphasize student and postdoc collaboration between the nodes. The course portfolio that we are developing within PoreLab has now been tested through the year that has passed. We will continue to develop it, but with the ambition that students at other institutions, including international ones, also join in.

We will in the coming year put more emphasis on sending junior members to work with our international collaborators. This will be part of our effort to strengthen even further our contacts abroad. Several Memoranda of Understanding with foreign institutions are in the pipeline and will come to fruition this year.

The year 2019 will see the hiring of associate professors in experimental porous media physics and in physical chemistry.

As for the recruitment of doctoral students and postdocs, we recognize the gender skewness in the field. We have an ongoing internal discussion on how to overcome – or as a first step, dampen – this. Other Centers of Excellence have found solutions that are interesting, and we are looking over their shoulders to see what we may emulate.

PoreLab supports open science and as a consequence, Plan S. We pledge to publish accordingly.

## RESEARCH PROJECTS

Charles Ives wrote a piece for chamber orchestra in 1906 entitled "Central Park in the Dark". He envisioned sitting on a bench in the park hearing different sounds simultaneously. They are dissonant, coming from the close-by casino, from street singers, from marching bands playing different tunes simultaneously while getting closer. But, they blend into a whole, the whole which is Central Park. There is unity. The short research project descriptions on pages 16 to 39 are a visual counterpart to "Central Park in the Dark". They are different from each other; perhaps even mutually dissonant, but they are part of what makes PoreLab what it is.

$$p^r - p^t = \frac{2\gamma}{R}$$

$$\hat{p}^r - p^r = \frac{\gamma}{R}$$

# COMMENTS FROM THE CHAIR OF THE BOARD

*Øyvind Gregersen,*
*Dean of the Faculty of Natural Sciences, NTNU*

The goal of PoreLab is to advance the understanding of flow in porous media. Starting from a sound basis in physics, we aim for a better description of flows that range from geology to biology and technology.

PoreLab is a Norwegian Center of Excellence created in 2017 and situated at the Norwegian University of Science and Technology (NTNU) in Trondheim, and the University of Oslo (UiO). The center is highly cross-disciplinary spanning the fields of physics, physical chemistry and reservoir engineering focusing on the physics of porous media using experimental, theoretical and computational methods.

PoreLab is a continuation of a long tradition of NTNU and UiO on combining excellent and groundbreaking research with highly applied and important areas for the society and commercial sector. Porous media are all around us. In the ground, water fills the pores of aquifers, oil is found in porous medium. When underground water rises during earthquakes, they may push the soil particles apart so that it loses it strength with the results that buildings topple.

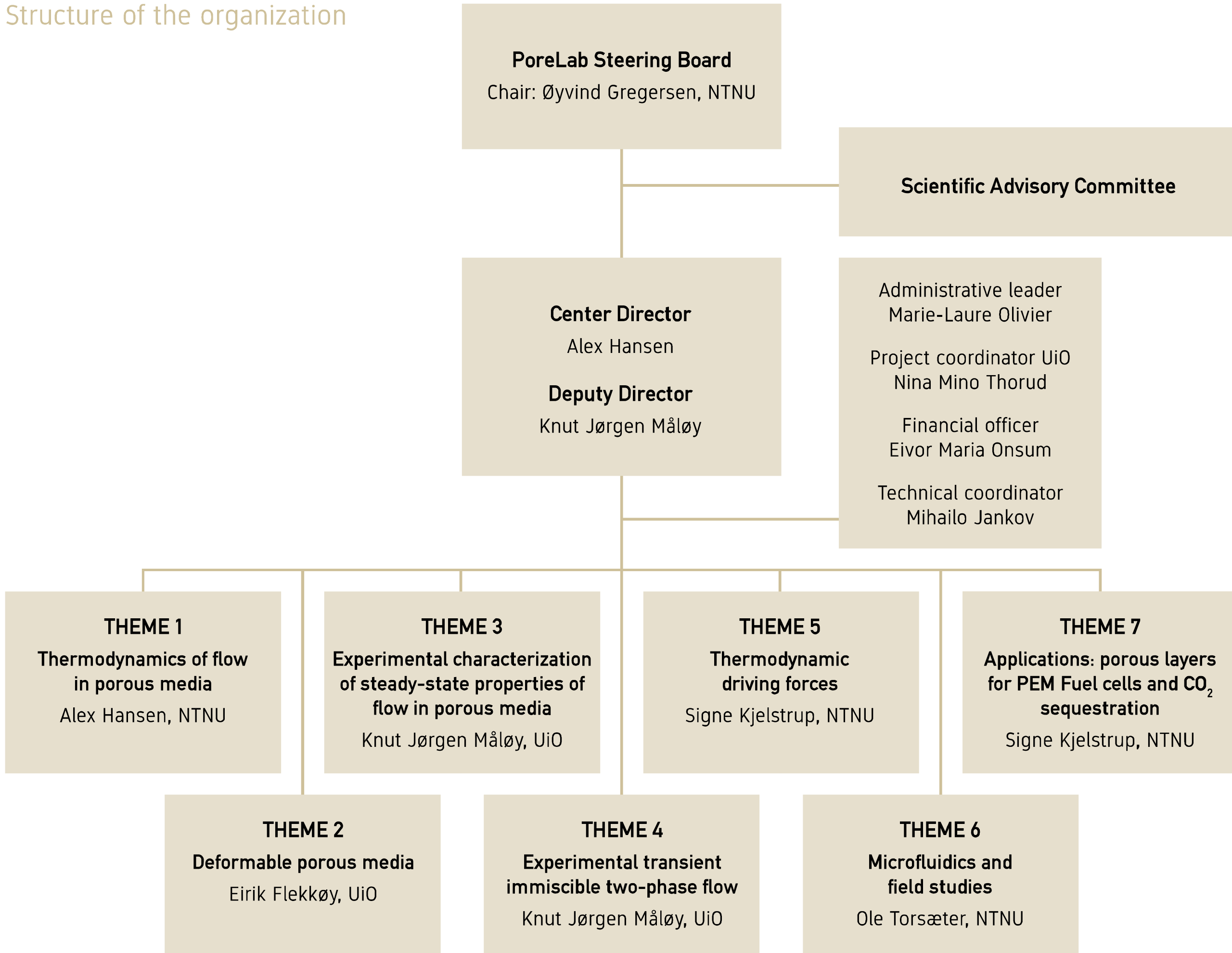
Since the start in 2017 the center has progressed well. The focus has of course been scientific and already we see groundbreaking cross-disciplinary research being published from PoreLab. During the startup, it has also been important to gather the researchers physically in Trondheim and Oslo. In Trondheim, we are well pleased with the premises in the Petroleumsteknisk Senter that allows a tight collaboration between physics, chemistry and reservoir engineering.

Another highly important task during the startup has been recruiting highly talented researchers, PhD-fellows and master students to the center. The board has been well satisfied with the scientific progress, cross-disciplinary collaboration and progress of PoreLab.



# ORGANIZATIONAL CHART OF PORELAB

Structure of the organization




PoreLab gathers scientists from 4 departments at NTNU. The Department of Physics is the host. Partners are the Departments of Chemistry, Geoscience and Petroleum, Civil and Environmental Engineering, all at NTNU, and Department of Physics at UiO. SINTEF Industry and WesternGeco are external research partners.

The Center is managed by the Director, Alex Hansen NTNU jointly with the Deputy Center Director, Knut Jørgen Måløy (UiO). The Center Administrative Leader is Marie-Laure Olivier (NTNU).

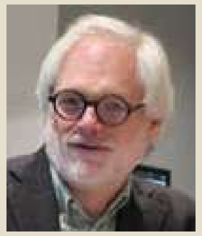
The organizational structure of the Center is flat. PoreLab's research has been organized in seven Research Themes lead by the Principal Investigators (PIs). The team of five Principal Investigators and the Administrative Leader forms the Leader Group and has weekly meetings to discuss administrative and scientific issues and update each other on developments and progress. The system for immediate updates ensures interdisciplinary progress.

The PoreLab Executive Board includes members from the Faculties involved at NTNU and UiO. The board is responsible for overseeing that the activity takes place according to the contract with the funder, the Research Council of Norway. A central task of the Executive Board is to enhance the collaboration among participating Departments at NTNU and UiO.

The Scientific Advisory Committee of international experts aids in the development of a strategy for the scientific development of the center, thereby helping the leadership group to achieve the stated scientific aims.

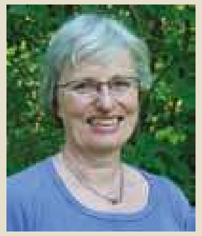
# MANAGEMENT AND ADMINISTRATION

## THE LEADER GROUP


Alex Hansen
Director
Professor, PI Theme 1


Eirik Flekkøy
Professor
PI Theme 2


Knut Jørgen Måløy
Deputy Director
Professor, PI Themes 3 and 4

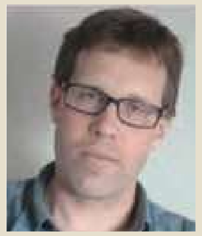

Signe Kjelstrup
Professor
PI Themes 5 and 7


Ole Torsæter
Professor
PI Theme 6


Marie-Laure Olivier
Administrative leader

## PORELAB EXECUTIVE BOARD


Øyvind Gregersen
Dean
NV faculty, NTNU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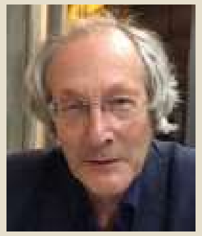
Department of Physics
NTNU


Ingrid Schjølberg
Vice Dean Research and Innovation
Director NTNU Ocean
IV Faculty, NTNU


Jøran Idar Moen
Head of Department
Department of Physics
University of Oslo


Brit Lisa Skjelkvåle
Head of Department
Department of Geosciences
University of Oslo

## SCIENTIFIC ADVISORY BOARD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United Kingdom


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Co-director of Energy Futures Lab
Imperial College London
United Kingdom


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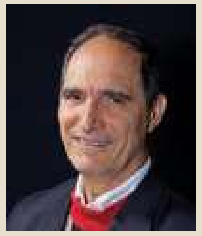
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Chief Technology Officer
Digital Rock Services
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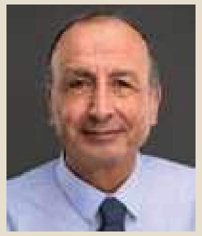
Norway


Dani Or
Professor
Soil and Terrestrial
Environmental Physics
ETH, Zürich
Switzerland

## PARTNERS

NTNU

UiO : University of Oslo

SINTEF

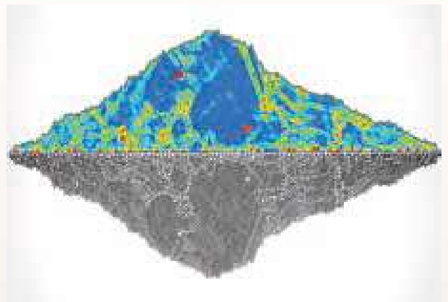
WesternGeco

# HIGHLIGHTS

**August 15, 2017**
PoreLab starting date

**October 18, 2017**
1st National InterPore Workshop on Porous Media, Trondheim

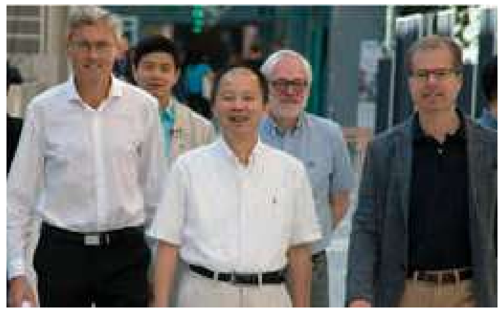
**September 6-8, 2017**
**The Grand Opening of PoreLab**
PoreLab's first international workshop



**November 8-9, 2017**
Workshop on deformation, flow and fracture of disordered material, Oslo

**May 1, 2018**
NTNU PoreLab team moves together

**June 1, 2018**
Opening seminar with Rebekka Borsch, State Secretary, and Liv Furuberg from the Research Council of Norway



**June 18-22, 2018**
Beijing Computational Research Science Center (CRSC) visits PoreLab Trondheim and Oslo
A workshop is organized

**August 26-31, 2018**
32nd International Symposium Annual Meeting of Society of Core Analysts
Trondheim

**November 9, 2018**
2nd National InterPore Workshop on Porous Media, Oslo

**December 2018**
University of Oslo
Physical restructuring of former labs and construction of new one

# DISPERSION IN COMPLEX MEDIA

Kristian S. Olsen[1], Luiza Angheluta[1], James Campbell[1], Bjørnar Sandnes[1,2], Le Xu[1], Renaud Toussaint[1,3], Benjy Marks[4], Eirik Grude Flekkøy[1], Knut Jørgen Måløy[1], Steven R. Pride[5] Donald W. Vasco[5], Ran Holtzman[5,6]

[1] PoreLab, The Njord Center, Department of Physics, University of Oslo, Norway
[2] College of Enginering, Swansea, United Kingdom
[3] IPGS, CNRS, University of Strasbourg, France
[4] The University of Sydney, Sydney, Australia
[5] Lawrence Berkeley National Laboratory, Earth Science Division USA
[6] The Robert H. Smith Faculty of Agriculture, Food and Environment, Hebrew University of Jerusalem, Israel

Dispersive mixing of fluids in a porous may take on unconventional features for a number of reasons. We look at three particularly interesting cases where the transport is governed by the following complex boundary conditions: (1) the flux of the mixed fluid in one direction is caused by a concentration gradient in the transverse direction, (2) the solid boundaries are changed by dissolution, and (3) the porous medium that defines the boundaries have dead ends of all sizes in which a diffusive agent may get trapped.

## DISPERSION AND CROSS-COUPLING

It has long been assumed that the dispersion tensor which relates the solute current and concentration gradient, is symmetric. The basis for this assumption has been to cite the Onsager reciprocity theorem. We show here that, in general, the dispersion tensor is not symmetric when advection of solute is important. On the contrary, it only becomes symmetric when the background flow field is reversed, that is, the transport in the x-direction due to gradients in the y-direction is the same as the transport in the y-direction due to gradients in the x-direction, provided the flow field is reversed everywhere. This symmetry is demonstrated analytically and investigated by lattice-Boltzmann simulations, as is illustrated in Figure 1.

## FLOW IN FRACTURES WITH RAMIFIED PATTERNS

The injection of a reactive fluid into an open fracture may modify the fracture surface locally and create a ramified structure around the injection point. This structure will have a significant impact on the dispersion of the injected fluid due to increased permeability, which will introduce large velocity fluctuations into the fluid. Here, we have injected a fluorescent tracer fluid into a transparent artificial fracture with such a ramified structure. The experiments have been compared to two dimensional (2D) computer simulations that include both convective motion and molecular diffusion. A comparison was also performed between the dispersion from an initially ramified dissolution structure and the dispersion from an initially circular region. A significant difference was seen both at small and large length scales. At large length scales, the persistence of the anisotropy of the concentration distribution far from the ramified structure is discussed with reference to some theoretical considerations and comparison with simulations.

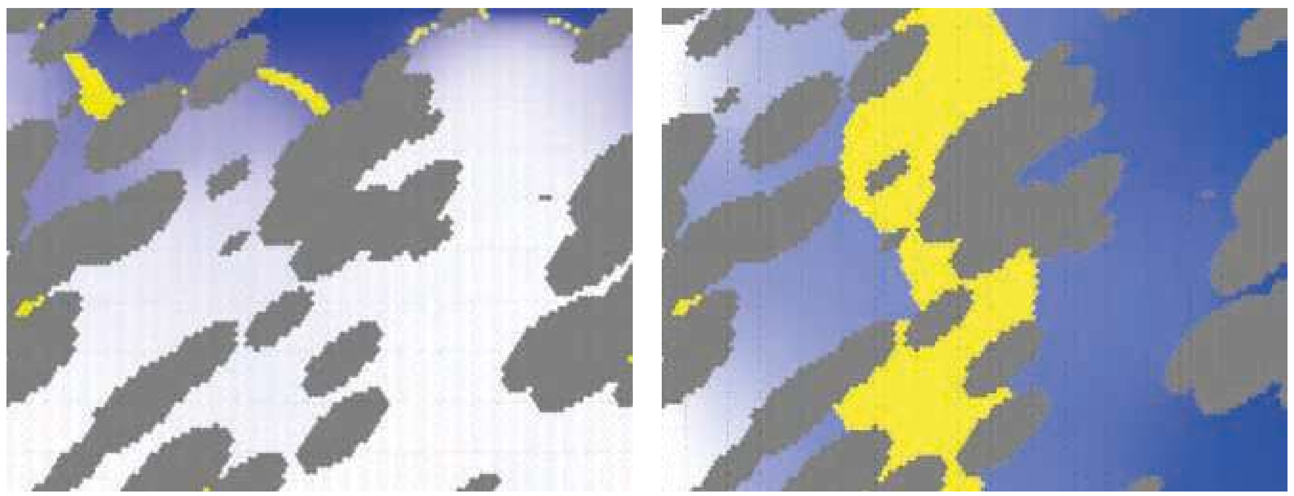


*Fig. 1: Lattice Boltzmann simulations of dispersion in a porous media (gray). High tracer concentration are shown by white, low concentrations by blue and intermediate values by yellow. The background flow is in the diagonal direction in both figures, but the concentration gradient is vertical in the first- and horizontal in the second figure.*





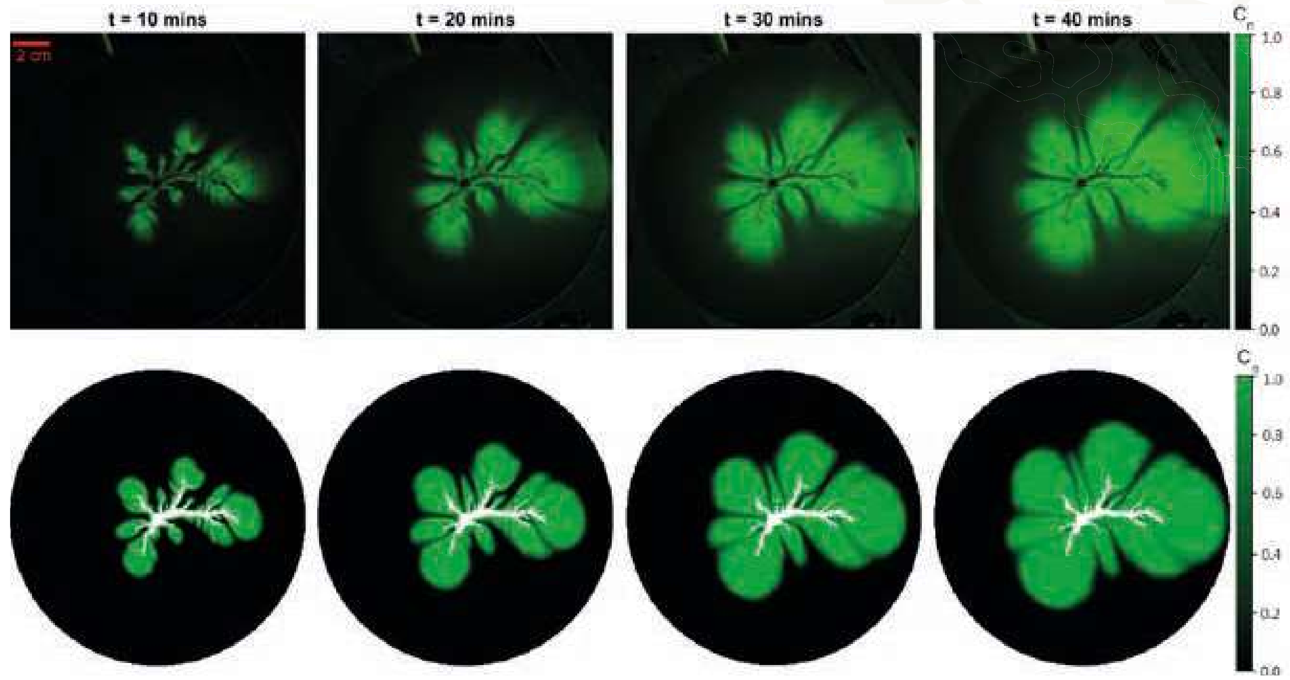



*Fig. 2: Experimental results compared with simulation images. Top: Experimental images. Bottom: Simulation output of the dissolution pattern. The green intensity represents the normalized tracer concentration in the simulation. The vertical pairs of images show comparison after an injection lasting respectively 10/20/30/40 minutes.*

## ANOMALOUS DIFFUSION AND THE GEOMETRY OF FRICTIONAL FINGERS

Deformable porous media is a source of a myriad of complex patterns. Frictional fingers appear due to flow instabilities in quasi-2D systems dominated by frictional and capillary forces. These are complex branching structures that are space-filling in the sense that their standard Euclidean fractal dimension is very close to 2. When a random walker explores such a geometry, its dynamical properties reflects many geometric and topological properties. We can therefore think of a random walker not only as a way to study transport in complex systems, but also as a probe of the geometry. In particular, we have studied the relation between the anomalous diffusion exponent and geometry of the frictional finger patterns. The random walker as a probe of geometry contains two essential facts about the frictional fingers: its space-filling nature and the fractal properties of the branches. We have numerically tested this prediction, with a positive outcome. Another fractal dimension, based on Horton-Strahler ordering, is also estimated using both analytical and numerical results.

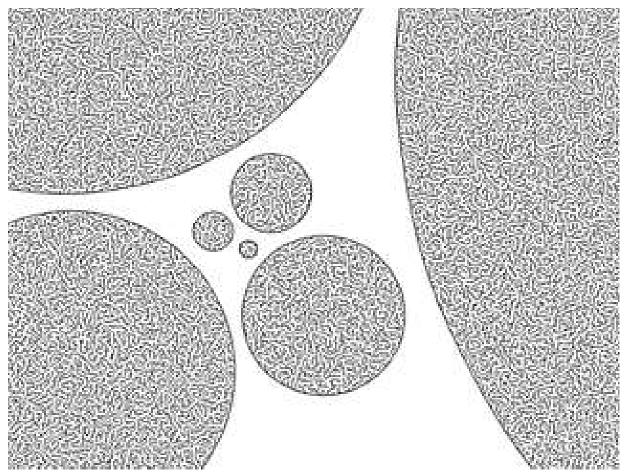


*Fig. 3 Frictional finger patterns of different sizes generated numerically. The simulations, which take capillary forces and friction into account, correspond to the experiments, but are much larger in size.*

## RECOMMENDED READING

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

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

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

Le Xu, Benjy Marks, Renaud Toussaint, Eirik Grude Flekkøy and Knut Jørgen Måløy. Dispersion in fractures with ramified dissolution patterns. Frontiers in Physics, 6:29, 2018.

# IMPACT OF FLUID FLOW IN DEFORMABLE POROUS MEDIA

F. K. Eriksen[1,2], R. Toussaint[1,2], A. L. Turquet[2], K. J. Måløy[1], J. A. Eriksen[1], H. A. Knudsen[1], B. Sandnes[1,3], O. Galland[1], E. G. Flekkøy[1], G. Dumazer[1] and M. Ayaz[1]

[1] Porelab, The Njord Center, Department of Physics, University Oslo, Norway
[2] IPGS, CNRS, University of Strasbourg, France
[3] College of Engineering, Swansea University, United Kingdom

When fluids flow in deformable porous media, a wide range of flow patterns and deformation dynamics can emerge. The observed patterns and deformation depend on the fluid flow rate and overpressure, external forces, and the physical properties of the porous medium. Since deformation of porous media by fluids occurs in many natural and industrial processes, it is important to fundamentally understand pattern formation phenomena and deformation dynamics at different conditions. Experiments and simulations in analog models are good ways to simplify and explore the topic.

