CSD Annual Report 2023

VISTA Center for Modeling of Coupled Subsurface Dynamics

UNIVERSITY OF BERGEN
Center for Modeling of Coupled Subsurface Dynamics

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Director's comments

In 2023, CSD was halfway through the center period. This was marked by a mid-term meeting at Solstrand with insightful discussions of ongoing research in the center with international collaborators, the industry reference group and the center's Scientific Advisory Board.

Another highlight of the year was the CSD Winter School in Myrkdalen. More than 60 participants gathered to learn about modeling and simulation of coupled subsurface processes, discuss political and ethical perspectives and train soft skills. The participants got to know each other through lectures, discussions, group activities and social events, and the students reported that the winter school had provided a great opportunity for networking with other participants and faculty. You can read more about the winter school on p. 18-19.

In 2023, we have recruited two new PhD students and one new postdoc. With these new members of our team, we will reach 22 early career researchers affiliated with our researcher training program. Enrico Facca is a new PI in the center, he leads the MSCA project "Network Inpainting via Optimal Transport" that you can read more about on p. 16.

Now that we have passed the midpoint of the center's period, it is good to be able to confirm that the dissemination of the conducted research is also increasing in the form of several published journal articles, also documenting how new collaborations have thrived because of the center.

Finally, I seize this opportunity to thank the CSD team and our collaborators for their contributions to joint research efforts, center activities and collaborations in the past year.