## FLUID DRIVEN DEFORMATION AND CHANNEL FORMATION IN CONFINED GRANULAR MEDIA

A fluid injected into a porous or granular medium at a sufficient overpressure or flow rate will deform the medium and open up flow channels as shown in Figure 1. The formation of such channels increases the permeability of the medium, which can be an advantage. Processes like this are for example used to enhance oil & gas recovery, in $CO_2$ storage, and water 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 surrounding region. In this project, we study and characterize the phenomena of fluid driven deformation and channel formation in a fine grained medium (80 µm beads) confined between two horizontal glass plates (separated by 1 mm). In the experiments, we inject air with overpressures in the range 50 – 250 kPa while filming from above with a high speed camera. We obtain channel structures and deformation over time from the images, and evaluate the pore pressure evolution numerically. We present fundamental observations and theoretical models from the results.

## PATTERN FORMATION OF FRICTIONAL FINGERS IN A GRAVITATIONAL POTENTIAL

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

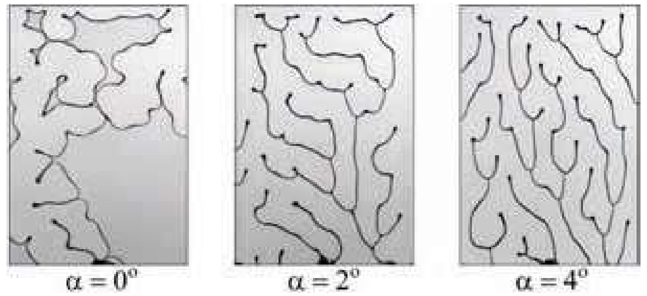



*Fig. 2: Examples of experimental patterns in a deformable porous medium at different tilt angles.*

## FRICTIONAL FLUID DYNAMICS AND PLUG FORMATION IN MULTIPHASE MILLIFLUIDIC FLOW

We study experimentally the flow and patterning of a granular suspension displaced by air inside a narrow tube. The invading air-liquid interface accumulates a plug of granular material that clogs the tube due to friction with the confining walls. The gas percolates through the static plug once the gas pressure exceeds the pore capillary entry pressure of the packed grains, and a moving accumulation front is reestablished at the far side of the plug. The process repeats, such that the advancing interface leaves a trail of plugs in its wake (see Figure 3).

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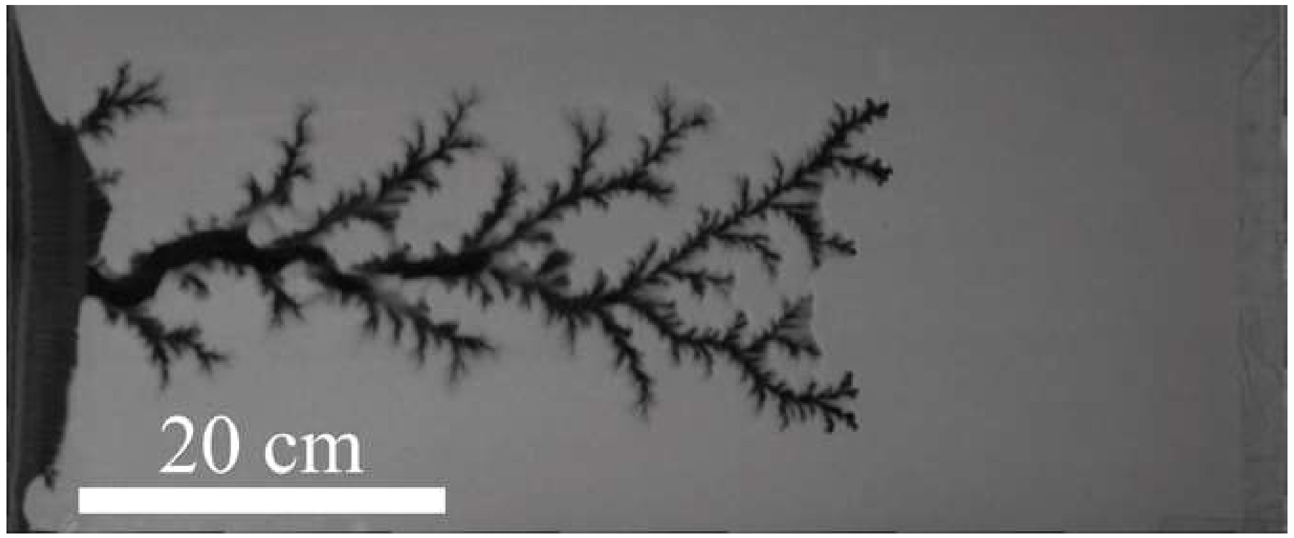


*Fig. 1: A top-down image of the invasion channels (black) formed in a granular medium between two glass plates (gray) when air is injected from the left side at a constant pressure of 200 kPa. The long sides of the cell are completely sealed, while the right side has a filter which stops beads but allows air to escape. In this experiment, pressurized air forces its way from the left through the medium, leading to the formation of these branched channels.*

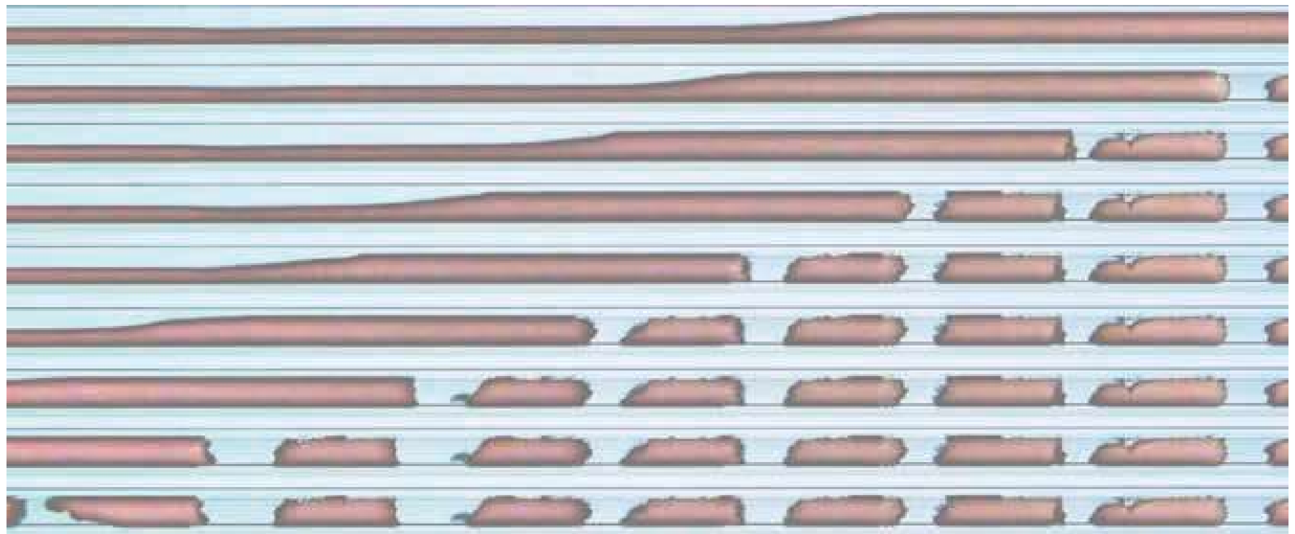

*Fig. 3 Detail pictures of the plug formation over time. The flow moves towards left.*

# INTERMITTENT DYNAMICS OF SLOW DRAINAGE FLOWS

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The process of drying of a porous or fibrous network is probably one of the most common examples of two-phase flow in porous media. Water evaporates from the soil when the sun shines after a rainy day, and wet clothes hanging on a string are not too wet anymore after a couple of hours. Although extremely common, upon close inspection one quickly realizes that this process is in fact a lot more interesting than it might seem: the apparently continuous motion of the drying front actually happens as a rich succession of pore invasion events, one following the other in an intermittent manner. This is something that would be hard to guess if one looked only at the macroscopic perspective. In each invasion event, air penetrates into one or several pores, removing the liquid that previously filled the pore-space. In this project, we have performed experiments in artificial transparent porous networks to study slow two-phase flows systematically. In the first part, we have analyzed the relative probability of pore-invasion events during the slow drainage of a porous network [1] and in the second part, we have studied how thin liquid films found inside the porous medium can influence the drainage process [2].

## THE RELATIVE PROBABILITY OF PORE INVASION EVENTS DURING THE SLOW DRAINAGE OF A POROUS MEDIUM

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

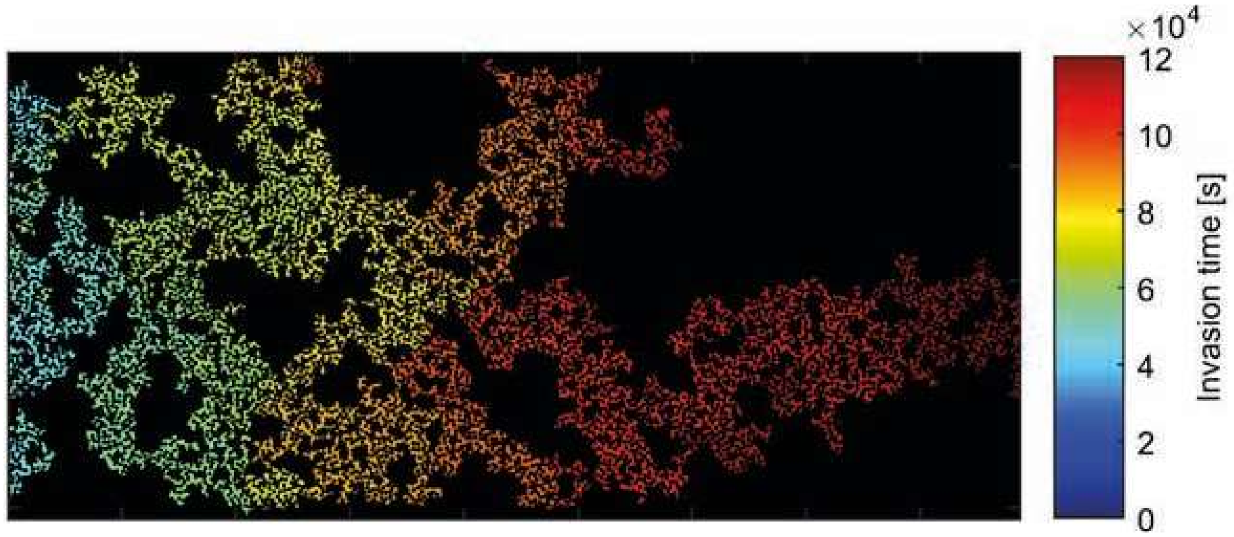


*Fig. 1: Spatiotemporal map of a slow drainage experiment in a porous network. Air invades the system from left to right, displacing a liquid from the initially saturated medium. The color map indicates the time at which a given pore is invaded by air.*

## CONNECTIVITY ENHANCEMENT DUE TO THIN FILM FLOW IN POROUS MEDIA

The standard fluid transport processes in porous media happen through the usual network of interconnected pore bodies and pore throats (here called the primary network). When air displaces water from a porous rock, thin films of water are left behind, covering the rock grains. In general, when a non-wetting phase displaces a wetting phase from a porous sample (drainage), thin films of the wetting phase are bound to be left on the surface of the constituting grains. Under certain conditions, isolated liquid films can eventually merge, forming a secondary network of interconnected films and capillary bridges that can effectively enhance the overall connectivity of the medium and act as a new pathway for fluid transport. Experiments in transparent networks have shown the existence of an active zone behind the main invasion front where the probability of drainage (via the secondary network) of seemingly trapped clusters is maximized. Fig. 2 shows an experiment in which a monolayer of glass beads, initially saturated with a viscous liquid (wetting phase, dark color), is slowly invaded by air (non-wetting phase, light color). After the usual drainage process, a set of trapped liquid clusters remains in the sample, but we observe that a small portion of them can (surprisingly!) still be drained. The three frames in the rightmost panel in Fig. 2 show the drainage of a cluster that would otherwise be trapped if transport happened only through the primary network. This kind of drainage event can only be possible due to the enhanced connectivity introduced by the secondary network of thin films and capillary bridges (red and green arrows in the figure).

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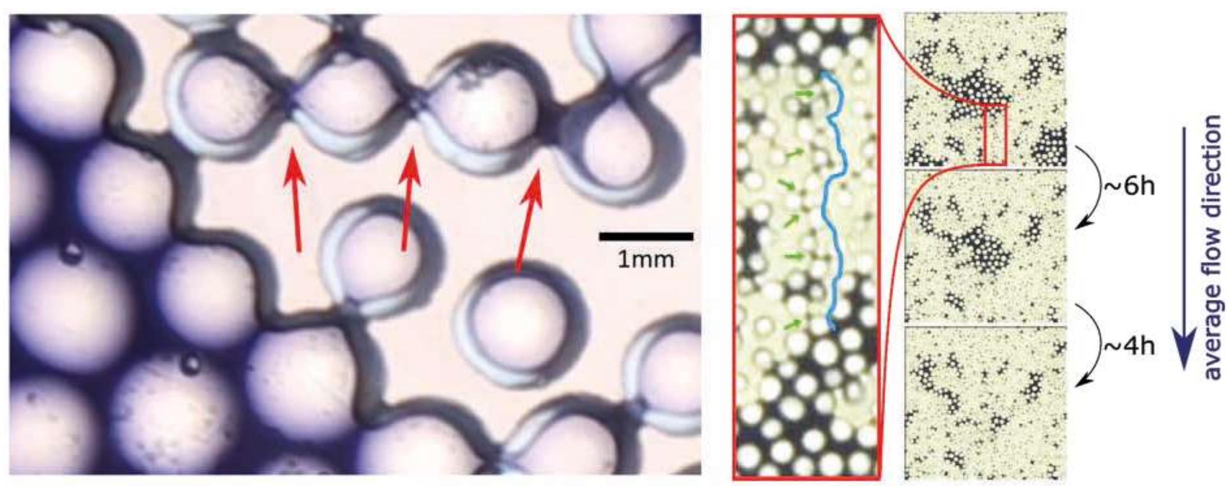


*Fig. 2: Thin liquid films and capillary bridges (red arrows in the left panel and green arrows in the central panel) can enhance the connectivity of a porous medium leading to the drainage of seemingly trapped liquid clusters (as seen on the right part of the figure). The central panel shows an enlarged view of the red rectangle, indicating that the capillary bridges help to form a connected pathway (schematically shown by the blue line) between the cluster being drained and the outlet of the system.*

# CRACK PROPAGATION AND ENERGY DISSIPATION AS HEAT

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Fracture and micro-fracture development is of central importance for breakdown and wear of materials. In particular for porous materials the time dependence of the porosity, and the porous structure itself will depend on both creation of new fractures and fracture healing. In this project we focus on two particularly cases: (1) fracture dynamics and extremal value statistic of an in-plane fracture and (2) the heat dissipation and influence of a finite temperature on the fracture dynamics.

## DYNAMICS AND STRUCTURE OF INTERFACIAL CRACKS

In the experiments, we have used a state-of-the-art fast microscopy techniques to dynamically analyze the nucleation and propagation of fractures between two sintered polymethyl methacrylate plates. Real-time dynamic measurements of the nucleation of micro-fractures are challenging to perform and mostly absent in the scientific literature. Our experimental setup provides the means to perform those measurements in a controlled manner.

Several of our recent experiments on fracture deal with the fracture front dynamics, in which we have been able to measure the detailed velocity fluctuations and local burst activity of the fracture front. The observed velocity fluctuations are very large, containing sudden avalanches that span a wide range of sizes and duration. Such complex spatiotemporal dynamics, generically called crackling noise, arise also in a wide variety of other physical systems, for instance, magnetic domain wall motion in disordered ferromagnets, vortex lines in type-II superconductors, and dislocation lines in defective crystalline solids. Our high-resolution and large dataset allows to characterize in detail the observed intermittent crackling dynamics. We find that the crackling dynamics follow robust power-law distributions, in agreement with results obtained in numerical simulations of the critical depinning of a long-range elastic string, slowly driven in a random medium.

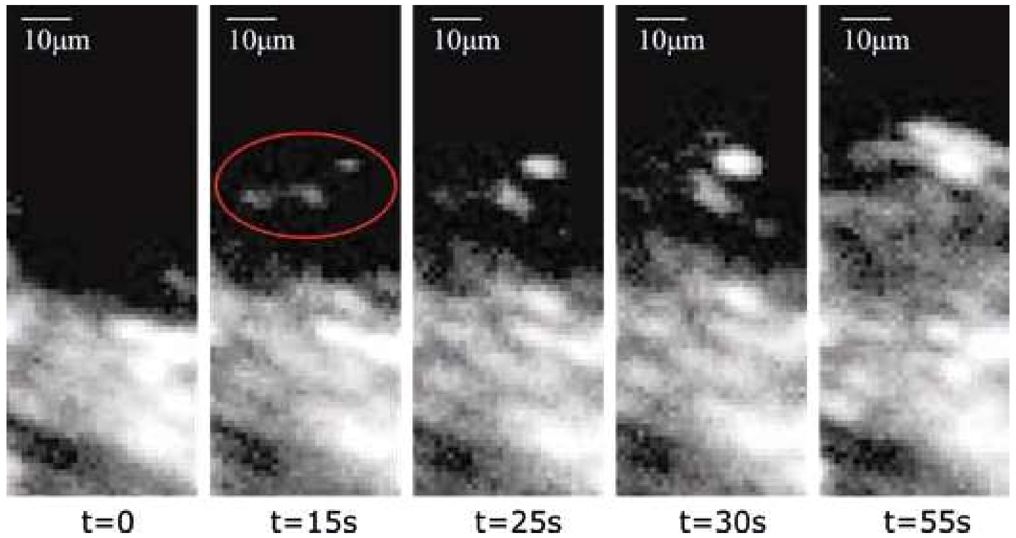


*Fig. 1: The figures show the nucleation and growth of micro-fracture, seen as white spots and indicated by the red ellipse. The micro-fractures grow with time and finally merge with the main fracture interface.*





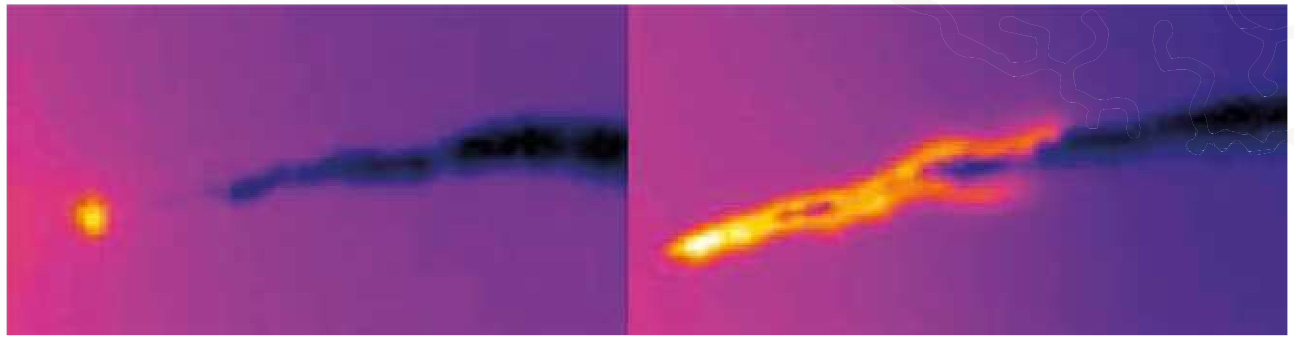

*Fig. 2: Heat dissipation of fracture growth in paper. The increase in temperature is observed in front of the initial notch just before the main crack starts to propagate, seen as a bright yellow spot just in front of the fracture tip. The temperature rise from blue to yellow corresponds to 6°C*

## HOW CRACKS ARE HOT AND COOL

Material failure is always accompanied by very high local dissipation rates. Temperatures at the crack tip may reach thousands of degrees centigrade. Such temperatures may subsequently alter the mechanical properties of stressed solids, and finally facilitate their rupture.

By monitoring the slow crack growth in paper sheets using an infrared camera, we measure a significant fraction of 12% heat dissipation. Besides, we show that (self-generated) heat accumulation could weaken our samples by microfiber combustion, and lead to a fast crack/dynamic failure/regime. The impact of temperature in fracturing processes can be sorted into two categories: background effects where the temperature is treated as an environmental constant affecting the rates at which the defects of a medium are propagating or healing, and dynamic effects where the propagation of fractures self-induces a rise in temperature in the vicinity of the crack front. In the latter case, the heat elevation can be an active process back affecting the crack propagation. This phenomenon will be here referred to as "thermal weakening." Thermal weakening processes could explain stick-slip motion and even be responsible for deep earthquakes. Therefore, to better understand catastrophic rupture events, it is crucial to establish an accurate energy budget of fracture propagation from a clear measure of various energy dissipation sources. In a recent project, we combine analytical calculations and numerical simulations, and directly relate the temperature field around a moving crack tip to the part a of mechanical energy converted into heat.

We use a theoretical model which focuses on the statistical physics consideration of higher reactions rates (i.e., quicker fracture propagation) at higher temperatures, as implied by an Arrhenius law. We show that the propagation of a crack can then be described as a phase transition, where a crack can either be in a weakened or a non-weakened state. Such transitions, together with the toughness heterogeneities of a body, can potentially explain the common stick-slip behavior observed in fracturing processes. In addition, we predict a critical ambient temperature above which the weakened phase ceases to exist. This critical point could be directly related to the brittle-ductile transition of rocks at a higher geological depth.

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# STEADY STATE TWO-PHASE FLOW IN POROUS MEDIA:

## LINKING EXPERIMENTS, SIMULATIONS AND A THERMODYNAMIC DESCRIPTION

Fredrik Kvalheim Eriksen[1], Joachim Falck Brodin[1], Marcel Moura[1], Alex Hansen[2], Signe Kjelstrup[3], Dick Bedeaux[3], Knut Jørgen Måløy[1] and Eirik Grude Flekkøy[1]

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During the previous decade, much attention was focused on understanding the flow instability that occurs when one fluid invades a porous medium saturated with another fluid at rest. On the other hand, the simultaneous flow of both such fluids in a porous medium also occurs in many situations, but has received far less attention. Earlier experimental work has been done on simultaneous two-phase flow in porous media, however mainly in horizontal Hele-Shaw cells. An important observation in previous work is that a steady state configuration is eventually reached for the fluids. The influence of gravity on the flow, as well as 3D flow, has not yet been studied in this type of fundamental experiments. The projects described below are motivated by further exploration of simultaneous two-phase flow in porous media by including gravitational fields in 2D models, and expanding to 3D models.

### STEADY STATE IN 2D: THE ROLE OF GRAVITY

In our 2D experiments, we use a large Hele-Shaw cell that we systematically tilt to tune the influence of gravity on the flow, while the flow rate is systematically varied to explore the different flow regimes. In addition, the measurements performed here aid the development of a new thermodynamic model for steady state two-phase flows in porous media. Currently, we have completed the construction of this experimental setup, and experiments are running well. In the experiments, the wetting (water-glycerol) and the non-wetting (air) phases are injected simultaneously from alternating inlet points into a Hele-Shaw cell containing one layer of randomly distributed glass beads, initially saturated with the wetting fluid. We capture high resolution images in time-lapse series during the experiments, record the pressure at 8 locations in the cell, and systematically vary the influence of gravity and flow rate. Image and signal processing is used to analyze the results. Fig. 1 shows the development of the invasion dynamics until steady state is reached.

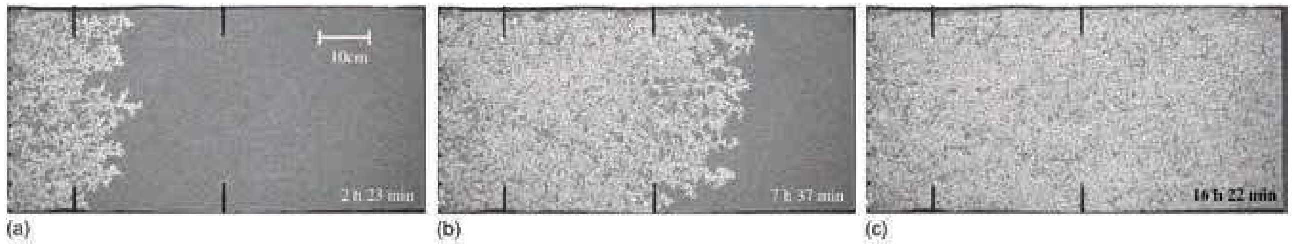


*Fig. 1: Top-down photos of the two-phase flow experiment at three different times. Both fluids are injected at the left hand side; the outlet is at the right. The water-glycerol mixture is of dark color and the air is white. In a) we see the early transient regime, where air is invading the initially liquid saturated sample. Panel b) shows a later stage in the transient regime with a local steady state behind the front, and panel c) shows the fully developed steady state flow where the system is in a statistical equilibrium. In this state, both fluids are flowing through the system while the distribution of the air and liquid phases remain more or less constant over time.*

### STEADY STATE IN 3D: THE DEVELOPMENT OF A FAST SCANNING SETUP FOR TWO-PHASE FLOWS

In this project we scale the 2D two-phase flow experiments up to 3D. Since the process of imaging a 3D sample is more complicated than in 2D (where we benefit from the camera-friendly Hele-Shaw geometry), we have developed an optical 3D scanning technique. The basic idea is to make the porous media and the liquids used in the experiments transparent by matching the respective refractive indices. A sample is prepared with glass beads of uniform size, fully immersed in an index-matched liquid with fluorescent particles. Illumination from a green laser sheet highlights a 2D slice of the sample (liquid in the laser sheet emits light, while beads are not) that can be recorded with a high-resolution camera. By putting the camera and the laser on motorized stages and scanning the laser sheet through the sample, a 3D recording of the full sample is realized. During experiments, a second liquid (immiscible with the first liquid) with fluorescent particles that emits at a different wavelength is flowed through the porous network while scanning the sample. The data from several parallel 2D sheets within the sample is combined using image analysis codes, which yields full 3D maps of both liquid phases and the porous network (see results in Fig. 2). In addition, pressure sensors are mounted at the inlet and outlet of the flow cell. At this point, we have developed a working setup for 3D steady state flow experiments, and experiments are now running well.

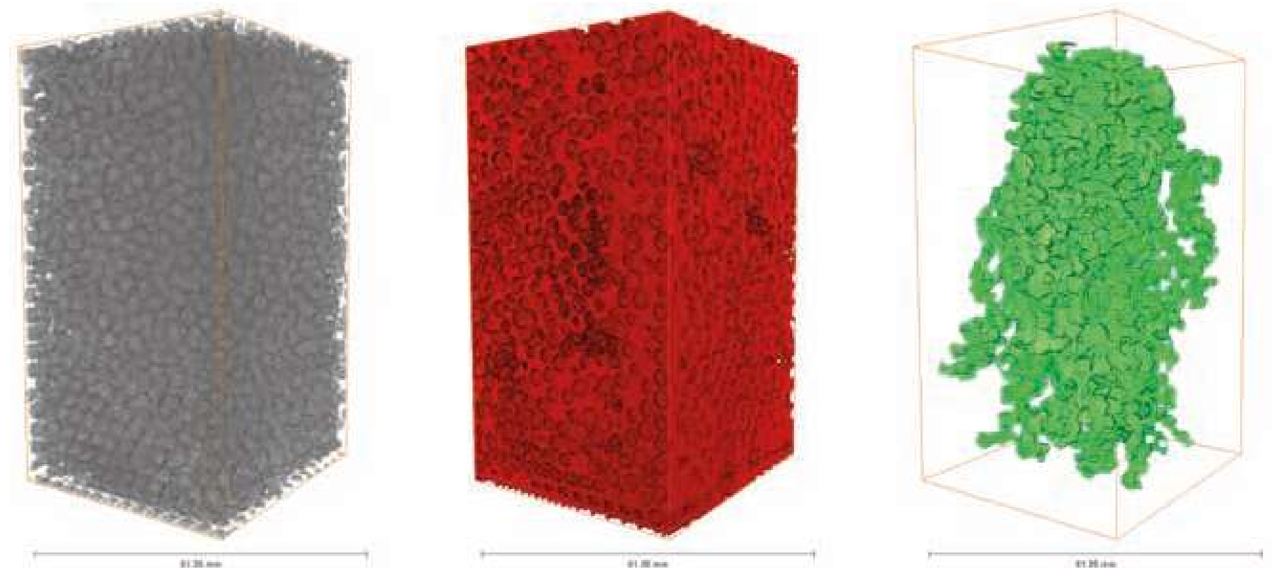

*Fig. 2 Results from the two-phase flow 3D scanner experiment. The bead packing (3 mm glass beads) is shown on the left. The pore fluids, canola oil (red) and glycerol (green), are shown in the middle and right panels respectively. The experimental results show that the optical technique can clearly distinguish the porous media and pore fluids in a 3 dimensional flow cell.*

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# SYMMETRY AND NEW EQUATIONS

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Here is how *dictionary.com* defines the term *symmetry*: "the quality of being made up of exactly similar parts facing each other or around an axis." In physics, the definition is much wider, richer and therefore more useful. Here, symmetry means that your object is unchanged after you have done something to it. For example, if you rotate a spinning top, it will look the same afterwards. The fact that an object is symmetric with respect to some transformation has profound consequences in theoretical physics. It leads to relations between variables that describe the behavior of the object that otherwise would remain undetected. For example, the symmetry of the top leads to relations between the forces acting upon it that explain its motion; for example, why it does not tip over when rotating.

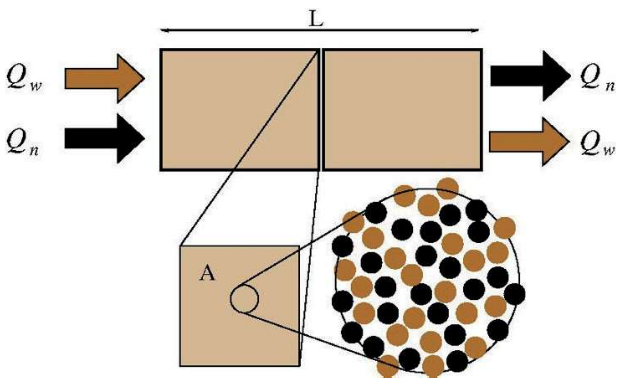


*Fig. 1: Here we show a porous medium seen from the side. We are pumping two immiscible fluids through it at the vertical side to the left and the leave the porous medium at the opposite side. The rates at which we pump the two immiscible fluids are Qw and Qn. The length of the porous medium is L and the area orthogonal to this axis is A. As explained in the text, we make an imaginary cut through the porous medium along a plane parallel to the two planes at which the fluids enter and leave the porous medium as indicated. We show in the lower right of the figure a blow-up of a small region of the porous medium, indicating the pores, which are filled with either of the two fluids.*

Some symmetries are obvious. Others can be quite hidden. We have discovered an overlooked symmetry in the flow of immiscible fluids in porous media. Before describing it, we need to describe the system.

Suppose we have a porous medium, in which two immiscible fluids are competing to flow through it. The porous medium has a given length L in the flow direction and a given cross-sectional area A in the plane perpendicular to the flow direction, see the first figure. We pump the two immiscible fluids through the porous medium at volumetric rates $Q_w$ and $Q_n$ respectively. We assume that all transients occurring when initiating the flow experiment have died out so that the system is in a steady state. Suppose we now make an imaginary cut through the porous medium along a plane perpendicular to the flow direction as shown in the figure. We will see the matrix material and the pores. Some of these pores will contain the "w" (for "wetting" – shown as brown) fluid whereas the other pores will contain the "n" (for "non-wetting" – shown as black) fluid. There is an area $A_s$ associated with the matrix material, an area $A_w$ associated with the brown fluid and an area $A_n$ associated with the black fluid, and we have that $A=A_w+A_n+A_s$. Inside the porous medium, the fluid will move with average velocities of the fluids in the pores, $v_w=Q_w/A_w$ and $v_n=Q_n/A_n$ respectively.

Suppose we now change the cross-sectional area A of the porous medium by a factor λ. That is, we transform the porous medium by scaling the cross-sectional area by $A \to \lambda A$ without changing the pore sizes. In practice, this means replacing the original porous medium by another one made from the same material but with the changed cross-sectional area. We do not change the length L of the porous medium. We illustrate the transformation below.

If we now transform the volumetric flow rates of the fluids $Q_w \to \lambda Q_w$ and $Q_n \to \lambda Q_w$, we see that the average seepage velocities $v_w$ and $v_n$ remain unchanged. In fact, the flow properties inside the porous medium are unchanged. This is the hidden symmetry.

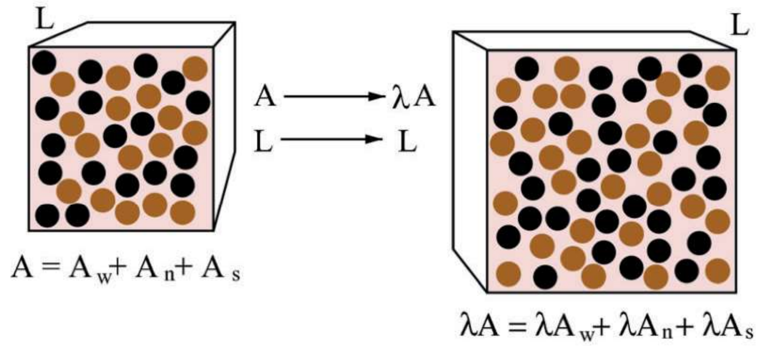


*Fig. 2: Our symmetry transformation consists in changing the area A perpendicular to the flow direction while leaving the length of the porous medium unchanged.*

The symmetry just described leads to relations between the seepage velocities of the two fluids. If $S_w$ and $S_n$ are the saturations of the two fluids, defined as pore volume of the porous medium occupied by one of the fluids divided by total pore volume, we have for example that

$$S_w\,(dv_w/dS_w) + S_n\,(dv_n/dS_w) = v_m,$$

where $v_m$ is a new velocity parameter, – we have named it the co-moving velocity – which characterizes the relative motion of the fluids.

So, what is this good for? From a theoretical point of view, this symmetry and the ensuing relations open the door to a vast simplification of the problem by reducing the number of variables that describe the problem. We have relations that transcend the detailed physics of the fluid flow. This is reminiscent of thermodynamics. Thermodynamics is a body of relations between quantities one measures in connection with heat flow and work. These relations are the results of symmetry considerations much like those we have outlined here. The thermodynamic relations transcend the detailed physics of system. The physics of the system is coded into the equation of state, which is all we need to know about it. We then use the thermodynamic relations combined with the equation of state to calculate whatever we wish to know. In our system, the co-moving velocity and the seepage velocity averaged over the two fluids together play the role of the equation of state. Knowing these, we may answer all question pertaining to the macroscopic flow parameters.

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# DISSIPATION IN POROUS MEDIA

Signe Kjelstrup[1], Dick Bedeaux[1], Bjørn Hafskjold[1], Olav Galteland[1], Kim R. Kristiansen[1], Marco Sauermoser[1], Astrid F. Gunnarshaug[1], Øivind Wilhelmsen[1], Alex Hansen[2], Magnus Aa Gjennestad[2], Eirik Flekkøy[3], Knut Jørgen Måløy[3], Marcel Moura[3], Natalya Kizilova[4], Maria Barragan[5], Odne S. Burheim[6], Ali Seyed Amiri[7]

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A spontaneous process will take place when it implies a positive entropy change in the system plus surroundings. These changes in entropy can be measured in terms of changes in temperature and mass. The entropy produced can also be formulated by the product sum of all driving forces and corresponding fluxes. This is done in the theory of non-equilibrium thermodynamics, a theory founded by the Norwegian-American Lars Onsager in 1931, see [1-3].

From knowledge of relevant forces and fluxes, we can model a process, or design experiments that help us to understand the underlying reason for the entropy production. The theory is well understood for uniform systems [1,2], even for layered systems [3]. There are many applications; to batteries, fuel cells, electrolysis systems, multicomponent diffusion, thermal diffusion, and viscous flow, to name a few [1-3].

We can measure the entropy production, or the energy dissipated as heat, on the macroscopic scale. But for a porous system it is difficult to relate such a measurement to the events on the pore scale. Vice versa, there is no consensus about how one can integrate over the collection of pores and obtain results on the macroscale. We have recently proposed a method that may solve this problem [4,5]. We first find a volume that is large enough to represent the medium in an average way, but small enough to serve as a volume element in the integration procedure. This volume is the so-called representative elementary volume (REV). The REV is described by a small set of coarse-grained variables.

Consider as an example Figure 1. A pressure difference is applied to a porous medium A between two reservoirs $B_1$ and $B_2$. The nanoporous medium is represented by part a) of the figure. In order to study the system we use molecular dynamics simulations. A lattice is made of blue particles. In between, these rock-like model particles, there is a single fluid of red particles. The smallest REV is illustrated in the figure. It contains sufficient blue and red particle volumes and interface areas between them, to obtain a good average compressional energy. The various contributions to this energy are illustrated in part b) of the figure.

Within the REV there is a variation in the particle interactions. For the REV as a whole we may speak of a representative pressure, defined from the compressional energy. It remains to verify this hypothesis by experiment, but first molecular simulations for a simple system seems to work. This procedure gives access to a local description which is required for integration between the reservoirs.

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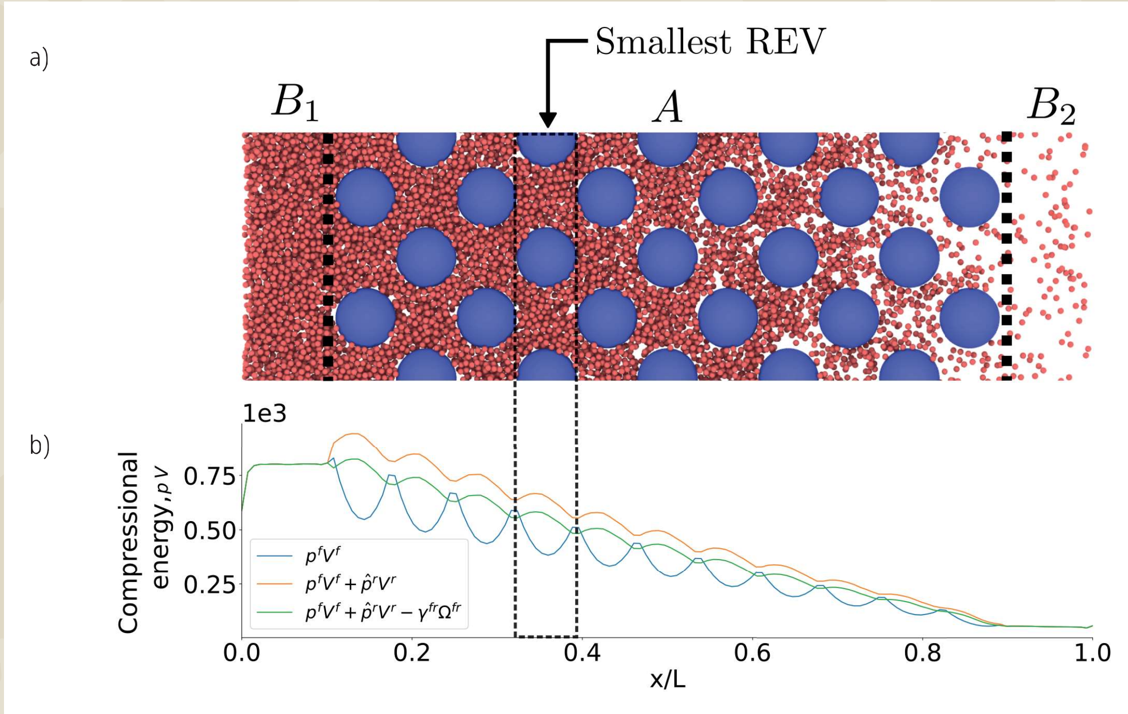


*Fig.1. A regular lattice of large particles surrounded by smaller fluid particles (Part A). Contributions to the total compressional energy vary over the REV (figure b), but the average total value falls on a straight line between two reservoirs ($B_1$ and $B_2$) of different pressure.*

# DESCRIPTION OF TWO-PHASE FLOW IN POROUS MEDIA BY TIME DEPENDENT GEOMETRICAL MEASURES

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The current macroscopic modeling of two phase flow in porous media, based on the two variables pressure and saturation only and saturation dependent constitutive equations (capillary pressure and relative permeability), have long been recognized as being too simplified to represent many important flow scenarios. As an example, a physically more correct description is needed to understand how additives such as surfactants and nanoparticles effect the flow, for instance in the context or planning enhanced oil recovery (EOR) projects.

This project focuses on pore scale images (synchrotron X-ray microtomography) of flooding experiments in order to extract macroscopic geometrical measures and investigate how these correlate to the flow properties. We have in particular been interested in a set of measures called intrinsic volumes. The intrinsic volumes are especially promising as candidates for an improved macroscopic description since they, according to the Hadwiger characterization theorem (Hadwiger 1957), in some sense represent a complete geometrical description of the state of the system. We have published two articles in this project (Khanamiri and Torsæter 2018, Khanamiri et al 2018). The summaries follow.

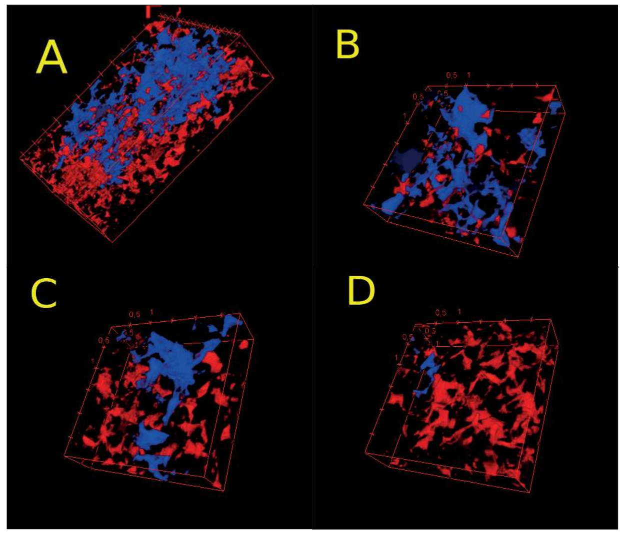


*Figure 1. 3D images of nonwetting connected pathway (blue) and ganglia (red) visualizes the clusters at a volume of 598x594x150 voxels (A); and the sub-volumes of A, each with a volume of 274x276x75 voxels, chosen at three different places where the volumes of pathway and ganglia are different relative to each other (B, C and D). Voxel length is 3.25 μm*

## ARTICLE 1.
## FLUID TOPOLOGY IN PORE SCALE TWO-PHASE FLOW IMAGED BY SYNCHROTRON X-RAY MICROTOMOGRAPHY

HAMID HOSSEINZADE KHANAMIRI, OLE TORSÆTER

A flow experiment including drainage and imbibition by water and surfactant was performed on a water-wet Berea sandstone. The three-dimensional (3-D) pore scale changes of the fluid configuration were captured under flow using synchrotron X-ray computed microtomography. The experiment was performed at the synchrotron facility of Swiss Light Source (SLS) at the Paul-Scherrer Institute (PSI). A fluid phase is normally composed of a large connected cluster (connected pathway) and numerous disconnected smaller clusters (ganglia), as shown in Figure 1. By analysis of the microtomography images, we calculated topology of these two parts separately. Results revealed that topology of a fluid mainly depended on topology of the corresponding ganglia and was less sensitive to topology of the corresponding connected pathway. A fluid phase and its corresponding ganglia had hysteresis in the topology during imbibition and drainage. However corresponding connected pathway had insignificant hysteresis, i.e. the hysteresis in topology of the phase was caused by the ganglia.

## ARTICLE 2.
## DESCRIPTION OF FREE ENERGY FOR IMMISCIBLE TWO-FLUID FLOW IN POROUS MEDIA BY INTEGRAL GEOMETRY AND THERMODYNAMICS

HAMID HOSSEINZADE KHANAMIRI, CARL FREDRIK BERG, PER ARNE SLOTTE, STEFFEN SCHLÜTER, OLE TORSÆTER

Advanced geometry was utilized to give a description for free energy of a system of immiscible two-fluid flow based on microscopically evolving geometrical variables. Based on characterization theorem (Hadwiger, 1957), the free energy was described as a linear combination of intrinsic volumes of fluids, fluid-fluid and fluid-solid interfaces and the three phase contact lines (Figure 2). Intrinsic volumes are defined as volumes, surface areas, integrals of mean curvature and integrals of Gaussian curvature (Euler characteristic) of different domains. We investigated how a number of the intrinsic volumes were related. This helped simplifying the description for energy as a function of the intrinsic volumes and reducing the number of geometrically independent variables to seven with no limiting assumption on wettability (Eq. 1). The number of geometrically independent variables for extreme wetting conditions where nonwetting phase has no contact with solid surface was found to be four. The energy of the system was also approximated by a simple thermodynamic approach based on macroscopically measurable variables (Eq. 2), assuming that the flow happens very slowly with low capillary number. By merging these two descriptions of the free energy we found the constant coefficients of the intrinsic volumes ($\Delta\hat{F}(S_n) = \hat{c}_0 S_n + \hat{c}_{1n}\hat{A}_n + \hat{c}_{2n}\hat{H}_n + \hat{c}_{3n}\hat{\chi}_n + \hat{c}_{1w}\hat{A}_w + \hat{c}_{3w}\hat{\chi}_w + \hat{c}_{wns}\hat{L}_{wns} - \hat{F}_i$'s in Eq. 1) for a set of quasi-static spontaneous imbibition experiments. We then used (Eq. 1) to find the free energy of a full cycle primary drainage (PD), main imbibition (MI), main drainage (MD) experiment (Figure 3). Given that the external work was measured in the experiment, the theory enabled us to estimate the amount of dissipated energy along the imbibition and drainage processes (Figure 3).

$$\Delta\hat{F}(S_n) = \hat{c}_0 S_n + \hat{c}_{1n}\hat{A}_n + \hat{c}_{2n}\hat{H}_n + \hat{c}_{3n}\hat{\chi}_n + \hat{c}_{1w}\hat{A}_w + \hat{c}_{3w}\hat{\chi}_w + \hat{c}_{wns}\hat{L}_{wns} - \hat{F}_i \qquad \text{(Eq. 1)}$$

$$\Delta\hat{F}(S_n) = 0.925 \int_{S_i}^{S_n} \Phi P_c \, dS_n \qquad \text{(Eq. 2)}$$

$S_n$ nonwetting saturation; $\hat{A}_n$ and $\hat{A}_w$ nonwetting and wetting surface area; $\hat{H}_n$ integral of mean curvature over nonwetting surfaces; $\hat{\chi}_n$ and $\hat{\chi}_w$ integral of Gaussian curvature (Euler characteristic) over nonwetting and wetting surfaces; $\hat{L}_{wns}$ length of three-phase contact lines; $\Delta\hat{F}(S_n) = \hat{c}_0 S_n + \hat{c}_{1n}\hat{A}_n + \hat{c}_{2n}\hat{H}_n + \hat{c}_{3n}\hat{\chi}_n + \hat{c}_{1w}\hat{A}_w + \hat{c}_{3w}\hat{\chi}_w + \hat{c}_{wns}\hat{L}_{wns} - \hat{F}_i$ and $\hat{F}_i$ constant coefficients; $\Phi$ porosity; $P_c$ difference of macroscopic wetting and nonwetting pressures (gauge pressure).