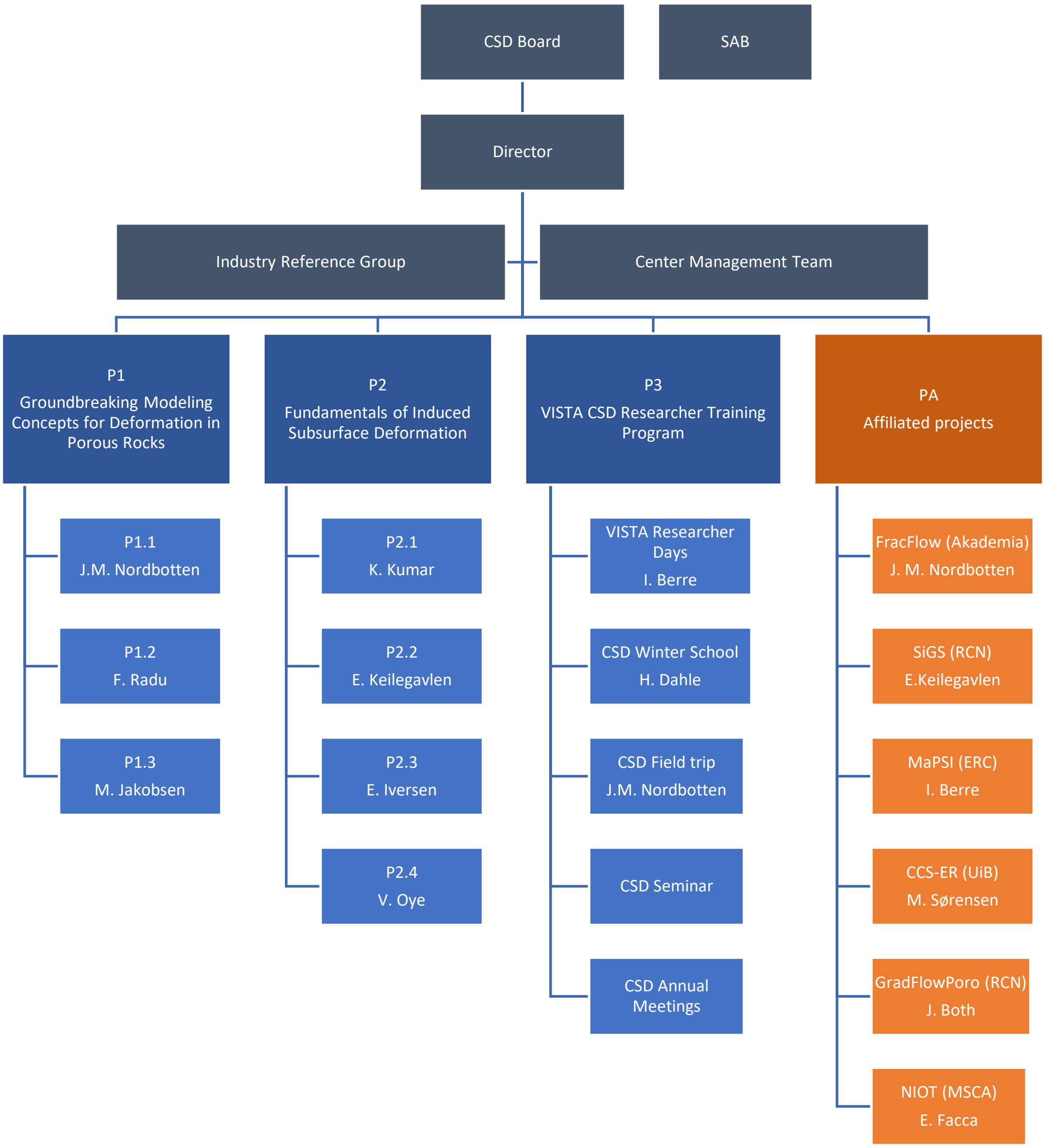
Inga Berre
Center Director

Photo: Eivind Senneset

About the center

VISTA CSD's primary objective is to develop fundamental knowledge and educate next generation researchers to understand how subsurface fluid injection and extraction results in deformation, fault reactivation and fracturing.

The two research pillars of the center address the potential of Groundbreaking *Modeling Concepts for Deformation in Porous Rocks* (P1) and the demand for understanding of *Fundamentals of Induced Subsurface Deformation* (P2). The third pillar of the center is dedicated to support education and career development for PhD and postdoctoral candidates: The *VISTA CSD Researcher Training Program* (P3). In addition, the center currently has six affiliated research projects, structured in a separate pillar. The structure of the center is shown in Figure 1.



Center organization

Through mathematical and numerical modeling and data analysis VISTA CSD targets the critical and fundamental research questions: How do thermal, hydraulic, mechanical and chemical processes interact with the geological structure of the formation to cause significant deformations under production and injection of fluids? What are the appropriate mathematical models to handle the strong and nonlinear interactions between multiphysics couplings and the complex, but crucial, geometries of existing fault networks? How can new methods aid in seismic data analysis of deforming faulted and fractured formations? How can advanced mathematical and numerical modeling be combined with seismic data analysis in understanding governing mechanisms in induced deformation?

To achieve this, the VISTA CSD has the following secondary objectives:

- provide the mathematical models and simulation technology required to assess interaction between subsurface processes and geological structure
- develop geophysics methods for induced seismicity event location and characterization
- combine simulations with field observations and data analysis
- develop tools to assess the risk of geohazards related to fluid injection and extraction
- train early stage researchers in an integrated scientific environment with day-to-day interaction and collaboration with leading international groups

There are seven research projects funded by VISTA in CSD. These are the projects P1.1-P1.3 and P2.1-P2.4. In addition, eight projects are affiliated with CSD. All projects are reviewed below.

Research

Groundbreaking modeling concepts for deformation of porous rocks

P1.1 Mathematical framework for handling complex geometries

Duration	2022-2025
PI	Jan M. Nordbotten, Dept. Math., UiB
Team	Daniel Førland Holmen (PhD student, started February 2022), Jon Eivind Vatne, Einar Iversen

The goal of this project is to further close the gap between theoretical developments and efficient computational tools in the context of quasi-2D structures such as complex fault and fracture networks and quasi-1D structures such as wells. This project already achieved a major milestone in 2022, by developing a “road-map” for the overall strategy for handling the intersection of fractures and wells within the CSD center.

In 2023, we have worked on establishing the theoretical foundations for implementing the “road-map”. Technically speaking, the main theoretical tools are the development of non-standard differential complexes, and exploiting general theory for such structures. In particular, we emphasize two publications that were published in 2023: In Boon and Nordbotten, we provide the continuum mechanical foundations for finite-strain poroelasticiy in the context of mixed-dimensional representations of complex fractured materials. This paper also includes significant well-posedness results for the mathematical model.

The work in this project has been presented at various international conferences and workshops.