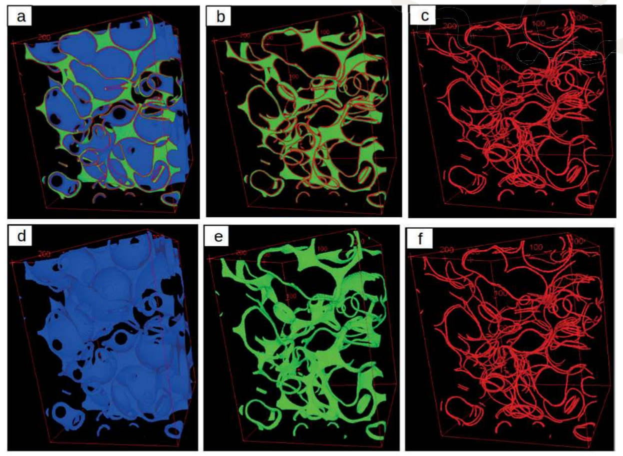


*Figure 2. Experimental 3D example of the geometrical sets and the constituent parts. The size of the cropped volume is 2270×2540×2940 (μm)³. In all figures, the solid and one of the fluids were removed to accentuate the examined fluid. (a) the fluid α (blue), the interfaces of fluids α and β (green) and the three-phase contact lines (red); (b) the interfaces of fluids α and β, and the three-phase contact lines; (c) the three phase contact lines; (d-f) are the corresponding constituents parts of (a), (b) and (c).*

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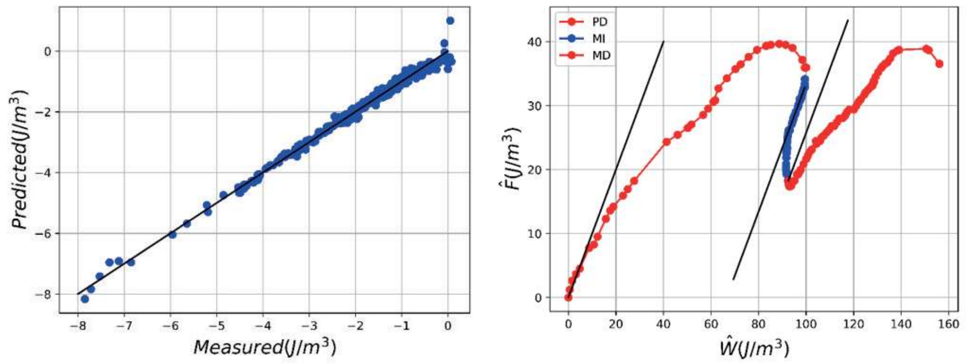


*Figure 3. The change in free energy (Eq. 1) calculated by the geometrical parameters versus the external work (Eq. 2). The constant coefficients in (Eq. 1) were calculated by a linear regression for the low-dissipation spontaneous imbibition (left chart), and then specific free energy $\hat{F}$ calculated from the geometrical parameters (right chart) versus the specific external work $\hat{W}$ calculated from the saturation change and external pressure difference for a PD-MI-MD full cycle experiment. The straight lines indicate the reversible processes.*

# NANOCELLULOSE AS A GREEN ADDITIVE FOR ENHANCED OIL RECOVERY

Reidun Cecilie Grønfur Aadland[1], Carter J. Dziuba[2], Ellinor B. Heggset[3], Kristin Syverud[3], Ole Torsæter[1], Haili Long-Sanouiller[1], Torleif Holt[4], Ian D. Gates[2] and Steven L. Bryant[1,2]

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The application of nanotechnology to the petroleum industry has sparked recent interest in increasing oil recovery, while reducing environmental impact. Nanocellulose is an emerging nanoparticle that is derived from trees or waste stream from wood and fiber industries (Fig. 1). Thus, it is taken from a renewable and sustainable source, and could therefore serve as a good alternative to current Enhanced Oil Recovery (EOR) technologies. The application of nanocellulose in EOR requires understanding of its transport behavior and retention in porous media.

So far we have investigated the retention mechanisms that occur during nanocellulose transport. In a series of experiments, nanocellulose particles dispersed in brine were injected into sandpacks and Berea sandstone cores. A schematic drawing of the flooding apparatus for sandpack is shown in Fig. 2a. The calculation of retention was mainly based on the flooding experiments with tracer (base case) and nanocellulose, while the retention mechanisms were characterized from additional measurements like atomic force microscopy, nanocellulose aggregate size measurements, zeta potential, and batch adsorption.

The flooding parameters that were varied include sand grain size, nanocellulose type, salinity, and flow rate. Under low salinity conditions, the dominant retention mechanism was adsorption and when salinity was increased, the dominant retention mechanism shifted towards log-jamming (Fig. 2b). Retention and permeability reduction increased as grain size decreased, which results from increased straining of nanocellulose aggregates. Higher flow rates gave reduced retention and permeability reduction. Increased velocity gave increased shear rate inside the porous medium, which is believed to promote breakdown of nanocellulose aggregates.

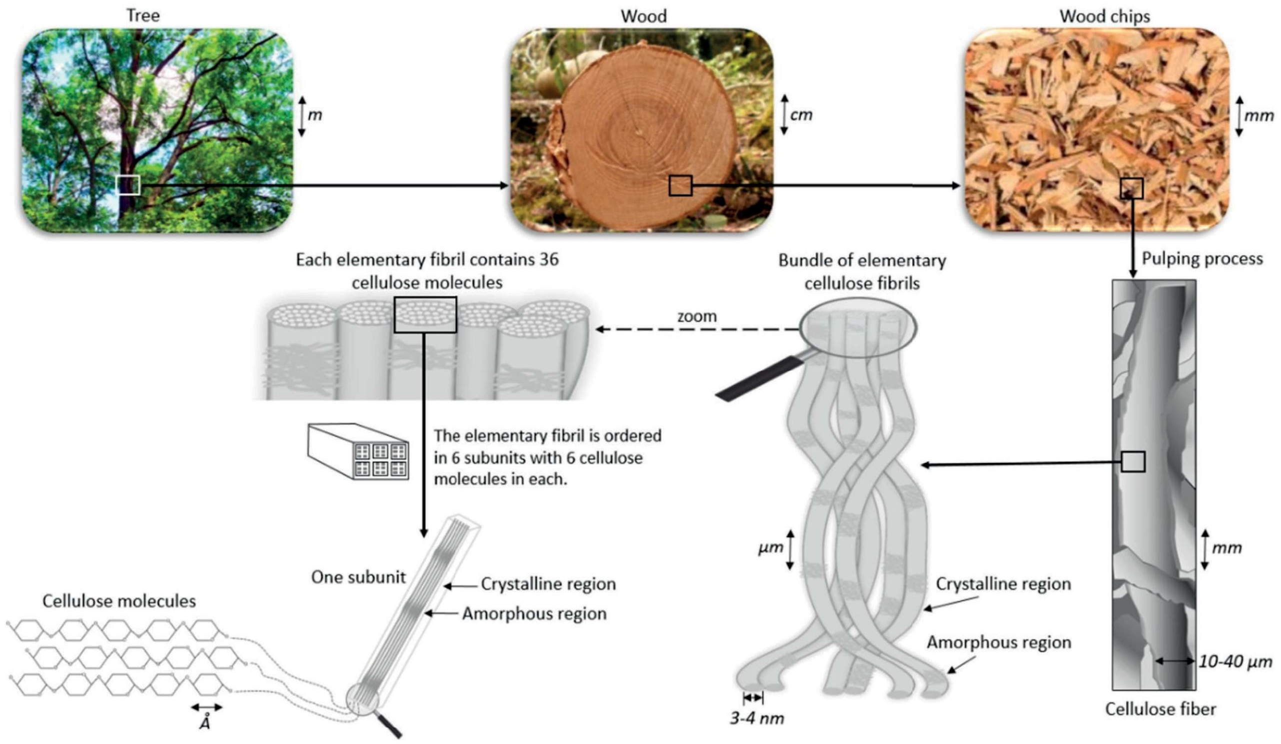


*Fig. 1: Illustration of the product line from a tree to nanocellulose.*

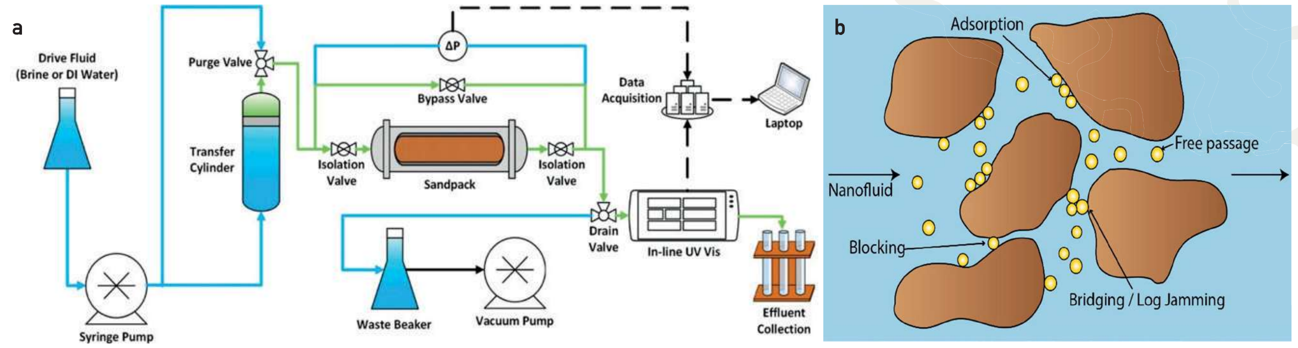


*Fig. 2: a) Schematics of the experimental setup used for sandpack retention flood. b) Possible transport outcomes (blocking, log jamming, adsorption) for nanoparticle flow. Rock grains are brown, nanocellulose is yellow and the porosity is blue.*

For qualitative analysis of retention in sandpack we "baked" (heated to 300 °C) the sandpack after each experiment. The results from the heating of the post-flood sandpacks confirmed the retention results calculated from the flooding effluent concentration. The left image in Fig. 3 is from the low salinity (0.1 wt.% NaCl) nanoparticle flood. The entire sandpack had darkened slightly and uniformly. This is consistent with a small amount of irreversible adsorption throughout the sand and negligible straining of aggregate log-jams. In the high salinity (1.0 wt.% NaCl) flow, however, aggregates are evident at inlet (Fig. 3 right). There is a notable darkening at the front of the pack, while the outlet seems to be unaffected. Thus, nanocellulose retention occurred most heavily at the inlet of pack. This is consistent with log-jamming leading to straining and filter caking. Filter cake was visually observed at the inlet end of the sandpack.

For polymers, 200 µg/g is considered a maximum retention value for EOR application. The results from this nanocellulose research show that the retention is below this maximum in all cases, except for very high salinity and tight rock. A drawback for chemical EOR methods is that they are efficient in limited area around the well due to extensive adsorption and retention. Nanocellulose has low retention and it is therefore worthwhile continuing the evaluation of nanocellulose for EOR.

Of special interest is the viscosity behavior of nanocellulose, which is the subject for future studies. It is known that the viscosity of aqueous cellulose nanocrystals dispersions increases during heat aging at temperatures above 90 °C. This distinct change in material properties at very low concentrations could be an effective mechanism for EOR, as a highly viscous fluid may improve macroscopic sweep efficiencies and mitigate viscous fingering.

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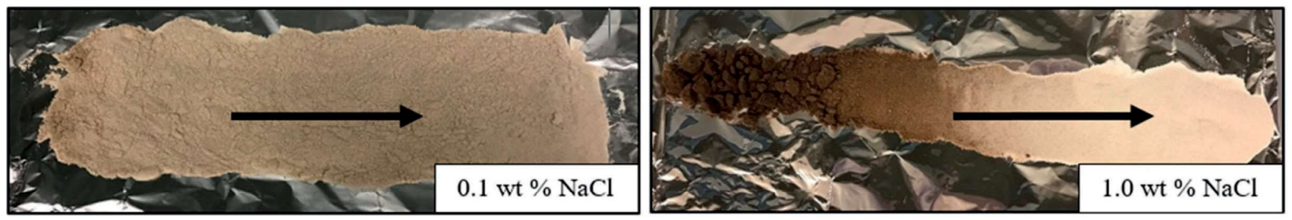


*Fig. 3: Evidence of nanocellulose retention from post-flood sand baking. Darkness correlates with mass of nanocellulose retained in sand after flush. Arrows indicate flow direction. Left: 0.5 wt. % nanocellulose in 0.1 wt. % NaCl resulted in uniformly distributed retention. Right: 0.5 wt. % nanocellulose in 1.0 wt. % NaCl resulted in large retention near inlet. Both flows where at a velocity of 1.4cm/min and 50–70 mesh sand was used.*

# ENHANCED OIL RECOVERY BY STABLE SILICA-BASED NANOFLUIDS ON CORE AND PORE SCALES

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Nanotechnology applications have received significant attention in the oil industry, and an important application is using nanoparticles for enhanced oil recovery. Previous studies at the Norwegian University of Science and Technology (NTNU) have shown that silica nanoparticles significantly improved waterflooding performance. In the early work, it was found that nanofluids increased the oil recovery mainly via wettability alteration and interfacial tension reduction [1, 2].

Recently, experimental work presented new stable surface-modified silica nanoparticles as EOR agents [3]. In this work, an extensive screening procedure was adopted in an attempt to find the best formulated nanoparticle [3]. The procedure consisted of injecting the nanoparticles through a glass micromodel as secondary recovery agents. Promising samples followed injection in water- and neutral-wet Berea sandstone as secondary and tertiary recovery agents [3]. In addition, detailed studies of fluid-fluid and fluid-rock interactions were conducted to gain fundamental knowledge about how the particles increase oil recovery [3]. The main conclusion of this work is that some surface-modified nanoparticles effectively increased the crude oil recovery from the Berea sandstone samples [3].

A pore-scale study was recently conducted using one of the best performers in the aforementioned core-scale study on the surface-modified nanoparticles. This study integrated a core-flooding setup with a micro-CT scanner in the Reservoir Laboratory at NTNU.

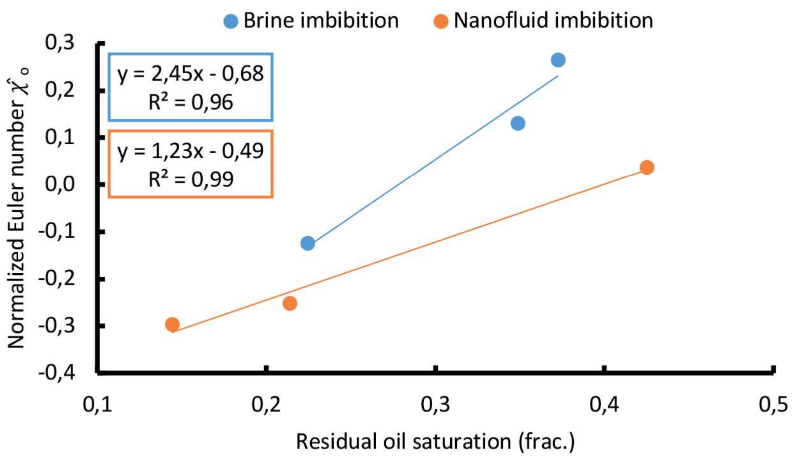


*Figure 1: Normalized Euler number ($\hat{\chi}_o$) of the remaining trapped crude oil in the miniature samples as a function of residual oil saturation ($S_{or}$). It shows that the nanofluid led to lower values of $\hat{\chi}_o$ indicating the ability of the nanoparticles to fragment the non-wetting phase within the sample.*

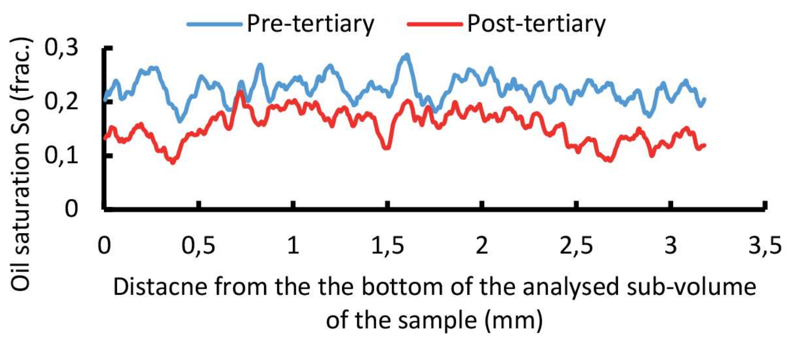


*Figure 2: Vertical variation in oil saturation pre- and post-tertiary recovery*

The results showed that the use of nanoparticles led to a higher reduction in the amount of remaining oil and smaller sizes of the residual oil clusters compared with non-nanofluid as secondary recovery agent [4]. Furthermore, it was found that the nanoparticles had a unique ability to disconnect the remaining oil phase even when the remaining oil phase saturation was high, see Figure 1 [4].

Furthermore, the nanoparticles were able to detach the oil phase from the grain surfaces, as shown by a surface area index. The surface area indices evaluated for the nanofluid experiments were always higher compared to the brine imbibition experiments at the same capillary numbers [4].

Moreover, the modified-surface silica-based nanofluid was a successful EOR fluid as it induced positive pore-scale changes within the sample. Following a brine flooding with a nanofluid flooding resulted in a reduction in the amount of trapped oil within a Bentheimer sample by roughly 30%, leading to an incremental oil recovery of 9.54% [4]. In addition, the connectedness of the oil phase dropped further by 74% and an additional 6.1% of the grain surfaces became wetted with the nanofluid [4]. See Figure 2 and Figure 3.

Future work will be devoted to explore in-situ changes in the non-wetting phase under different conditions such as concentration. It also aims to use the surface area index proposed in [4] to understand the structural disjoining pressure which is considered to be a mechanism contributing to the rock wettability alteration when nanoparticles are introduced to a porous system. It will be supported with information about the change of wettability described by in-situ contact angle between the pre- and post-tertiary recovery.

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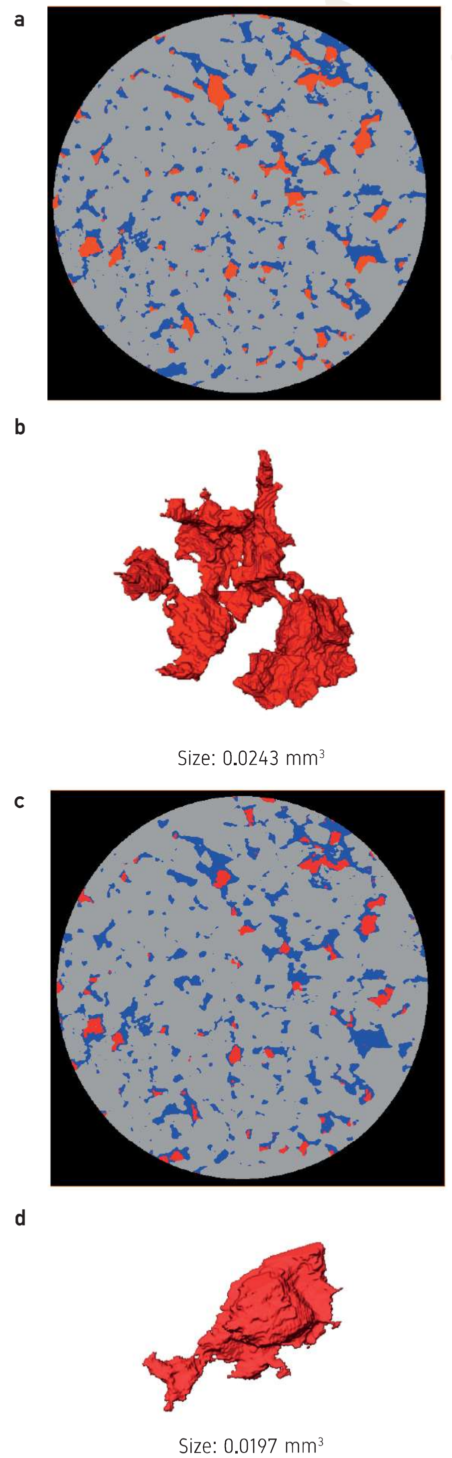


*Figure 3: 2D image of Pre-tertiary (A) and post-tertiary (C), where: oil in red, brine or nanofluid in blue and grain in gray. (B) is the largest resdiual oil cluster within the sample pre-tertirary and (D) for post-tertiary.*

# THE ICE LENS IN FROST HEAVE

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When the ground temperature drops below zero, a flow of ground water to the cold surface may occur, if the soil has so small pores that water is kept in the liquid state. This transport of water due to a temperature difference, leads to the growth of ice lenses near the soil surface. In winter, the growth can lead to 11 bar overpressure per degree temperature difference [1]. It is therefore of interest to control the force of disruption that arises. Figure 1 shows how it is measured in the field. When spring comes, the ice will melt and further disrupt the foundations of the constructions.

The phenomenon, called frost heave is an example of thermal osmosis [2]. It takes place in many porous media, like clayish soil, but also in polymer membranes for fuel cells.

The practical motivation of the project is thus clear: We want to avoid frost heave. The theoretical motivation is general; to formulate a description of transport of water in nano- and micro-porous media in the presence of a liquid-solid phase transition. The phase transition makes the problem into a discrete one, while we are seeking a continuous description of the heat and mass transport to use in practice [3].

The problem of the Frost Heave Group in PoreLab is to first understand the mechanism of ice lens formation and next, in a longer perspective, to find a coarse-grained description of the phenomenon. This description will enable us to model frost heave, from the nanoscale and up to a meter scale. The continuous description is needed in construction engineering [3].

Frost heave has been observed in nature as well as under controlled conditions in the laboratory, but a full thermodynamic description of the transport of two phases, liquid and ice, has not been yet given. The PoreLab group has designed controlled experiments in agreement with a non-equilibrium thermodynamic framework [2]. We have also made a successful description of the formation of a first ice lens (Fig.2). So far, the model is for steady state. This does not properly take into account how the soil deforms upon the growth of the lens. Work will continue in the interdisciplinary group to deal with transient behavior.