P1.2 Simulation tool for fully dynamic Biot equations

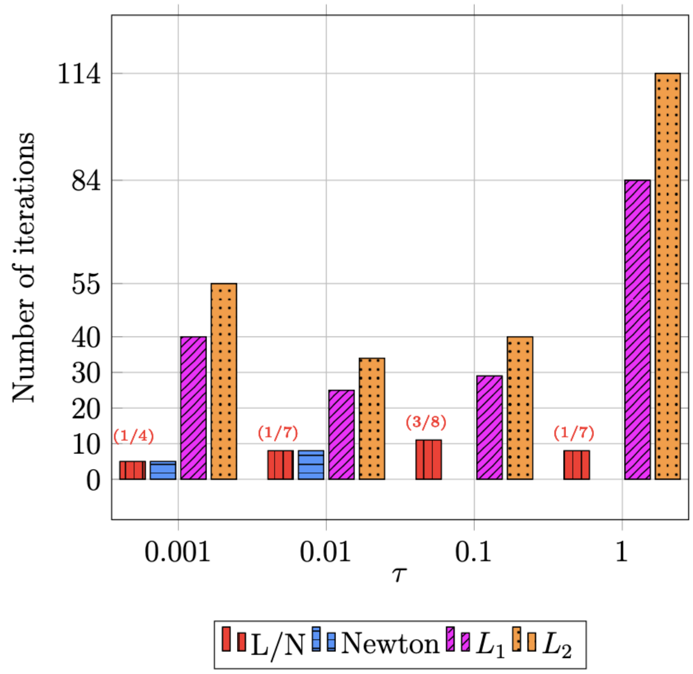
Duration	2023-2026
PI	Florin A. Radu
Team	Jakob Stokke (PhD student, started February 2023), Kundan Kumar, Morten Jakobsen

The aim of the project is to develop an advanced, energy-preserving numerical model and simulation tool for the fully dynamic Biot equations. This will include the prediction of seismic waves.

We have started with the study of different fully dynamic Biot models, with the aim of identifying which one is the most appropriate for the prediction of seismic waves. This is an interdisciplinary task, done together with the department of earth science. In the same time we started building a numerical code for the dynamic Biot equations. As a first step, the quasi-static Biot equations were implemented (we use the DUNE software). Further, we added an acceleration term and a history dependent permeability (expressed through a convolution integral). In the moment we are designing, analyzing and implementing splitting schemes for the fully dynamic Biot case (with or without convolution). Preliminarily work on a simplified dynamic Biot model was performed.

In 2023 we also worked on developing an adaptive linearization scheme based on L-scheme and Newton method for Richards´ equation, which later will become also relevant for the fully dynamic Biot model. We published the results for Richards´ equation in Stokke et al. (2023).

Markus Bause from the Federal Army University Hamburg, Germany is involved in the numerical analysis regarding discretization and splitting schemes for the fully dynamic Biot model.



Illustrative example of the effectiveness of the new developed adaptive linearization scheme (L/N) for Richards´ equation. The figure is taken from Stokke et al. (2023).

P1.3 Microseismic imaging using rock physics-based FWI

Duration	2021-2025
PI	Morten Jakobsen
Team	Ujjwal Shekhar (PhD student, started August 2021), Florin A. Radu, Inga Berre, Einar Iversen, Morten Jakobsen

The main goal of this project is to develop scattering based approaches to microseismic full-waveform inversion (FWI). This includes developing efficient integral equation methods for solving the direct scattering problem; that is, to compute the microseismic wavefield in a heterogeneous anisotropic elastic medium due to a moment tensor source. Also, it includes the development of efficient nonlinear tensorial inverse scattering algorithms for reconstruction of the anisotropic elastic background model as well as the parameters of the microseismic source (source location, ignition time and moment tensor) from seismic and/or microseismic waveform data.

We have formally achieved a first major milestone; that is, we have developed an efficient (matrix-free and FFT-based) integral equation method for modelling of the microseismic wavefield due to a moment tensor source in an anisotropic elastic media with variable stiffness tensor and mass density fields (Shekhar et al., 2023). However, the fast integral equation solver we have developed can of course be further improved and implemented in a more optimal manner.

Together with our international collaborators at TU Delft, we have also made significant progress towards the next major milestone; that is, to develop methods for reconstructing the background velocity model from a combination of microseismic and surface seismic waveform data (Jakobsen et al., 2023). Our main focus will be on anisotropic elastic media, but we use the acoustic approximate to reduce the computational cost and to introduce new concepts and algorithms (Jakobsen et al., 2023).

Together with our international collaborator at the Czech Academy of Sciences, we are currently investigating different parameterizations of anisotropic and fractured elastic media that can potentially help us to mitigate effects of multi-parameter cross-talk in the context of multi-parameter FWI. We are also considering alternative optimization (quasi-Newton) methods for solving inverse scattering problems in anisotropic elastic media.

We have also performed some initial research related to the inversion of microseismic waveform data for the parameters of the microseismic source in isotropic and anisotropic elastic media. Some of this work is based a combination of integral equation and local optimization methods, but we have also investigated the use of finite difference and global optimization methods in this context.

It appears that we will not only reach our goals but also be able to do some additional work related to the quasi-static Biot equations. Essentially, we are exploiting synergies between projects P.1.2 and P.1.3 and trying to make use of our previous experience from the development of rock physics models for the viscoelastic phenomenon of seismic attenuation by wave-induced fluid flow in this context.

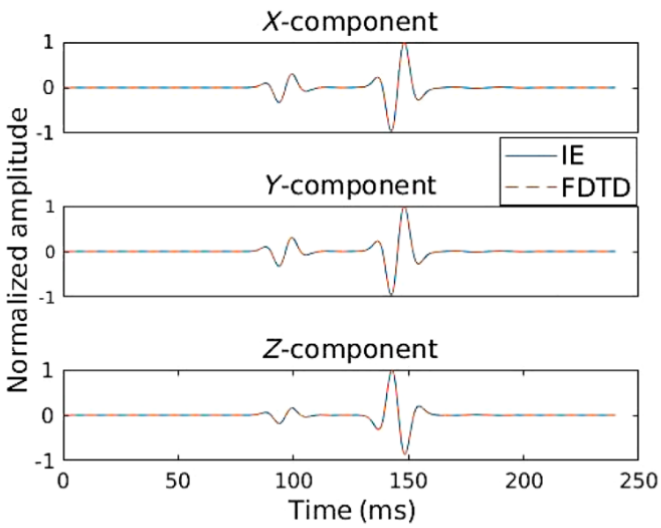


Illustration of microseismic waveform modelling in anisotropic elastic media with a moment tensor source. The figure shows that the new integral equation (IE) method developed by Shekhar et al. (2023) agrees with an existing finite difference time domain (FDTD). The 3D seismic model considered here is homogeneous but transversely isotropic model with a vertical symmetry axis. Displayed are the three components of the particle velocity field. Figure from Shekhar et al. (2023).

Fundamentals for induced subsurface deformation

P2.1 Solvers for mixed dimensional flow and mechanics on the fractured-matrix interface

Duration	2021-2025
PI	Kundan Kumar
Team	Inga Berre, Ivar Stefansson, Nadia S. Taki (PhD student, started August 2021), Jan M. Nordbotten

The goal is to develop mathematical model and solution approaches to rupture dynamics including advanced friction laws in the presence of fluids. The project will consider the evolution of spontaneous ruptures embedded in an elastic deforming body, governed by contact mechanics (rate-and-state friction laws). The particularity is in the description is accounting for the fluid flow. The resulting model is based on coupled differential equations of different dimensions: Biot-Allard in the matrix coupled to flow (on 3D) on the fracture surface as well as friction laws on the fracture interfaces (2D surface embedded in 3D domain). The objective is to propose a novel scheme that exploits the different time scales for the rate- and state-dependent friction laws, the mechanics and the flow. Moreover, the numerical schemes based on splitting of multiphysics will be developed and analyzed to ensure convergent and efficient solution schemes.

The project consists of several multi-physics effects coupled together; we divided the problem in several sub-problems to understand the complexity and interaction of the fewer effects. The different ingredients include contact mechanics, friction, flow, and elasticity equations. So far, we have obtained results for the following subproblems. 1. Linear elasticity including normal forces and friction and rate and state friction model – without considering the flow has been discussed in a paper by Taki and Kumar and has been accepted for publication. 2. Multi-rate schemes (different time stepping schemes for the different physical effects) for coupled mechanics and flow – without considering the friction and contact forces has been discussed in the paper by Almani et al. (2023). 3. We have considered a continuous problem formulation for flow, mechanics, friction for a fractured porous medium and proved the well-posedness of the continuous model. This is under reviewing process. Besides, the results have been presented in international conferences and seminars.