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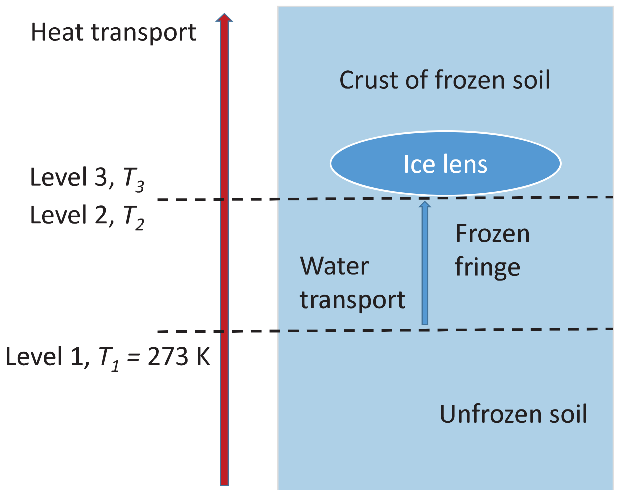


*Figure 2. The formation of the first ice lens, schematic illustration of the continued water flow caused by a temperature difference.*



*Figure 1. Field tests to measure pressures exerted by ice lenses that form inside partly frozen soils.*

# RED HOT BLUE ENERGY

Kim Roger Kristiansen[1], Signe Kjelstrup[1], Maria Barragan[2], Torleif Holt[3], Knut Jørgen Måløy[4]

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Can the abundance of industrial waste heat be used to our advantage when developing environmentally friendly energy concepts?

Imagine that you have two glasses of water – one with fresh tap water, and one with seawater. Now, mix the two, and what do you get? A glass of salt-ish water, of which you would not like to take a sip. This process of mixing cannot be reversed by means of ordinary kitchen equipment – it must be done by adding energy in just the right way so that fresh water and seawater separate. Does this imply that, somehow, energy was released in the process of mixing the two solutions? Yes! This energy, called the energy of mixing, is exactly the target of a rising class of technologies which aim to supply the world with eco-friendly, baseline energy.

One such technology is known as reverse electrodialysis, or RED for short, defining the word in the Title. The RED process is the reverse of something called electrodialysis, which is a way of adding electrical energy in just the right way so that salt migrates from one water solution to another leaving the fresh water behind. The process finds its use in water purification for production of drinking water. Thus, you might guess correctly that RED extracts electrical energy by allowing the two solutions to mix in a controlled manner. A pilot plant in the Netherlands has been producing 50 kilowatts of energy since its invention in 2013, in exactly this way. The project is run by the RED-stack company, who has dubbed this concept "blue energy".

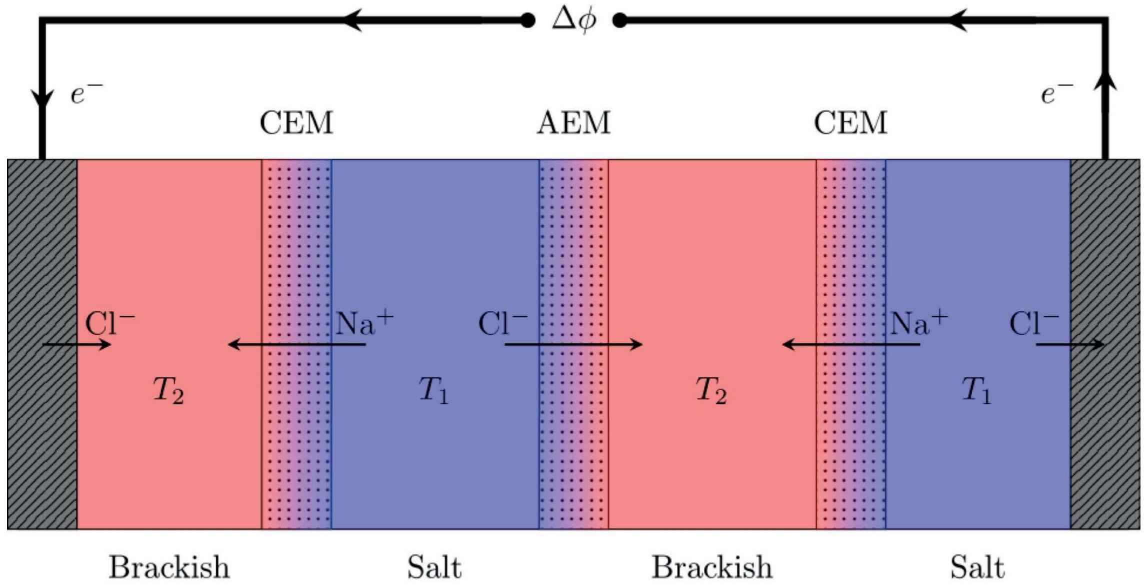



*Figure 1. Illustration of the saline power process, with alternating cation (CEM) and anion exchange membranes (AEM). Transports of Na+ and Cl- ions are indicated. By also raising the temperature in the brackish water to $T_2$ above $T_1$, the measured electric potential, Δφ, can be increased significantly.*

The problem is now: Can we help improve this concept? To answer this question, we have started an experimental program.

Salt solutions are electrical conductors. In the case of salt water, it turns out that a higher temperature will decrease the electrical resistance, thus reducing the energy dissipated by electrical currents, so-called resistance losses. Recent experiments in our laboratory indicate further that there is an extra advantage with hotter fresh water than salt water: There is an addition to the electric potential generated by the RED process; a thermoelectric potential. The technique requires the use of nano-porous charged membranes, i.e. ion-exchange membranes. An analysis has been carried out to examine the potential of this energy source [1], and we are planning a systematic follow up.

We propose to use industrial waste heat, or any other low-grade heat, to heat the incoming fresh water of a RED power plant. In this manner we can recover energy that is otherwise irretrievably lost to the environment.

The project is an application of nonequilibrium thermodynamic theory. It can also be regarded as continuation of the activity on Pressure Retarded Osmosis in SINTEF Industry.

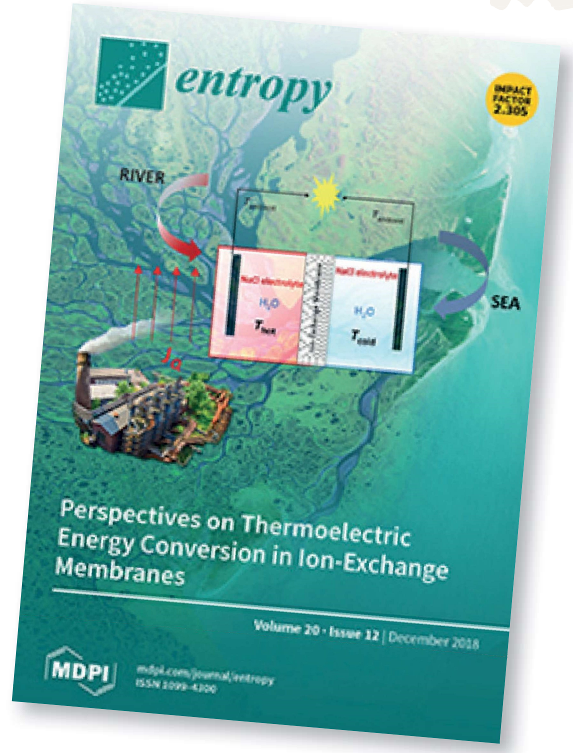



*Figure 2: Front cover of review article in the journal Entropy. Ion ex-change-membranes are needed for the RED technology, and we examine how they perform in a temperature gradient. The outcome of the analysis is that heat should be added to the fresh water side.*

## RECOMMENDED READING

V.M. Barragan, K.R. Kristiansen, S. Kjelstrup, Perspectives on Thermoelectric Energy Conversion in Ion-Exchange Membranes, *Entropy*, 20 (2018)

T. Holt, Pressure Dependency of the Membrane Structure Parameter and implications in Pressure Retarded Osmosis, Chapter, pages 111-128, Osmotically Driven Membrane Processes. Approach, Development and Current Status, IntertechOpen, 2018, ISBN 978-953-51-3921-8

RESEARCHER

# SRUTARSHI PRADHAN

Department of Physics, NTNU

### Who are you? What is your background?

I am Srutarshi Pradhan, working as a Researcher at PoreLab, NTNU, Trondheim. My academic background is Physics. I did a Master of Science (1997-98) in Physics at the University of Calcutta, India and had a PhD (1999-2004) on *Dynamics of Fracture and Failure in Disordered Systems* from Saha Institute of Nuclear Physics, Kolkata, India. I was a Post Doc. Fellow at the Physics Department, NTNU, for 4 years (2004-2007). I worked at SINTEF Petroleum Research, Trondheim, for some time (2008-2016) as a Research Scientist. I got a chance to serve PoreLab as a Researcher and application Coordinator in 2017 when PoreLab started its journey as a prestigious Center of Excellence (SFF).

### How did you come being interested in physics?

In my childhood, I became very much curious when I accidentally found two small iron-like black pieces inside an old box in our store room. They were pulling each other sometimes and were pushing each other away sometimes. It was like a miracle to see this behavior at that age. I spent a few days with my two pets. When I asked my parents, I came to know that they were "*magnets*" and there are "*Science*", specifically "*Physics*" behind such behavior. I believe that this incident created my "*First Love*" towards Science and Physics and it made my life simple and easy. *Physics* was always my first choice for College and University study/courses.

### What are your activities at PoreLab?

According to my contract with PoreLab, I should share my work-time between Coordination-work (50%) and Own-research (50%). I am helping our colleagues in preparing Applications/Research proposals for different funding schemes, like NFR calls, ERC calls and internal University calls. I have been attending the Workshops on H2020 proposals, ERC grant proposals and sharing funding information (and what I have learnt in the workshops) with our colleagues at the PoreLab group meetings.

Currently, I am organizing proposal presentation sessions for all the proposals to be submitted to NFR, H2020 and ERC calls. We are discussing together the weaknesses and strengths of the proposals and planning together how to improve the quality of our proposals.

In my own-research time, I am working on two specific problems: 1) *Fracture propagation in porous media during fluid injection* 2) *Estimation of the strength of porous systems using Fiber Bundle Model (FBM).* The first problem is in line with PoreLab research objectives towards field-scale applications like Enhanced Oil Recovery, $CO_2$ Sequestration and Geothermal Energy Production. The second topic is scientifically interesting and challenging, as it is a new approach to use FBM directly in Porous media research.

### How is it to be a researcher at PoreLab?

I *feel* that PoreLab is a nice and attractive work place. The wishes and constant efforts by the directors and the PIs have created a healthy and warm research atmosphere with a family feeling among the group members. We meet every day for Coffee at 10:00 and for Lunch at 12:00. It is easy to meet Seniors and discuss/express our doubts – in scientific matters or in any other issues – even this has been encouraged and assured by our senior members – *"there should not be any barrier for communication within our group".*

### What about the future, where do you see yourself in 5 years?

I am happy with my work in PoreLab and I like to continue my academic/research carrier at PoreLab. In PoreLab we have experts from all three research fields: Experiment, Theory and Simulation. This is Unique and I believe not many SFF centers have these three expertise together. There are lot of things you can learn from the experts.

### What is your wish for PoreLab?

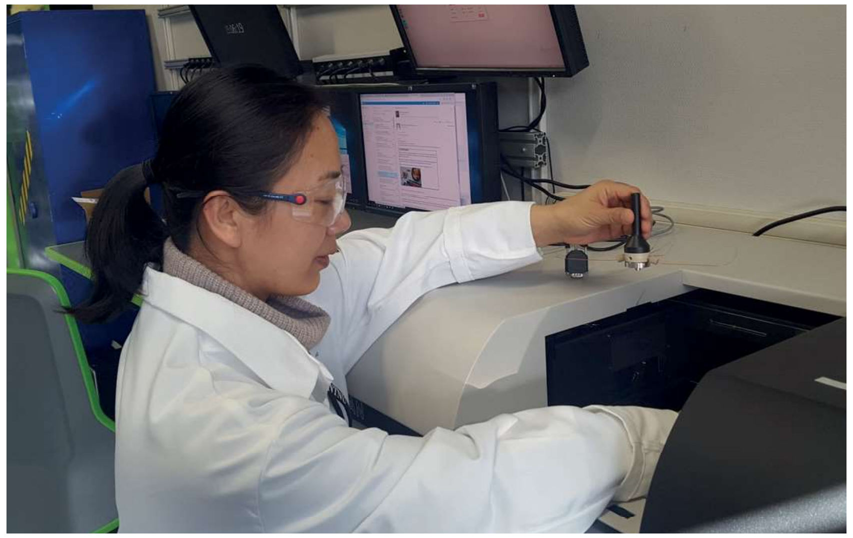
I wish that PoreLab will become a Unique Hub for porous media research to the scientific community and it will earn its identity and status, not only by producing good scientific results but also by producing world-class research talents through proper training and guidance. One day our students and researchers will be known and recognized as "fruits of PoreLab". We will work together as a Team and surely, we will earn this Status.



POSTDOC

# HAILI LONG-SANOUILLER

Department of Geoscience and Petroleum, NTNU



### Who are you? What is your background?

My name is Haili Long-Sanouiller, from China. I did my Bachelor and Master degree of Geophysics in China. I completed my PhD in Geology in KU Leuven, Belgium, in 2010. The research topic of my PhD was about applying mCT (microfocus X-ray computed tomography) technique to sandstone study. Afterwards, I worked in a mCT laboratory of a private oil & gas service company. I was in charge of mCT imaging and image analysis for 7 years. In 2018, I joined as a postdoctoral fellow the PoreLab center of excellence, NTNU division. My major research subject is about applying mCT technique to multiphase flow experiment.

### How did you come being interested in geosciences?

I was always fascinated by natural science since I was a kid, and I was very fond of physics and geography when I was in high school. It was very difficult for me to decide which one I should choose as the subject for my university study. At the end, I chose geophysics although it was not exactly the combination of geography and physics as I expected. It has its own charm that caught my interests.

### Do you think that the work you are doing now can help changing the oil and gas industry?

Yes, I do. What we are doing now is trying to use non-traditional method to study reservoir properties. mCT technique has been applied in oil and gas industry for many years, but the acceptance is not wide enough due to the lack of understanding. However, with its unique advantages, i.e. 3D visualization and non-destructive, mCT technique can help to open the black box of reservoir properties, and visualize the inside of rock samples, e.g. pore space. The fast speed mCT scanning technique even can capture the moment of flow distribution and 4D process of flow experiment. The achievement will give better understanding of reservoir properties, hopefully to help the production process of oil & gas to be more efficient and economical

### What made you decide to come to Trondheim?

This is a very frequent question to me. I came to Trondheim because I found a job here after I finished my PhD study. Moreover, the work scope matched my skills very well although I knew nothing about Trondheim at that moment. However, after 8 years, I want to say that I made a correct decision to move here.

### How is it to be a post-doctoral researcher at PoreLab?

It is a great opportunity for me to be able to work here. I have 10 years working experience on mCT application. These last few years, I had a plan to develop my skills on flow experiment with mCT technique, but did not get the opportunity to do so. This post-doc project is perfect for me. I can bring to the project my expertise and learn at the same time new skills. PoreLab is an interdisciplinary hub that brings together scientists from various fields as reflected by the research themes. The synergy that the center offers not only allows me to improve my knowledge in reservoir engineering, but to re-connect with other disciplines, such as physics and chemistry.



SPOTLIGHT ON SIX YOUNG RESEARCHERS

POSTDOC

# MARCEL MOURA

Department of Physics, University of Oslo

### Who are you?
### What is your background?

My name is Marcel Moura and I am a postdoc at PoreLab. I am originally from Brazil and I am used to 25°C winters so you can imagine moving to Norway was quite an experience! My background is in Physics. I had a pretty linear career path so far: BSc in Physics, MSc in Physics and PhD in Physics. I guess I am somewhat of a physicist by now.

### How did you become interested in physics and how did that bring you to PoreLab?

I have always been interested in science, mostly because of my grandfather Mauricio who was quite clever and really liked to spend time talking with me. We had a telescope at home so whenever he was around he would take the telescope to the street to show me the Moon and the stars. So that made me interested in space stuff. Space stuff then evolved in my head into an interest for airplanes and aerodynamics.

Fast forward 10 years and I was a Physics student at the Federal University of Pernambuco, in Brazil. During my second year of the bachelors, a course on Fluid Mechanics was offered and since that is related to aerodynamics, I had to take it! We had an excellent lecturer, Giovani Vasconcelos, and I decided to take a Master with him on the motion of vortices in ideal fluids. I really liked it, but felt that in a field as visual as fluid mechanics, doing experiments would be nice.

I first came to Norway in 2011 for a winter school in Geilo and I really liked the place. When I met Knut Jørgen Måløy in a conference in 2012 and he told me about the experimental activity in porous media flows in Oslo, it just clicked! I decided to apply for a PhD position at the University of Oslo and was very fortunate to get it.

### What are you doing now in your research?

My work mostly focuses on experiments on slow drainage flows. We make artificial transparent porous networks in the lab. We can see how fluids move inside the network and how they push one another. This process generates some very interesting patterns that we study. We also use image analysis routines to measure quantities that are nearly impossible to measure in real porous samples, like rocks and soils. We can for example have information about the relative probability of pore invasion events. We also perform pressure measurements on the system and try to understand what the pressure signal tells us about the dynamics of the flows.

### How is it to be a postdoc at PoreLab?

I think one very important aspect that needs to be taken into account for a successful PhD or postdoc (in PoreLab or elsewhere) is the balance between expert guidance and independent research activity. Before arriving at PoreLab, my background was mostly on theoretical fluid mechanics so I had almost no expertise on experimental science. I think it was very good to get proper guidance then, while I was still very new to everything. However, I think it was also very important that this guidance never became excessive, in the sense that I never felt that I was just following some recipe predefined by the experts. This was crucially important for me, because it allowed me to learn how to develop my own ideas and to grow as a researcher in my own right. I think this is one excellent feature of PoreLab, being both a place where we can find an array of highly qualified and helpful professionals, who tackle the porous media problems from different perspectives, but also a place where your own individual ideas are taken into account and can flourish.

### What about the future, where do you see yourself in 5 years?

One great thing about research on porous media is that the field is very broad and the problems involved are of relevance for several segments of society. There are therefore many opportunities for professional activity in the academic, industrial and government sectors. Myself, I think I was bitten long ago by the university bug: I like the university environment too much to leave it, so most likely I will continue with an academic career. Maybe in 5 years I could be starting my own research group, we will see what happens.



POSTDOC

# FREDRIK K. ERIKSEN

Department of Physics, University of Oslo

### Tell us about yourself

My name is Fredrik K. Eriksen. I am from Oslo and 31 years old. I am working as a postdoctoral fellow at the Oslo division of the PoreLab center of excellence. Here, we focus on experimental work with complex systems, including fluid flow in porous media. Some of my academic interests are one- and two-phase flow in porous/granular media, flow instabilities, deformation and fracturing, which fits perfectly within the scope of PoreLab. I hold a bachelor's degree in physics and a master's degree in condensed matter physics, both from the University of Oslo. After my master's, I went to the University of Strasbourg and completed a Ph.D in experimental geophysics.

### How did you come being interested in physics?

I have always enjoyed natural sciences and to understand how things work. So I began taking physics courses in high school, found it to be very interesting, and decided to study physics at the university. Later, when searching for a project for my master thesis, I met Knut Jørgen Måløy (PI, Oslo) and learnt more about flow in porous media. It fascinated me how complicated such systems could be, in addition to that they are poorly understood. This made the physics of porous media very interesting to me. Flow in porous media has not been given much attention in research compared to other fields, and I enjoy exploring fundamental processes, particularly by doing experiments.

*Photo top right:*
*Preparing the simultaneous two-phase flow experiment*

*Photo to the left:*
*Experimenting with oil and water in a vertical porous medium*

### Can you explain a little more about your experimental research?

Currently, I am doing experiments to study the simultaneous flow of immiscible fluids in a porous medium. We do such experiments by injecting water and air (immiscible fluids) together into a model porous medium between two glass plates. The flow happens through the porous medium between the glass plates, and therefore we can see directly what is happening. The behavior of the flow is captured by a camera and studied by image analysis. This type of setup has been studied before in a horizontal model, but the new aspect now is that we are studying the impact of gravity by tilting the model at different angles. There is a porous media flow theory under development in PoreLab Trondheim, and we think that analysis of these experiments can give helpful insight for that work.

### How is it to be a post-doctoral researcher at PoreLab?

I think that it is very nice to be a post-doc at PoreLab. The center provides support from a network of leading researchers in the field of porous media and the necessary funding to build state-of-the-art experimental setups, in addition to great individual networking and collaboration opportunities.

PHD

# HAO GAO

Department of Civil and
Environmental Engineering, NTNU

SPOTLIGHT ON SIX YOUNG RESEARCHERS

### Who are you? What is your background?

My name is Hao Gao, and I come from Beijing, China. I am a PhD candidate at the Department of Civil and Environmental Engineering, NTNU. My project is a joint research project between the Geotechnical research group and PoreLab. I got my bachelor's and master's degrees in engineering from Beijing Institute of Technology and my major was about engineering mechanics. During my master's degree, I worked on material and explosive mechanics and numerical simulation. Then I worked as an assistant researcher in a Standards Institute of a state-owned enterprise in China for more than 2 years.

### How did you come being interested in physics and geosciences?

My passion for physics began with a Math teacher from high school. Although he taught mathematics, he talked about real world and actual engineering projects. I ceased to see physics and math as a collection of arbitrary equations and meaningless mathematical procedures, and began to view the disciplines as intimately and delicately intertwined subjects that explain an infinite number of phenomena. The best part of Physics is to see the underlying elegance beyond the equations. My interest for geoscience comes from daily life since civil engineering is all around us. And infrastructure development is flourishing in China. Civil engineering is at all corner of the world, so how could it not be interesting?

### What are you doing now in your research?

My research project focuses on the modelling of freezing, frozen and thawing soils. The objective of my PhD is to develop a discontinuous computational model for the physical and thermodynamic processes in water saturated porous media during freezing and thawing. Now I am working to modify the existing continuous Thermo-Hydro-Mechanical modeling of frozen soil to discontinuous modeling, then using finite element method and programming the code in Fortran to solve it.

### Do you think that the work you are doing now can help changing the discipline?

In my opinion, this research is very meaningful. Why? Because soils freezing and thawing often cause a lot of fatal damage to the engineering building. By better understanding the frozen soil, we might be able to prevent damages before they happen. Besides, 24% of the land surface area of the northern hemisphere is occupied by permafrost, a large part of it is in the Arctic Circle. The Arctic has many resources available and many countries show interest for Arctic development. Our topic is therefore long lasting. For us in Norway, one third of our land is in the Arctic Circle, so our research is also important for national development strategies.

### What made you decide to come to Trondheim?

When I decided to continue my studies, the Nordic topic was sweeping the world, and of course it is still very popular now. For the geotechnical engineering I am interested in, NTNU is the best choice, not only because of its high academic level, but also because of the complex geological environment of Norway and the prosperity of infrastructure caused by the current economic development. With the quiet environment of Trondheim, it can be said that this is a fertile ground for research. So when I saw this PhD position that fits well with my research background, I did not hesitate to submit the application. I can only say that I am very glad I did it.

### How is the working environment at PoreLab?

I must say it is great, here you can meet a lot of people who have different majors but have the same research interests. When you encounter difficulties in your research, you can always find professionals who can help you solving problems here. Moreover, people in different professional fields can see the same problem from different aspects, and the collision of thoughts will always produce unexpectedly good results. So I think Porelab provides us a such platform for communication and learning.