P2.2. Simulation technology for injection-related fault and fracture reactivation and induced seismicity

Duration	2021-2025
PI	Eirik Keilegavlen
Team	Inga Berre, Einar Iversen, Volker Oye, Ivar Stefansson, Yuri Zabegaev (PhD student)

The project goal is to develop simulation technology for studying reactivation of faults and fractures related to fluid injection, under influence of a combination of mechanical, fluid, and thermal forces.

The main focus of the project in 2023 has been the development of a framework for automatic selection and tuning of linear solvers for multiphysics simulations. During this activity, the project milestone of developing an 'Initial algorithm for automatic selection of solvers for multiphysics problems implemented' (originally due Q42023) was reached. The results have been published in a pre-print, moreover, the algorithm developed is available as open-source software.

For non-linear problems, there has been development of linearization methods that specifically target challenges related to simulation of fault reactivation, as reported by Stefansson et al. (2023).

Overall, the work on this project is progressing according to plans and the project goals are expected to be fully completed.

P2.3 Exploring the subsurface using a generalization of Dix' classic time-to-depth mapping method

Duration	2022-2025
PI	Einar Iversen
Team	Jokhongir Khayrullaev (PhD student, started August 2022), Morten Jakobsen, Inga Berre, Einar Iversen

The goal of the project is to develop new tools for seismic exploration of the subsurface, which rely on a generalization of Dix' classic time-to-depth mapping method. The latter has been a cornerstone in seismic data processing for more than 60 years. Whereas the classic Dix method is based on an assumption of a 1-D subsurface, varying only in depth, the new (generalized) approach adopts the assumptions of 3-D seismic time migration. That means the subsurface properties may have a quite general variation with depth, while lateral variations are assumed to be weak or moderate. The new method combines 3-D velocity estimation with dynamic ray tracing. For some implementations we plan to replace the dynamic ray-tracing based algorithm by an artificial neural network (ANN).

The project is focused on three topics:

- Topic 1: Generalized Dix method with improved approaches to regularization and stability
- Topic 2: Generalized Dix method by means of an artificial neural network
- Topic 3: Common-angle prestack time migration

From mid January to mid March 2023 Khayrullaev visited Maarten de Hoop's research group at Rice University, Houston, USA. The purpose was to get a kick-start on working with deep learning methods, needed under topic 2.

By December2023 we are close to finalizing a generalized Dix algorithm mentioned under topic 1.

P2.4 Interpretation of fluid-induced seismicity patterns

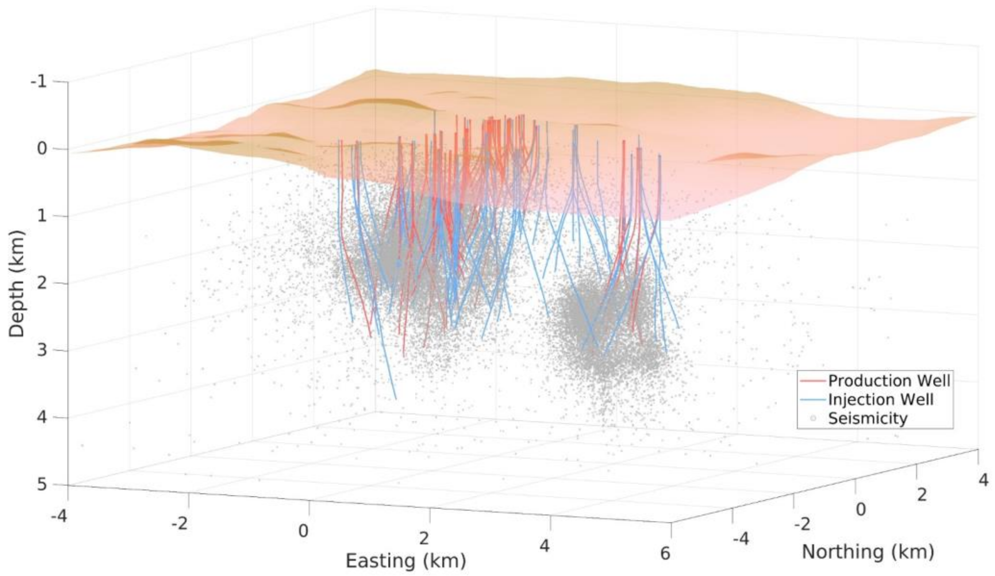
Duration	2023-2026
PI	Volker Oye
Team	Joanna Holmgren (postdoc, started June 2023), Joern Kaven, Inga Berre, Eirik Keilegavlen