PHD

# ASTRID FAGERTUN GUNNARSHAUG

Department of Chemistry, NTNU

SPOTLIGHT ON SIX YOUNG RESEARCHERS

### Tell us about yourself

My name is Astrid Fagertun Gunnarshaug, I am from Haugesund and 24 years old. I am a PhD candidate in PoreLab and at the department of chemistry at NTNU. I have a bachelor's and master's degree in chemistry from NTNU. In my project, which is a continuation of the project I worked with during my master's degree, I look at heat effects at specific locations inside lithium ion batteries.

### How did you come being interested in chemistry?

I have always thought that natural science and mathematics are fun and challenging. During upper secondary school, I realized that I really liked chemistry, and decided to study chemistry at NTNU. I like combining theory and experimental work, and for my master's I was lucky to be included in a project on heat effects in lithium ion batteries where I could do both.

### Tell us more about your project

If you are inside a room at 25 degrees, you may still burn your hand on a frying pan. Water vapor may still condense around the window on a cold day. These are examples of local heat sources and sinks. Inside a battery, the interface between different parts of the cell will act as heat sources or sinks. One of these local effects is the change in temperature when charge passes the interface. This happens whenever we charge or use a battery. The problem we face is that these effects are very difficult to measure directly because the interface is very thin, on the scale of nanometers! The interface is where the ageing of the battery happens, so knowing the temperature of it is very important. Fortunately, we know of an indirect way of finding this heat effect, which is easier to measure in the lab. I make cells only containing parts from one part of a battery cell and see what happens to the electric potential when I heat up one side and cool the other. We can then relate this to the local effect we want to find in the full battery. This we do from knowing how heat and charge transport are coupled through thermodynamics.

### Do you think that the work you are doing now can help the battery industry?

Temperature is extremely important for how fast the battery is ageing. This ageing mainly happens at the interface between the different parts in the battery. My goal is therefore to help understand these ageing processes. Temperature is also a major problem in lithium ion batteries. If it gets too high, the battery can explode. Knowing the highest temperature inside the battery is therefore very important, just as in the frying pan example mentioned before. Because we are measuring local heat sources, we will probably find the highest temperature inside batteries when it is charging or being used.

### How is it to be a PhD student at PoreLab?

It is fun and exciting. Because we are an interdisciplinary group, we work with people from different departments and universities and fields of research, which makes it an excellent learning environment. It is also great for me as a PhD student to have a network of experienced professors, post-docs, researchers and other PhD students in the office.

# LABORATORY FACILITIES

Several laboratories at both institutions, NTNU and the University of Oslo (UiO), are involved in PoreLab activities. All offer excellent working conditions and are equipped with the-state-of-the art equipment and instrumentation.

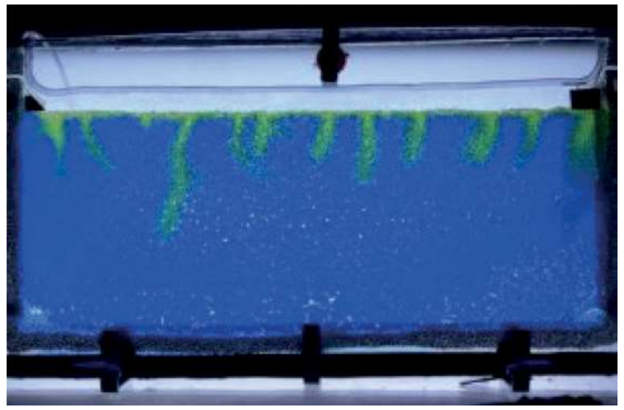
## LABORATORIES AT THE PHYSICS DEPARTMENT AT UIO

Four specialized laboratories at UiO are equipped to pursue a wide set of state-of-the-art techniques to study the dynamics and structure of flow in two- and three-dimensional porous media.

The laboratories offer a full range of high-resolution and high-speed imaging techniques, including two ultrafast *Photron Ultima* (*SA5* and *APX*) cameras with 7000 fps at a spatial 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 camera and accompanying optics. Microscale experiments can be imaged via far field microscopy using a Zeiss Stemi 2000°C distorsion-free stereo microscope which couples to our high-speed and high-resolution cameras.

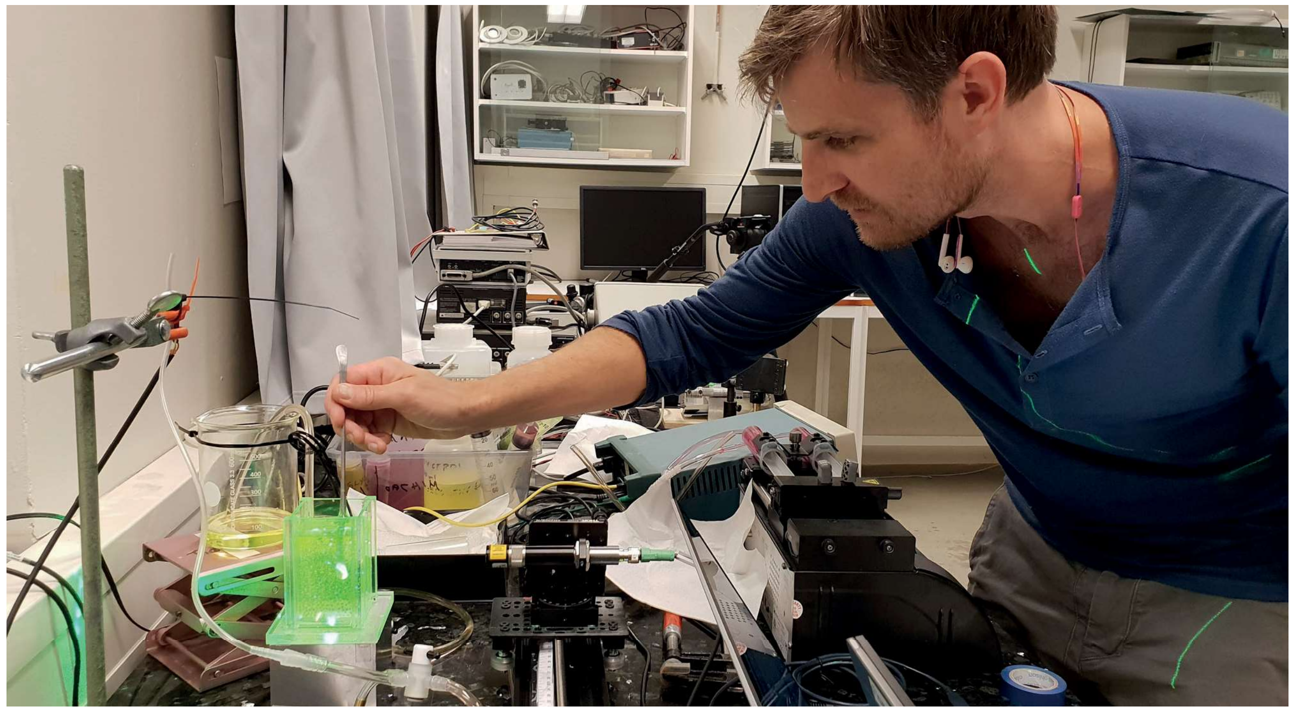
Flicker-free illumination sources tailored for the different applications (including high-speed microscopy) are also available.

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



*A layer of $CO_2$ above a water-saturated porous medium consisting of glass beads. An indicator of acidity has been added to visualize the $CO_2$ fingers (PoreLab at UiO)*

*Optical scanner for 3D imaging (PoreLab UiO)*



Additionally, the laboratories include a large set of different optical equipment, such as lasers with different intensities and wavelengths, lenses and other optical components, cameras and microscopes for Particle Image Velocimetry.

The laboratories are also well equipped to perform homodyne correlation spectroscopy for the measurement of particle velocity fluctuations in fluids, diffusion constants and viscosities.

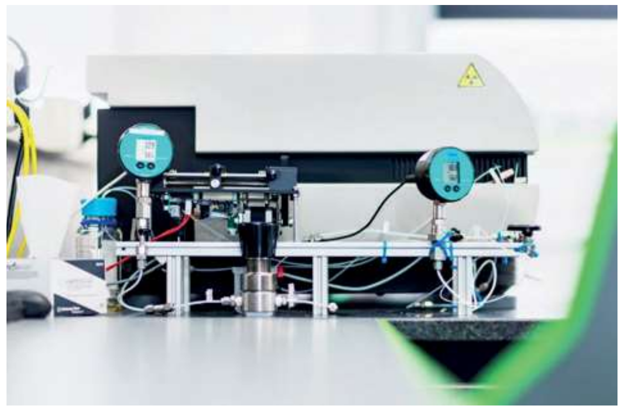
In addition to this wide variety of state-of-art techniques, the laboratories are also fully equipped with standard fluid mechanics labware, such as capillary viscometers, high-precision scales, pressure and temperature sensors, surface treatment chemicals for the control of wetting properties and general laboratories glassware.

## LABORATORIES AT THE DEPARTMENT OF GEOSCIENCE AND PETROLEUM, NTNU

The core analysis laboratory contains state-of-the-art equipment for routine and special core analysis. Included are core preparation equipment (drilling, cutting, cleaning and saturating core plugs), porosimeters, permeameters and apparatus for core plug resistivity measurements. The laboratory has specialized equipment like automated centrifuge for capillary pressure and relative permeability measurements and core flooding rigs for various enhanced oil recovery processes. The main components in the flooding rigs are core holders, pumps, fluid lines, fluid containers, pressure sensors and flow meters.

The laboratory is also equipped with micro-computer tomograph (CT). This micro-CT has a tailor made miniature (5mm diameter) core flooding set up which is used in pore scale studies. In addition the laboratory has microfluidics apparatus where the main components are glass micro models, syringe pumps, microscopes and digital cameras with large monitors.

Supplementary equipment for fluid and fluid/solid interaction analysis includes interfacial tension apparatus (pendant drop and spinning drop), contact angle apparatus, devices for zeta potential and particle size measurements, densitometers, viscosimeters and rheometers.



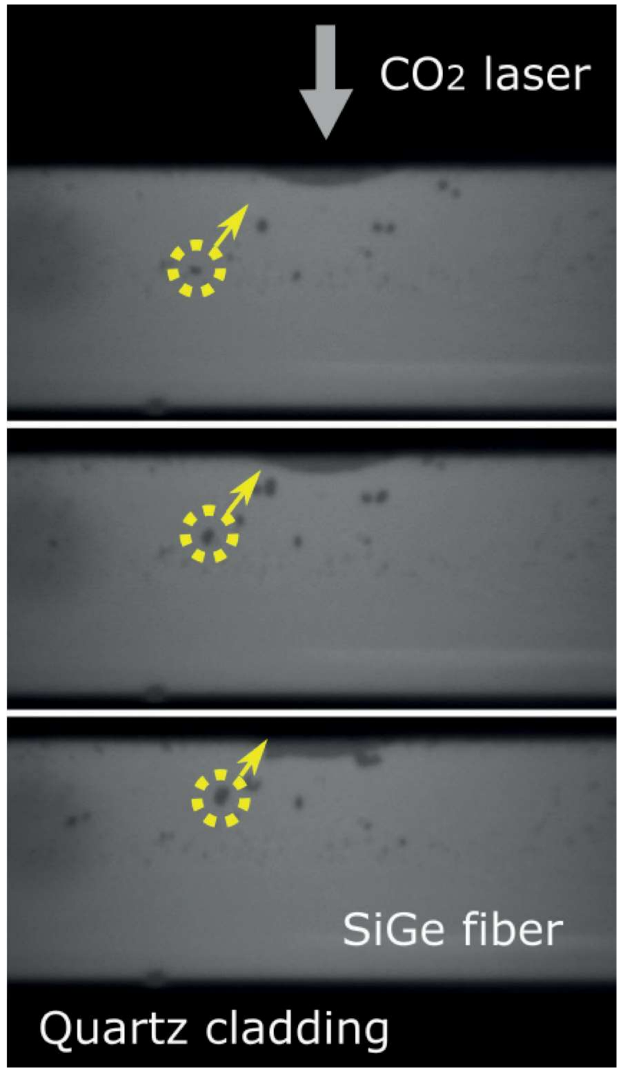
*Micro computer tomograph with flooding equipment (pressure transducer and syringe pump). In the scanning chamber (behind the shield) is the coreholder with miniature core plug.*

## LABORATORIES AT THE PHYSICS DEPARTMENT, NTNU

A laboratory at the Physics department at NTNU offers laser-induced heating and thermal emission imaging to study mass transport under steep thermal gradients. We are currently imaging liquid alloy flows through solid semiconductor-core fibers.

The laboratory has a $CO_2$ laser source (G48-2-28W, Synrad) which is used to impose a temperature gradient on a micro-system encapsulated by silica. A high-resolution USB CCD camera (DCU224M, ThorLabs) is used for real-time observation of liquid droplet flows through solid, made possible by differences in the emissivity of the liquid and solid. Software packages, including ImageJ, are used to track and analyze particle motion, and the temperature gradient is assessed with emission intensity mapping.

Materials analysis is carried out with NTNU facilities for XRD, XCT and microscopy at NORTEM and NanoLab.




*Frames from a CCD video showing Ge-rich SiGe liquid flowing through solid SiGe in a silica-clad fiber. Yellow circles highlight one of the flowing droplets and a gray arrow shows the illumination direction of the $CO_2$ laser. The three frames are arranged in chronological order. (U. Gibson laboratory)*

# PORELAB GRADUATE SCHOOL

## "TRAINING RESEARCH LEADERS OF THE FUTURE"

A core activity in PoreLab is the Graduate School. All senior researchers take part in the training of the junior ones; i.e. the PhD students and the post docs (PDs). In addition to the technical and general supervision connected with each individual project, there is joint and institutional effort to train non-technical skills, like communication and teaching skills, ethics in science, science dissemination.

It is our ambition that each junior researcher has a scientifically stimulating and inclusive workday, much above the level of a regular PhD/Postdoc program. Our PoreLab researcher training program is therefore organized across the institutions, and together with international partners to create an interdisciplinary, international training ground.

A total of 22 Ph.D. candidates and 12 postdoctoral fellows will be trained during the course of the center lifetime.

### PHD TRAINING

Each fellow follows her/his regular institutional training program, with specified demands for scientific work, supported by course work and other activities. Courses on ethics, rhetorics, dissemination and communication are for instance available at both NTNU and UiO.

The scientific work is organized in clusters around each Ph.D. candidate. Two supervisors are natural members of the cluster in addition to MSc students, post-doctoral researchers or guests that are working on the same problem, or takes an interest in it. This organization helps ensure the inter-disciplinary nature of our work, network creation and mentoring.

All homely-recruited Ph.D. candidates must spend a few months at one of our collaborating institutions. As an example, Ph.D. candidate Reidun Aadland from the Department of Geoscience and Petroleum, NTNU, spent 3 months in 2018 at the University of Calgary visiting the research group of our collaborating partner, Professor Steven Bryant.

PoreLab offers a range of courses open for all students at our host universities.
FYS4465/FYS9465 at UiO or KJ8210 at NTNU: *Theory and simulation of flows in complex media. YS4420/FYS9420 at UiO: Experimental techniques in condensed matter physics.*
PG8605 at NTNU: *Dual Porosity reservoirs or TPG4565 at NTNU: Petroleum Engineering, Specialization Course*

In order to strengthen the presence of PoreLab in our two host institutions as well as to reinforce cross-collaboration between NTNU and UiO, PoreLab pays for the adjunct professorships of Eirik Flekkøy and Knut Jørgen Måløy at NTNU, and for Ole Torsæter at UiO.

The PI advisory committee, led by professor Signe Kjelstrup, oversees that each student has an individual plan for interdisciplinary training.

### POSTDOCTORAL TRAINING

International collaboration is highly encouraged and therefore supported within our group of young researchers. As an example, Post-doctoral researcher Subhadeep Roy from the Physics department of NTNU spent a few months in 2018 at the Beijing Computational Research Science Center (CRSC) visiting the research group of our collaborating partner, Professor Hai-Qing Lin.

As far as possible and suitable for the projects, the PDs will co-supervise PhD students or MSc students. Teaching at the BSc and MSc-level is encouraged for PDs that want to build an academic career.

Post-doctoral researchers are offered a variety of courses and workshops suitable for their career plan at the host institutions, NTNU and UiO. Examples are courses on PhD supervision, or workshops on publishing practice in International Journals. Pedagogical courses, offered by Uniped (NTNUs Educational Development Unit) may be relevant. All candidates at NTNU take part in the one-day course for postdoctoral researchers. This course focuses on career development, ethics and integrity in research and education, as well as research projects and research leadership.

All PoreLab PDs need to work out a suitable career development plan in close collaboration with their supervisor. This plan comes in addition to the usual and annual appraisal interview that all employees need to follow with their manager.

### PORELAB: AN INCLUDING WORKING ENVIRONMENT

All PhD-candidates as well as PDs are members of PoreLab Junior Forum. They take part in the internal Journal Club, and in the weekly PoreLab lecture. Junior members are encouraged to submit abstracts and present posters or lectures at national and international conferences.

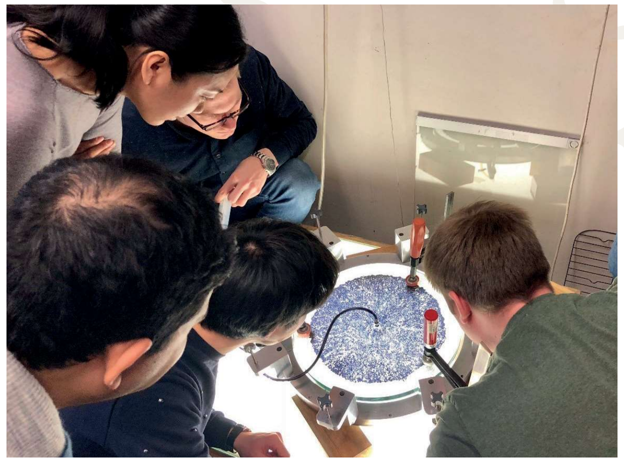
The center has already many visitors (more than 40 renowned national and international researchers so visited PoreLab for various periods since its creation), and the junior researchers obtain the opportunity to meet and interact with world leading scientists. A list of visitors is given page 56.

### PORELAB JUNIOR FORUM

The main goal of the PoreLab Junior forum is to bring together the group of PhDs, PostDocs and early career researchers of PoreLab with the objective of allowing them to better know each other and share their respective work/scientific interests. The idea is that the personal contacts will provide them with a network for the future. The Junior Forum meets regularly, presently twice a year. The group manages itself, and decides their representation in board meetings, or other meetings, when wanted.

The 1st PoreLab Junior 2-day Forum took place at UiO, March 2018 and the second one at NTNU in September 2018. The main event was project presentations and posters, labtours, and social time.

The junior forum is particularly important to PoreLab, also because it serves to bind two hubs in Oslo and Trondheim together. It is very important to make it clear, particularly to the newest members, that although the center has two physical locations, it is indeed a single center, and collaboration between the groups should not be hindered by physical distance.



*Lab tour during the 1st PoreLab Junior Forum: experiments on a circular Hele-Show cell with a non-deformable porous medium.*

*2nd PoreLab Junior Forum: Plenary session. A network for life?*
*Photo: Marie-Laure Olivier*

### PORELAB JOURNAL CLUB

The PoreLab Journal Club meets every week to discuss the scientific literature. Brand new or classical papers are chosen and presented by a PoreLab member. The presented papers are then peer-reviewed by the group. In this manner we keep each other updated, and well informed. In addition, the junior members can experience the review process.

*PoreLab Journal Club. Is this paper any good?*

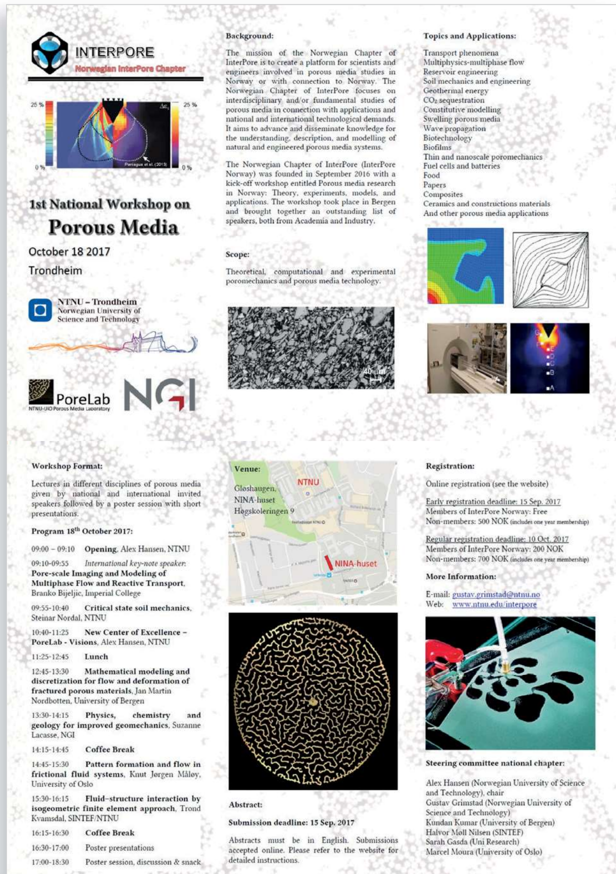
# PORELAB AND THE INTERPORE NETWORK

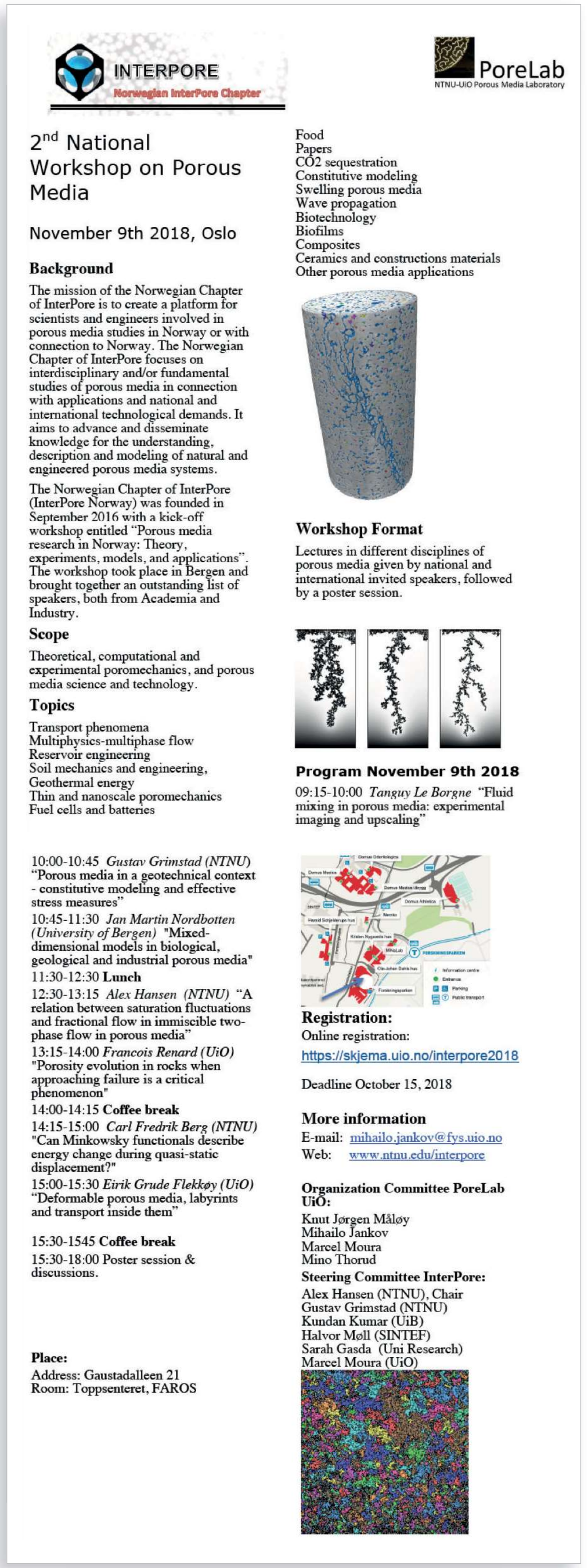
InterPore is an International Society for Porous Media where PoreLab is an institutional member. A national chapter of InterPore was established to benefit all of Norway's research in the field. PoreLab has also added to the development of the central organization. Both activities are described below.

## NATIONAL WORKSHOPS OF THE NORWEGIAN CHAPTER OF INTERPORE

PoreLab is a major contributor to InterPore Norway. The Norwegian Chapter of InterPore is meant to create a national hub for scientists and engineers involved in porous media studies.

The close cooperation between PoreLab and InterPore Norway led to the creation of the first annual National Workshop on Porous Media, in Trondheim, October 18th, 2017. The second workshop took place in Oslo on November 9th, 2018. Professor Alex Hansen, director for PoreLab, is elected chair of Interpore Norway.


INTERPORE
Norwegian InterPore Chapter
1st National Workshop on
Porous Media
October 18 2017
Trondheim
PoreLab NGI


INTERPORE
Norwegian InterPore Chapter
PoreLab
NTNU-UiO Porous Media Laboratory

2nd National Workshop on Porous Media

November 9th 2018, Oslo

**Background**

The mission of the Norwegian Chapter of InterPore is to create a platform for scientists and engineers involved in porous media studies in Norway or with connection to Norway. The Norwegian Chapter of InterPore focuses on interdisciplinary and/or fundamental studies of porous media in connection with applications and national and international technological demands. It aims to advance and disseminate knowledge for the understanding, description and modeling of natural and engineered porous media systems.

The Norwegian Chapter of InterPore (InterPore Norway) was founded in September 2016 with a kick-off workshop entitled "Porous media research in Norway: Theory, experiments, models, and applications". The workshop took place in Bergen and brought together an outstanding list of speakers, both from Academia and Industry.

**Scope**

Theoretical, computational and experimental poromechanics, and porous media science and technology.

**Topics**

Transport phenomena
Multiphysics-multiphase flow
Reservoir engineering
Soil mechanics and engineering,
Geothermal energy
Thin and nanoscale poromechanics
Fuel cells and batteries
Food
Papers
CO2 sequestration
Constitutive modeling
Swelling porous media
Wave propagation
Biotechnology
Biofilms
Composites
Ceramics and constructions materials
Other porous media applications

**Workshop Format**

Lectures in different disciplines of porous media given by national and international invited speakers, followed by a poster session.

**Program November 9th 2018**

09:15-10:00 *Tanguy Le Borgne* "Fluid mixing in porous media: experimental imaging and upscaling"

10:00-10:45 *Gustav Grimstad (NTNU)* "Porous media in a geotechnical context - constitutive modeling and effective stress measures"

10:45-11:30 *Jan Martin Nordbotten (University of Bergen)* "Mixed-dimensional models in biological, geological and industrial porous media"

11:30-12:30 **Lunch**

12:30-13:15 *Alex Hansen (NTNU)* "A relation between saturation fluctuations and fractional flow in immiscible two-phase flow in porous media"

13:15-14:00 *Francois Renard (UiO)* "Porosity evolution in rocks when approaching failure is a critical phenomenon"

14:00-14:15 **Coffee break**

14:15-15:00 *Carl Fredrik Berg (NTNU)* "Can Minkowsky functionals describe energy change during quasi-static displacement?"

15:00-15:30 *Eirik Grude Flekkøy (UiO)* "Deformable porous media, labyrints and transport inside them"

15:30-1545 **Coffee break**

15:30-18:00 Poster session & discussions.

**Place:**
Address: Gaustadalleen 21
Room: Toppsenteret, FAROS

**Registration:**
Online registration:
https://skjema.uio.no/interpore2018

Deadline October 15, 2018

**More information**
E-mail: mihailo.jankov@fys.uio.no
Web: www.ntnu.edu/interpore

**Organization Committee PoreLab UiO:**
Knut Jørgen Måløy
Mihailo Jankov
Marcel Moura
Mino Thorud

**Steering Committee InterPore:**
Alex Hansen (NTNU), Chair
Gustav Grimstad (NTNU)
Kundan Kumar (UiB)
Halvor Møll (SINTEF)
Sarah Gasda (Uni Research)
Marcel Moura (UiO)

## INTERPORE-PORELAB AWARD FOR YOUNG RESEARCHERS

The close collaboration between InterPore and PoreLab has led to creation of the *InterPore-PoreLab award for Young Researchers.* The award is given in recognition of outstanding contributions to fundamental research in the field of porous media. The research may be theoretical, computational, or experimental. Award winners get a stipend of 1 500 Euro per month for up to three months stay at PoreLab, NTNU or UiO. The stipend, which also covers travel and accommodation expenses, is financed by PoreLab.

The 2018 winner of the *InterPore – PoreLab Award for Young Researchers* is Qingwang Yuan, a postdoctoral fellow at the Department of Energy Resources Engineering from Stanford University, USA.

*Qingwang Yuan*
*2018 winner of the InterPore – PoreLab Award for Young Researchers*

INTERPORE Student Affairs

## THE INTERPORE STUDENT AFFAIRS COMMITTEE, SAC

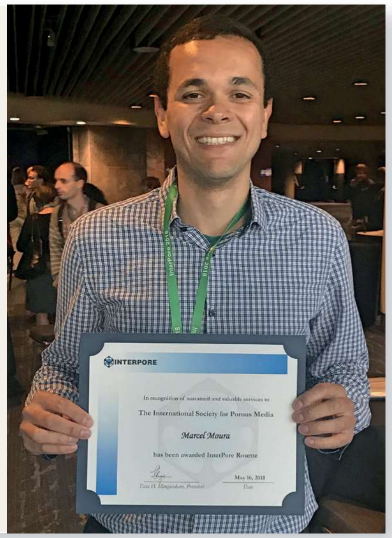
PoreLab PhD students and researchers have already from start been involved in the *InterPore Student Affairs Committee*. SAC aims to attract, involve and include more PhD students and postdocs into the InterPore activities, by organizing educational, career and social oriented activities. The objectives of the SAC is to support young researchers new to the field of porous media, to create a platform where students, academia and industry meet and to intensify collaboration among students of the InterPore Society.

The Committee consists of up to six young researchers who are members of the InterPore community. Three PoreLab PhD students and one postdoctoral researcher were members of SAC in 2018: Marcel Moura (Chair), Olav Galteland (Vice-Chair), Seunghan Song (Secretary and Communication Advisor) and Marco Sauermoser (Events Director). They organized a set of activities during the 2018 InterPore meeting in New Orleans: a career development event, a fun interactive game and a social night out.

## INTERPORE ROSETTE AWARD

Each year, InterPore honors selected individuals who have made very significant contributions to InterPore activities.

The 2018 InterPore Rosette award was given to Marcel Moura, postdoctoral researcher at PoreLab and Chair of the SAC 2018. Marcel received the award *"in recognition for sustained and valuable services to The International Society for Porous Media"*.



*Marcel Moura*
*2018 Winner of the InterPore Rosette award*

# PROMOTING PORELAB'S SCIENCE TO THE PUBLIC

An important goal of PoreLab is to communicate its research and findings, as well as to increase the appreciation and understanding of science in general. Our aim is to reach both Norwegian and international audiences.

## YOUNG PUBLIC

Bringing scientific culture and research closer to pre-university educational levels and promoting research vocation is of great importance to PoreLab. In 2018, PoreLab was involved in several events with this purpose.

In October 2018, 27 students from the natural sciences program at the Greveskogen high school from Vestfold Fylkekommune visited PoreLab facilities, spending half a day at PoreLab, visiting e.g. the laboratory of the Geoscience and Petroleum department where they could participate to the demonstration of experiments.

*Greveskogen high school visits PoreLab in October 2018. Photo: Srutarshi Pradhan*

PoreLab participated for the first time, September 2018, in Researcher's night. The *Researchers' Night* was launched at the European level under the initiative "Researchers in Europe 2005". It is meant to boost public awareness of the positive role of research in society, and especially among young people. Jonas Kjellstadli, Astrid Gunnarshaug and Kim Roger Kristiansen, PhD candidates at PoreLab, presented concepts relevant to porous media research. Examples of thermoelectric effects, converting temperature differences into electricity and vice versa were shown. Also demonstrated was an example of dilatancy in granular materials, highlighting the counter-intuitive effect this has on an interstitial fluid.

*Jonas Kjellstadli, Astrid Gunnarshaug and Kim Roger Kristiansen, PhD candidates at PoreLab, presented some concepts relevant to porous media research at the 2018 Researchers's night Photo: Per Henning*

PoreLab was also present in *Faglig-pedagogisk dag*, the year's largest educational day for school teachers at the University of Oslo. Marcel Moura, post-doctoral fellow at the Physics department, showed a set of inspiring experiments using only simple kitchen materials such as cinnamon, sugar, coffee and soap. The experiments can be easily performed for the students in class to teach basic physical concepts, such as surface tension and spontaneous granular stratification.



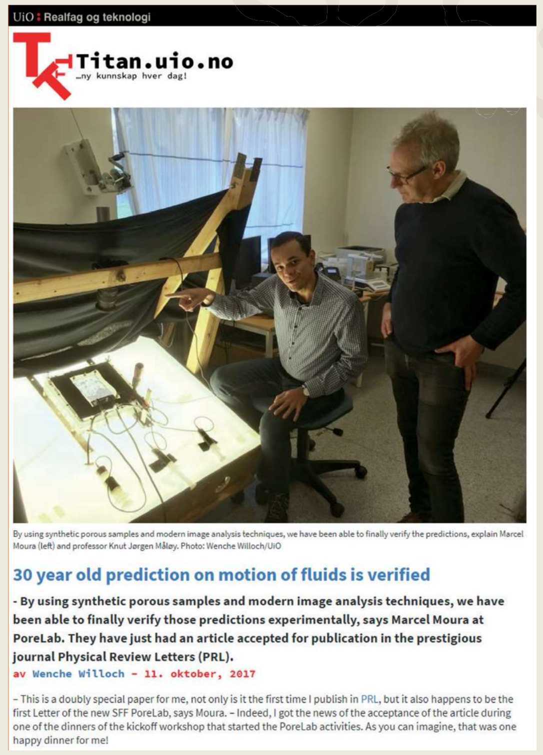
## PORELAB IN THE MEDIA

The members of PoreLab are accessible to media, and are encouraged to contribute their comments on issues of public concern whenever their expertise is applicable.

Here are some cases where PoreLab researchers participated during 2017 and 2018.


*Marcel Moura, postdoctoral researcher at PoreLab, gave a radio interview on June 3rd, 2018, at "Radio Cultura do Nordeste" (Brazil) about energy, technology and environmental challenges in Brazil and Norway and the importance of basic science in this context.*

*October 11, 2017 – Titan – 30 year old prediction on motion of fluids is verified:*



UiO : Realfag og teknologi

Titan.uio.no
...ny kunnskap hver dag!

By using synthetic porous samples and modern image analysis techniques, we have been able to finally verify the predictions, explain Marcel Moura (left) and professor Knut Jørgen Måløy. Photo: Wenche Willoch/UiO

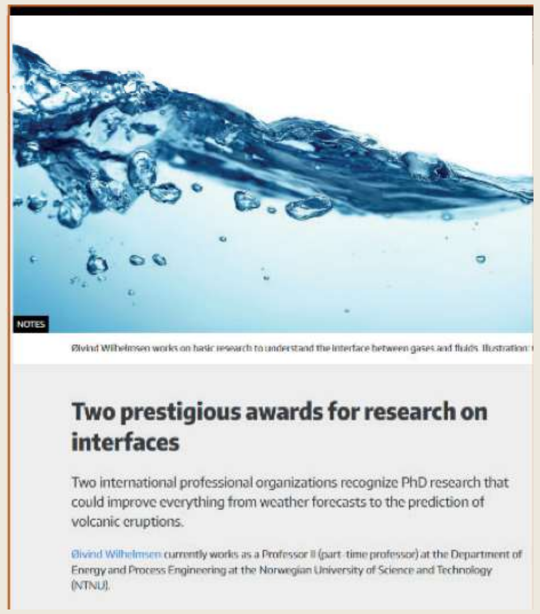
**30 year old prediction on motion of fluids is verified**

**- By using synthetic porous samples and modern image analysis techniques, we have been able to finally verify those predictions experimentally, says Marcel Moura at PoreLab. They have just had an article accepted for publication in the prestigious journal Physical Review Letters (PRL).**

av Wenche Willoch - 11. oktober, 2017

– This is a doubly special paper for me, not only is it the first time I publish in PRL, but it also happens to be the first Letter of the new SFF PoreLab, says Moura. – Indeed, I got the news of the acceptance of the article during one of the dinners of the kickoff workshop that started the PoreLab activities. As you can imagine, that was one happy dinner for me!

*June 12, 2017 – Gemini – Two prestigious awards for research on interfaces:*



NOTES

Øivind Wilhelmsen works on basic research to understand the interface between gases and fluids. Illustration:

**Two prestigious awards for research on interfaces**

Two international professional organizations recognize PhD research that could improve everything from weather forecasts to the prediction of volcanic eruptions.

Øivind Wilhelmsen currently works as a Professor II (part-time professor) at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU).

*13. desember 2018 – YouTube-hit om metallkjeder ble forskning på toppnivå:*

UiO : Realfag og teknologi

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...ny kunnskap hver dag!

Marcel Moura med en kjedefontene. Foto: Hilde Lynnebakken/UiO

**YouTube-hit om metallkjeder ble forskning på toppnivå**

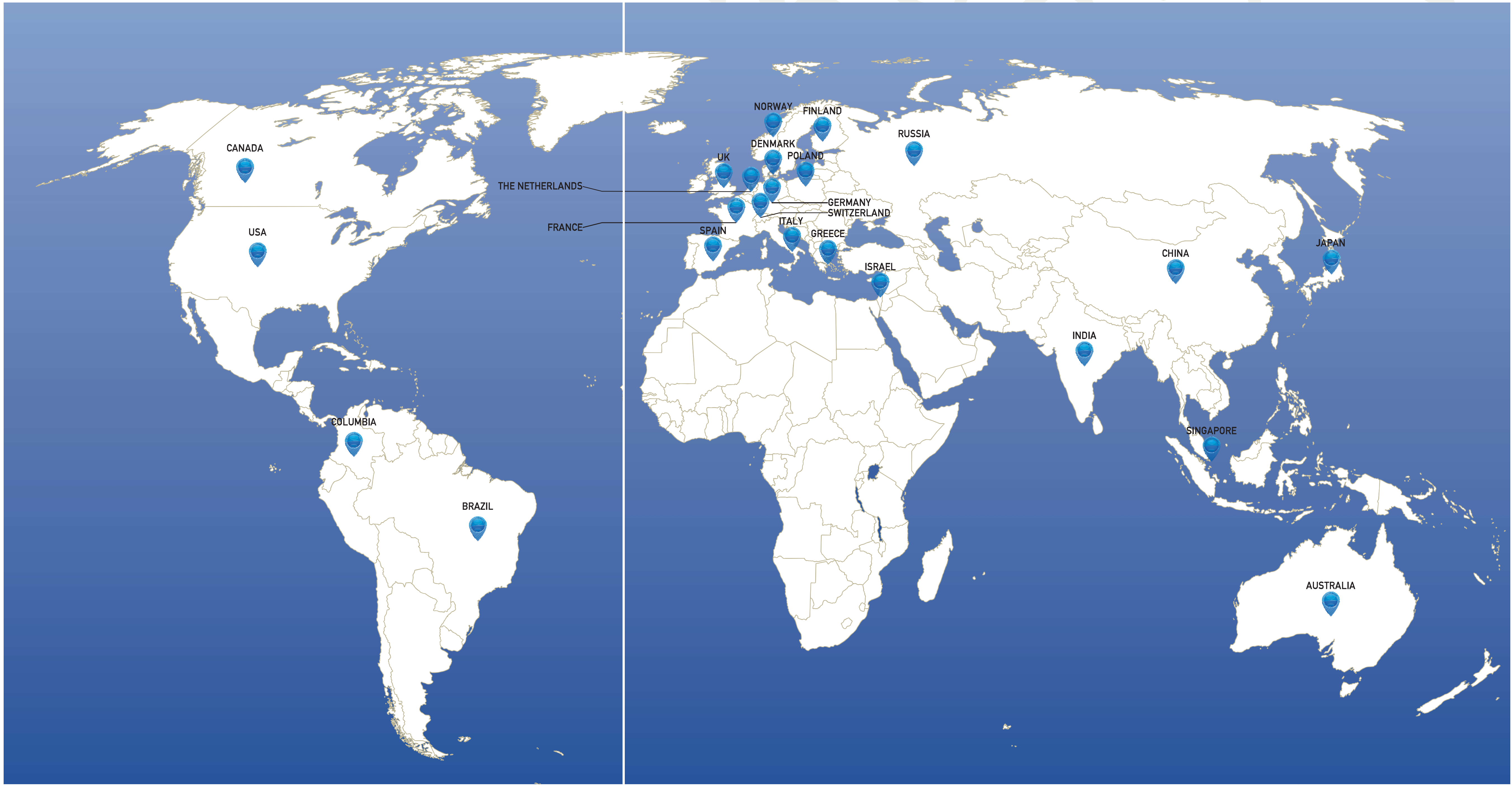
**«Så rart»-effekten: Ingenting vekker nysgjerrigheten hos forskere som når de ser noe de ikke forstår.**

av Hilde Lynnebakken - 13. desember, 2018

Ta et langt kjede av små metallkuler og slipp det ut fra en beholder. Kjedet glir ikke pent over kanten og ramler ned, slik som en kunne forvente, men står freidig rett opp fra beholderen i en bue.

SOCIAL MEDIA Visit our website **www.porelab.no** where you find daily updated information on our researchers, scientific findings, happenings, studies and many more. Follow us on Twitter as well!

# NATIONAL AND INTERNATIONAL COLLABORATION




**USA**
Sarah L Codd: *College of Engineering, Montana State University, Bozeman*
Daniel H. Rothman: *Department of Earth, Atmospheric, and Planetary Sciences, Massachussets Institute of Technology*
Steven Pride: *Energy Geosciences Division, Lawrence Berkeley National Lab*

**CANADA**
Steven Bryant, Marie Macquet, Somayeh Goodarzi, Ali Telmadarreie, Ellen Liu, Carter Jordan Dziuba, Ian Gates: *University of Calgary*
Francis Mujica Urbina: *Department of Earth Sciences, Memorial University of Newfoundland*

**COLUMBIA**
Daniel Barragán: *School of Chemistry, Faculty of Sciences, National University of Colombia*

**BRAZIL**
Ignacio Iturrioz: *Universidade Federal do Rio Grande do Sul*

**NORWAY**
Jan Øystein Haavig Bakke: *Schlumberger Stavanger*
Øivind Wilhelmsen, Asbjørn Solheim, Olaf Trygve Berglihn, Torleif Holt, Erik Lindeberg, Dag Wessel-Berg, Vegard Brøtan: *SINTEF*
John Ege: *ORG Geophysical AS*
Bjørn Skjetne: *CEGNOR AS*
Geir Helgesen, Kenneth Knudsen: *Institute for Energy Technology, IFE*
Mario Acquarone, Lars Folkow: *The Arctic University of Norway*
Bernt O. Hilmo: *Asplan Viak AS*
Ellinor B. Heggset, Kristin Syverud*: RISE PFI AS*
Harald Berland: *IRIS, NORCE Norwegian Research center AS*

**DENMARK**
Joachim Mathiesen: *Niels Bohr Institute, University of Copenhagen*

**GERMANY**
Rainer Helmig and Joachim Gross: *University of Stuttgart*
Andrzej Gorak: *TU Dortmund*
Steffen Schlüter: *Helmholtz Centre for Environmental Research, Leipzig*

**THE NETHERLANDS**
Thijs J.H. Vlugt, Ger J.M. Koper, Claire Chassagne: *Delft University of Technology*
Majid Hassanizadeh: *Multiscale Porous Media Laboratory, Utrecht University*

**UK**
Bjørnar Sandnes: *Energy Safety Research Institute, College of Engineering, Swansea University*
Fernando Bresme: *Department of Chemistry, Imperial College London*
Daan Frenkel, Erika Eiser: *University of Cambridge, UK*

**FRANCE**
Sunniva Indrehus: *Pierre and Marie Curie University, Paris 6*
Laurent Talon: *Laboratoire FAST, Université de Paris-Sud, Orsay*
Renaud Toussaint, Tom Vincent, Monem Ayaz, Antoine Léo Turquet: *Institut de Physique du Globe de Strasbourg, CNRS, Université de Strasbourg*
Tanguy Le Borgne: *University of Rennes*
Jean-Marc Simon: *University of Bourgogne, CNRS*
Stéphane Santucci, Michael Bourgoin: *Ecole Normale Supérieure de Lyon, UMR CNRS, Lyon*
Osvanny Ramos: *Department of Physics, Claude Bernard University, Lyon*

**SWITZERLAND**
Martin Hendrick: *Université de Neuchâtel*

**SPAIN**
Miguel Rubi, Xavier Cartoixa: *University of Barcelona*
Riccardo Rurali: *Theory and Simulation Department, Materials Science Institute of Barcelona (ICMAB-CSIC)*
María Barragán Garciá: *Department of Applied Physics, Complutense University of Madrid*

**ITALY**
Luciano Colombo: *University of Cagliari*

**GREECE**
Marios Valavanides: *Dept. of Civil Engineering, University of West Attica*

**POLAND**
A. Mikkelsen, K. Khobaib, R. Rozynek: *Institute of Acoustics, Faculty of Physics, Adam Mickiewicz University, Poznań*
Natalya Kizilova: *Institute of Aeronautics and applied Mechanics, Warsaw University of Technology*
Wojciech Debski: *Department of Theoretical Geophysics, Institute of Geophysics Polish Academy of Sciences, Warszawa*

**FINLAND**
L. Laurson, Mikko Alava: *Department of Applied Physics, Aalto University, Espoo*

**RUSSIA**
Sergey Abaimov: *Skolkovo Institute of Science and Technology*

**ISRAEL**
Ran Holtzman: *Hebrew University of Jerusalem*

**INDIA**
Ray Purusattam: *Institute of Mathematical Sciences, Chennai*

**CHINA**
Hai-Qing Lin, Rubem Mondaini, Tie-Fu Li, Li-Shi Luo, Santanu Sinha: *Beijing Computational Science Research Center*
Jingya Zhang: *College of Geosciences, China University of Petroleum, Beijing*
Ye Xu: *School of Mechanical Engineering and Automation, Beihang University, Beijing*
Fulong Ning: *China University of Geosciences Wuhan*
Xin Wang: *Institute of Oceanography Instrumentation, Shandong Academy of Sciences, Qingdao*