This activity focuses on the analysis and interpretation of real field data collected continuously over 14 years from the Coso Geothermal Field in California, US. The data types include earthquake origin time and location catalogue, seismicity recordings, and fluid injection and production data. The project aims to gain insight into the evolution of the local stress field and how it is affected by long-term injection.

The postdoc started only in mid-June 2023 and the first tasks were related to the transfer and organization of the 14 years of data, which consists of some 133.000 detected and located earthquakes and production/injection data from 146 wellbores. The injection and production well data consists of daily average rates, including wellhead pressures, cumulative fluid volumes, fluid rates, and wellbore status. The data management tasks included tasks such as initial quality control of the earthquake catalogue, the injection/production data, and the 0.5 TB of seismicity recordings from 27 seismic stations with metadata. Additionally, we have completed initial seismic station checks, such as noise and station azimuthal coverage control, to identify which periods of seismicity are most reliable in terms of earthquake catalogue coverage and where to focus our initial investigation of the stress field.

We are planning to use several techniques to examine the microseismicity, which is caused by both tectonic and anthropogenic stresses acting on the field. Spatial and temporal variations in microseismicity will be compared to operational parameters such as extraction and injection rates and volumes to examine their causality. Full waveform cross-correlation methods will be used to precisely relocate the observed microseismicity and classify and characterize individual events and clusters, highlighting faults and fracture systems within the field. Furthermore, investigation of the rupture properties, stress drops, and focal mechanisms of the microseismic events will shed light on any distinctive and unique behaviour caused by the geothermal fluid-injection setting.

To date, in terms of investigation, we have worked on ways to adequately visualize the daily seismicity and production/injection data to better understand the relations between the sheer number of wells and earthquake activity in this complex geothermal field. We have already identified periods of increased seismic activity that is related to pumping stops due to maintenance and shut-in periods. Additionally, our preliminary relocation and earthquake clustering results have identified swarms of microseismicity that occur primarily during these shut-in periods, whereas other swarms occur during regular production/injection periods. We are working on analysing and relocating these induced earthquakes to better understand their properties and how they differ. This has included tasks involving cross-correlation, spectral analysis, earthquake magnitude estimations, and analysing catalogue statistics. Furthermore, since the start of the project, we have had productive and useful bi-weekly meetings with our USGS collaborator.



Spatial distribution of microseismicity at the Coso Geothermal field between 1996 and 2010, highlighting the two sub-fields within the geothermal field. Additionally, the 146 active wellbores are shown (production in red and injection in blue). Figure: Joanna Holmgren.

Affiliated projects

FracFlow

Duration	2020-2023
PI	Jan Martin Nordbotten
Team	Martin Fernø, Bergit Brattekås, Jakub Wiktor Both, Eirik Keilegavlen.

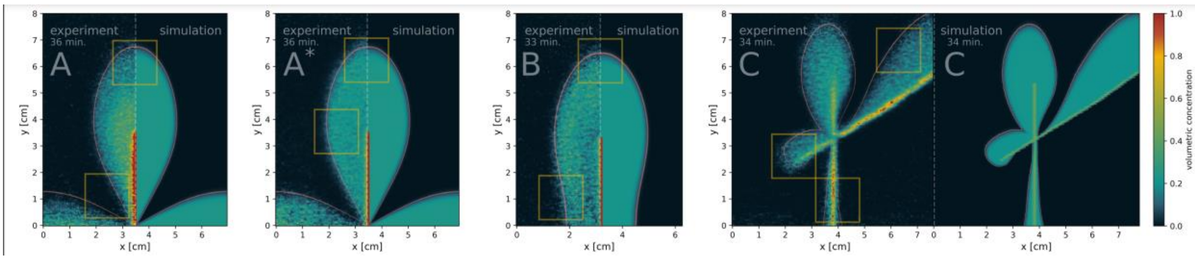
The FracFlow project has been an interdisciplinary collaboration between the Department of Physics and Technology and the Department of Mathematics. At the core of the project lies to establish strong cross-disciplinary collaboration to enhance our understanding of fluid flow in thin, quasi-2D structures, such as fractures. The FracFlow project concluded in 2023.