**JAPAN**
Pieter Krüger: *Graduate School of Science and Engineering, Molecular Chirality Research Center, Chiba University, Chiba*
Tamio Ikeshoji: *National Institute of Advanced Industrial Science and Technology, AIST*
Koji Amezawa: *Institute of Multidisciplinary Research for advanced materials, Tohoku University*
Hironori Nakajima: *Department of Mechanical Engineering, Faculty of Engineering, Kyushu University*
Satoshi Nishimura: *Faculty of Engineering, Field Engineering for the Environment, Hokkaido University*
Yasuhiro Fukunaka: *Research Organization for Nano and Life Innovation, Waseda University, Shinjuku, Tokyo*

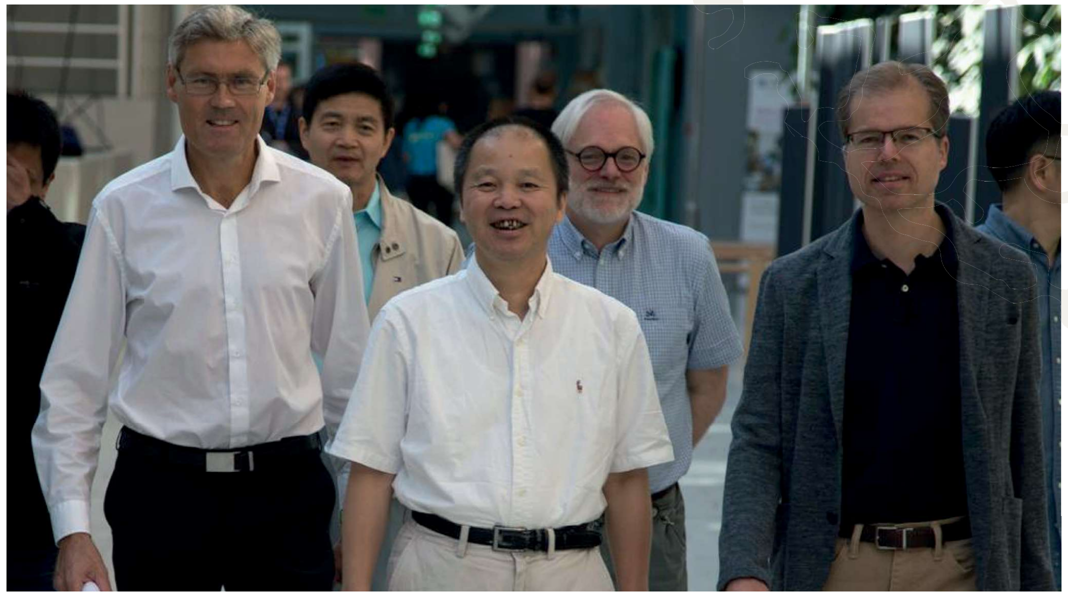
**SINGAPORE**
Shidong Li, Nanji Hadia, Yeap Hung Ng, Ludger Stubbs, Qi Hua Ng: *Institute of Chemical and Engineering Sciences (ICES), Agency for Science, Technology and Research*
Hon Chung Lau: *National university of Singapore*

**AUSTRALIA**
Benjy Marks: *University of Sydney*
Ryan Armstrong: *UNSW, School of Petroleum Engineering, Sydney*

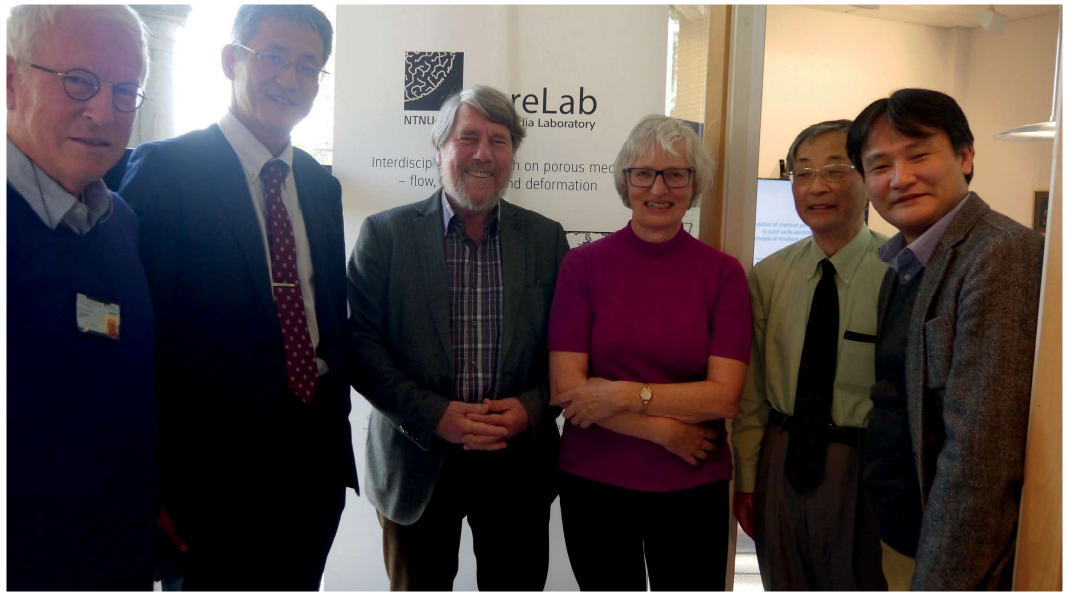
# GUEST RESEARCHERS AT PORELAB

Since PoreLab was born, we had the great privilege to host a number of guest researchers for shorter or more extended periods. These guests have provided PoreLab with important new research insights, friendship, and lively discussions in return for access to PoreLab's activities. Most of them gave lectures and workshops were organized when international delegations visited us.

| NAME | POSITION | AFFILIATION | PERIOD |
|---|---|---|---|
| Toshiyuki Nohira | Professor | Institute of Energy Science, Kyoto University, Japan | 15.09.17 |
| Thomas Ramstad | Researcher | Equinor Research Center, Trondheim, Norway | 15.09.17 |
| Pedro Neta | M. Sc. Student | University of Lisbon, Portugal | 14.07.17-11.09.17 |
| Purusattam Ray | Professor | Institute of Mathematical Sciences, Chennai, India | 14.07.17-14.09.17 |
| Ellen Nordgård Hansen | Senior Scientist | Teknova, Kristiansand, Norway | 14.09.17 |
| Fridtjov Ruden | Geologist | Ruden AS, Norway | 04.09.17 |
| Alexander Mikkelsen | Ass. Professor | Institute of Acoustics, Adam Mickiewicz University, Poland | 23.10.17-27.10.17 |
| Zbigniew Rozynek | Researcher | Institute of Acoustics, Adam Mickiewicz University, Poland | 23.10.17-24.10.17 |
| Khobaib Khobaib | PhD student | Institute of Acoustics, Adam Mickiewicz University, Poland | 23.10.17-26.10.17 |
| Steven Holdcroft | Professor | Dept. of Department of Chemistry, Simon Fraser University, Canada | 06.11.17-09.11.17 |
| Osvanny Ramos Rosales | Ass. Professor | CNRS, Université Claude Bernard Lyon 1, France | 08.11.17-14.11.17 |
| Stephane Santucci | Researcher | CNRS, Laboratoire de Physique, ENS Lyon, France | 08.11.17-15.11.17 |
| Laurent Talon | Researcher | Laboratory FAST, CNRS, Orsay, France | 27.02.18-01.03.18 |
| Daniel Barragan | Ass. Professor | School of chemistry, National University of Colombia, Bogotá | 31.03.18-05.05.18 |
| Sergey Abaimov | Ass. Professor | Skolkovo Institute of Science and Technology, Moskva, Russia | 03.04.18-10.04.18 |
| Santanu Sinha | Researcher | Beijing Computational Science research Center, China | 11.06.18-11.07.18 |
| Hai-Qing Lin | Director, Prof. | Beijing Computational Science research Center, China | 18.06.18-22.06.18 |
| Rubem Mondaini | Ass. Professor | Beijing Computational Science research Center, Beijing, China | 18.06.18-22.06.18 |
| Tie-Fu Li | Professor | Beijing Computational Science research Center, Beijing, China | 18.06.18-22.06.18 |
| Li-Shi Luo | Professor | Beijing Computational Science research Center, Beijing, China | 18.06.18-22.06.18 |
| Ignacio Iturrioz | Ass. Professor | Mechanical department, UFRGS, Argentina | 11.07.18-13.07.18 |
| Ali Telmadarreie | Researcher | Dept. of Chemical and Petroleum Engineering, U. of Calgary, Canada | 18.06.18-05.07.18 |
| Tamio Ikeshoji | Professor | National Institute of Advanced Industrial Science and Technology, Japan | 16.08.18 |
| Renaud Toussaint | Professor | CNRS, University of Strasbourg, France | 22.08.18-31.08.18 |
| Tom Vincent | PhD Student | University of Strasbourg, France | 22.08.18-08.09.18 |
| María Barragán García | Professor | Department of Applied Physics, Compluence University of Madrid, Spain | 27.08.18-03.09.18 |
| Monem Ayaz | PhD student | University of Strasbourg, France | 14.12.17-05.02.18 |
| Antoine Léo Turquet | Researcher | CNRS, ENS, Université Claude Bernard Lyon 1, France | 03.09.18-10.09.18 |
| Jingya Zhang | PhD student | College of Geosciences, China University of Petroleum, Beijing, China | 01.09.18-31.08.19 |
| Ryan Armstrong | Senior lecturer | UNSW, School of Petroleum Engineering, Sydney, Australia | 03.09.18 |
| Mikael Bourgoin | Professor | CNRS, Laboratoire de Physique, ENS Lyon, France | 24.09.18-27.09.18 |
| Stephane Santucci | Researcher | CNRS, Laboratoire de Physique, ENS Lyon, France | 24.09.18-27.09.18 |
| Natalya Kizilova | Professor | Warsaw University of Technology, Poland | 01.10.18-01.01.19 |
| Koji Amezawa | Professor | Tokohu University, Japan | 08.10.18 |
| Yasuhiro Fukunaka | Professor | Waseda University, Tokyo, Japan | 08.10.18 |
| Yuta Kimura,., | Ass. Professor | Tohoku University, Sendai, Japan | 08.10.18 |
| Hironori Nakajima | Ass. Professor | Kyushu University, Japan | 08.10.18 |
| Satoshi Nishimura | Professor | Hokkaido University, Japan | 16.10.18 |
| Erika Eiser | Professor | Cavendish Laboratory, University of Cambridge, UK | 18.10.18-22.10.18 |
| Bjørnar Sandnes | Ass. Professor | Swansea University, UK | 29.10.18-30.10.18 |
| Tanguy Le Borgne | Professor | Geosciences, University of Rennes, France | 09.11.18-16.11.18 |
| Janett Prehl | Res. Assistant | Fak. Naturwissenschaften, Technische Universität Chemnitz, Germany | 13.11.18-20.11.18 |
| Steven Bryant | Professor | Dep. Chemical and Petroleum Engineering, U. of Calgary, Canada | 14.11.18-15.11.18 |
| Marie Macquet | Postdoc Ass. | Department of Geosciences, University of Calgary, Canada | 14.11.18-15.11.18 |
| Somayeh Goodarzi | Postdoc Ass. | Department of Geosciences, University of Calgary, Canada | 14.11.18-15.11.18 |
| Ali Telmadarreie | Res. Associate | CERC, University of Calgary, Canada | 14.11.18-15.11.18 |
| Ellen Liu | Master student | University of Calgary, Canada | 14.11.18-15.11.18 |
| Riccardo Rurali | Deputy Director | Materials Science Institute of Barcelona (ICMAB–CSIC), Spain | 21.11.18 |



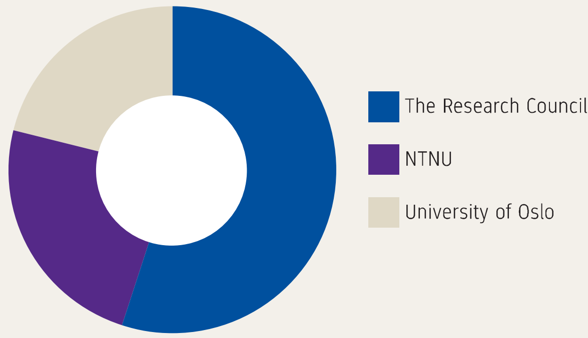
*Chinese delegation from the Beijing Computational Science Research Center (CSRC) visiting the two centers of Excellence, PoreLab and QuSpin, in Trondheim in June 2018. Our guests travelled then to Oslo to meet the PoreLab group at the University of Oslo. From left to right: Professor Asle Sudbø (QuSpin), Professor Hai-Qing Lin (CSRC Beijing), Professor Alex Hansen (PoreLab) and Professor Arne Brataas (QuSpin). Photo: Tore Oksholen*



*Japanese delegation visiting PoreLab Trondheim in October 2018. From left to right: Professor Bjørn Hafskjold (NTNU), Professor Koji Amezawa (Tokohu U.), Professor Emeritus Dick Bedeaux (NTNU), Professor Signe Kjelstrup (NTNU), Professor Yasuhiro Fukunaka (Waseda U.) and Ass. Professor Hironori Nakajima (Kyushu U.)*

# FUNDING 2018

| FUNDING (1000 NOK) | AMOUNT | PERCENTAGE |
|---|---|---|
| The Research Council | 14 247 | 55 % |
| NTNU | 6 196 | 24 % |
| University of Oslo | 5 416 | 21 % |
| Total | 25 859 | 100 % |



# PORELAB MEMBERS

## PoreLab Executive Board

**Øyvind Gregersen** – Dean, NV faculty, NTNU

**Erik Wahlström** – Head of Department, Department of Physics, NTNU

**Ingrid Schjølberg** – Vice Dean Research and Innovation, Director NTNU Ocean, IV Faculty, NTNU

**Jøran Idar Moen** – Head of Department, Department of Physics, UiO

**Brit Lisa Skjelkvåle** – Head of Department, Department of Geosciences, UiO

## The Leader Group

**Alex Hansen** – Director, Professor, Department of Physics, NTNU

**Eirik Flekkøy** – Professor, Department of Physics, UiO

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## Scientific Advisory Board

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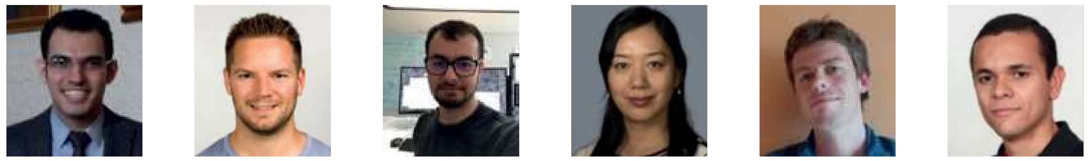
## PostDocs



**Ashkan J. Ghahfarokhi** – PostDoc, Department of Geoscience and Petroleum, NTNU

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**Hamid H. Khanamiri** – PostDoc, Department of Geoscience and Petroleum, NTNU

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**Kristian S. Olsen** – Department of Physics, UiO

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**Marco Sauermoser** – Department of Chemistry, NTNU

**Mohammad Hossein Golestan** – Department of Geoscience and Petroleum, NTNU

**Monem Ayaz** – Department of Physics, UiO

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**Seunghan Song** – Department of Physics, NTNU

## Researchers and Associates

**Bjørn Hafskjold** – Professor, Department of Chemistry, NTNU

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**Catharina de Lange Davies** – Professor, Department of Physics, NTNU

**Dag Kristian Dysthe** – Professor, Department of Physics, UiO

**Dag Werner Breiby** – Professor, Department of Physics, NTNU

**Dick Bedeaux** – Professor Emeritus, Department of Chemistry, NTNU

**Guillaume Dumazer** – Researcher, Department of Physics, UiO

**Gustav Grimstad** – Professor, Department of Civil and Environmental Engineering, NTNU

**Luiza Angheluta-Bauer** – Associate Professor, Department of Physics, UiO

**Mette Rica Geiker** – Professor, Department of Structural Engineering, NTNU

**Per Arne Rikvold** – Researcher, Department of Physics, UiO

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**Srutarshi Pradhan** – Researcher, Department of Physics, NTNU

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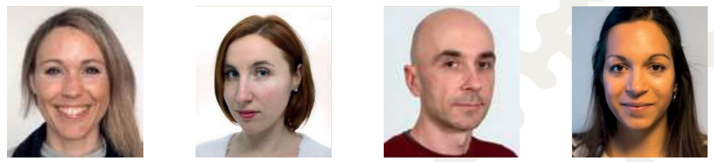
**Øivind Wilhelmsen** – Research Scientist, SINTEF Energy Research

## Administrative and Technical Staff



**Eivor Maria Onsum** – Senior executive officer, Faculty of Natural Sciences, NTNU

**Magdalena Edvardsen** – Research Consultant, Department of Physics, UiO

**Mihailo Jankov** – Senior Engineer, Department of Physics, UiO

**Nina Mino Thorud** – Administrative coordinator for Njord Center and PoreLab, Department of Physics, UiO

# PUBLICATIONS

The following lists journal publications, books, reports, conference lectures and academic presentations generated since September 2017 until the end of 2018.

## JOURNAL PUBLICATIONS

**Aadland, Reidun Cecilie Grønfur; Dziuba, Carter Jordan; Heggset, Ellinor Bævre; Syverud, Kristin; Torsæter, Ole; Holt, Torleif; Gates, Ian D.; Bryant, Steven.**
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Fluid-Fluid Interfaces of Multi-Component Mixtures in Local Equilibrium. *Entropy* 2018; Volume 20.(4) p. - NTNU

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Hill's nano-thermodynamics is equivalent with Gibbs' thermodynamics for surfaces of constant curvatures. *Chemical Physics Letters* 2018; Volume 707. p. 40-43 NTNU

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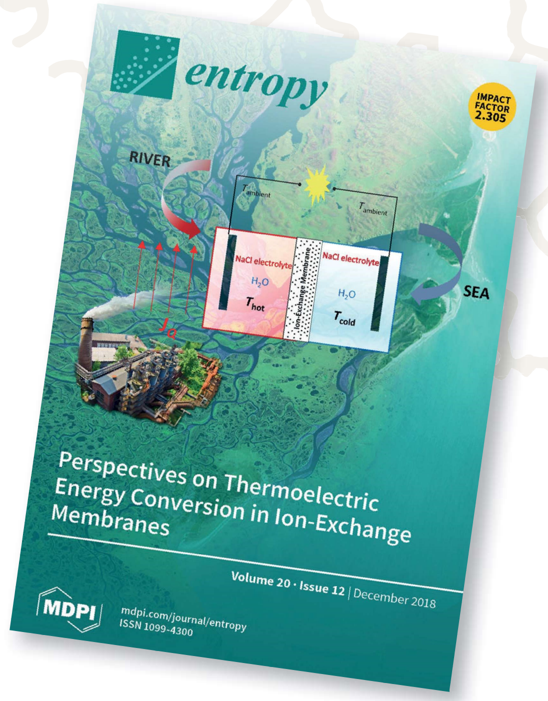


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**Toussaint, Renaud; Sandnes, Bjørnar; Koehn, Daniel; Szymczak, Piotr; Aharonov, Einat.**
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Transportation of nanocellulose dispersions through porous media.. International Symposium of the Society of Core Analysts; 2017-08-27 - 2017-08-30 NTNU UiO

**Bedeaux, Dick; Savani, Isha; Kjelstrup, Signe; Hansen, Alex; Vassvik, Morten; Santanu, Sinha.**
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**Berg, Carl Fredrik.**
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**Galteland, Olav; Hafskjold, Bjørn; Bedeaux, Dick; Kjelstrup, Signe.**
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**Galteland, Olav; Hafskjold, Bjørn; Bedeaux, Dick; Kjelstrup, Signe.**
Mass transport in porous media studied by non-equilibrium molecular dynamics simulations. Twentieth Symposium on Thermophysical Properties; 2018-06-24 - 2018-06-29 NTNU

**Galteland, Olav; Kjellstadli, Jonas Tøgersen; Kristiansen, Kim; Gunnarshaug, Astrid Fagertun.**
Porøse medier. Researchers' Night NTNU 2018; 2018-09-28 - 2018-09-28 NTNU

**Gjennestad, Magnus Aashammer; Vassvik, Morten; Kjelstrup, Signe; Hansen, Alex.**
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**Golestan, Mohammad Hossein; Aursjø, Olav; Berg, Carl Fredrik.**
Lattice-Boltzmann Simulation of Osmosis Effect During Low-Salinity Waterflooding. Interpore Norway 2018; 2018-11-09 - 2018-11-09 NORCE NTNU UiO

**Hafskjold, Bjørn; Kjelstrup, Signe; Edvardsen, Laura; Galteland, Olav; Bedeaux, Dick.**
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**Hansen, Alex.**
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**Hansen, Alex.**
Characterization of Fractures and Fracture Networks. Deteriotian Mechanisms; 2018-11-13 - 2018-11-14 NTNU

**Hansen, Alex.**
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**Hansen, Alex.**
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**Hansen, Alex.**
PoreLab: A Glimpse. QuSpin-PoreLab-CSRC Joint Workshop; 2018-06-19 - 2018-06-19 NTNU

**Hansen, Alex.**
The Fiber Bundle Model: Modeling Material Failure. CDMM Seminar; 2018-06-13 - 2018-06-13 NTNU

**Hansen, Alex; Sinha, Santanu; Bedeaux, Dick; Kjelstrup, Signe; Gjennestad, Magnus Aashammer; Vassvik, Morten.**
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**Hosseinzade Khanamiri, Hamid; Berg, Carl Fredrik; Slotte, Per Arne; Torsæter, Ole; Schlüter, Steffen.**
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**Hosseinzade Khanamiri, Hamid; Torsæter, Ole; Voss, Georg.**
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**Jahanbani Ghahfarokhi, Ashkan; Kleppe, Jon; Torsæter, Ole.**
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**Kjelstrup, Signe.**
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**Li, Shidong; Hadia, Nanji J.; Ng, Yeap Hung; Lau, Hon Chung; Torsæter, Ole; Stubbs, Ludger P..**
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**Strøm, Bjørn André; Simon, Jean-Marc; Schnell, Sondre Kvalvåg; Kjelstrup, Signe; He, Jianying; Bedeaux, Dick.**
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Transport of heat and mass across planar and curved vapor-liquid interfaces: From the Lennard Jones fluid to water and beyond. Physics and Chemistry at Fluid/Fluid Interfaces; 2017-12-11 - 2017-12-13 ENERGISINT NTNU

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Transport of Heat and Mass across Planar and Curved Vapor-Liquid Interfaces: from the Lennard Jones Fluid to Water and Beyond. Twentieth Symposium on Thermophysical Properties; 2018-06-25 - 2018-06-29 ENERGISINT NTNU

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Constitutive Relations for a New Theoretical Framework Describing 2-Phase-Flow in Porous Media. Interpore 10th annual meeting; 2018-05-14 - 2018-05-17 NTNU

**Winkler, Mathias; Kjelstrup, Signe.**
The Role of the Interface in Thermomigration in Alloys. 20th Symposium on Thermophysical Properties; 2018-06-24 - 2018-06-29 NTNU

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