A key component of the FracFlow project was the experimental validation of mixed-dimensional models for flow and transport in fractured porous media. This comparison, composed of both PET-CT experiments and high-resolution simulations, was completed in 2023, with the results submitted for journal consideration.

During the project period, the FracFlow team has also contributed to developing our understanding the flow in the “FluidFlower” experimental rig, which is a quasi-2D experimental concept at the laboratory scale designed to investigate multiphase flows of geological relevance. The experimental work is conducted in three different realizations of the FluidFlower rig.

For the quantitative analysis of the PET-CT experiments and FluidFLower images, we developed an open-source code for analyzing general images of porous rocks, termed “Darcy-Scale Image analysis”, or DarSIA for short. The DarSIA code is intended to be a bridge between experimental images and mathematical analysis across several different imaging modalities.

By leveraging the combined experimental results and imaging capabilities, we conducted a double-blind simulation validation study in 2021-2022, and contributed the “ground truth” results. The forecasting and numerical simulation component of the study was executed in collaboration with the University of Stuttgart, with several papers being published as part of an ongoing special issue in the journal Transport in Porous Media (Flemish et al., 2023; Keilegavlen et al., 2023; Nordbotten et al., 2023; Saló-Salgado, 2023).



An image of four experiments in the FracFlow project. Left side of each image is the experimental data from the PET-CT scanner, while the right side of each image is the numerical simulation with PorePy. Figure from submitted manuscript.

Simulation of governing processes in superheated and supercritical geothermal systems: mathematical models, numerical methods and field data (SiGS)

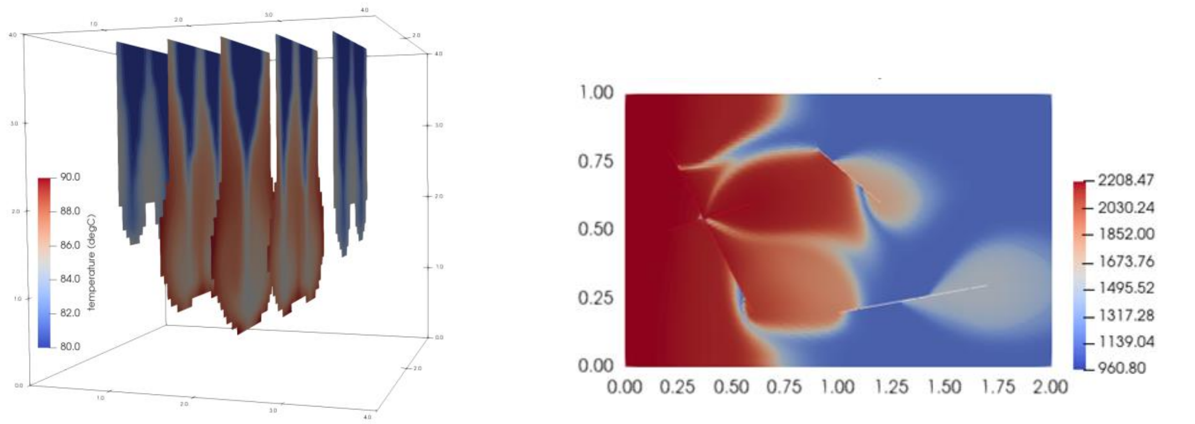
Duration	2020-2024
PI	Eirik Keilegavlen
Team	Shin Irgens Banshoya, Inga Berre, Sæunn Halldorsdottir

The project aims to combine simulation and field data analysis for thermal, hydraulic, mechanical, and chemical (THMC) processes in supercritical geothermal reservoirs. The project focuses on two mechanisms that are critical to understand superheated and supercritical geothermal systems: Heat transport from deep sources towards the geothermal reservoir and thermal stimulation caused by the introduction of cold fluids during drilling or reinjection. Development of simulation technology for multiphysics problems is also a core activity in the project.

This year, the project has studied the formation of pathways for transport of energy from the deep roots of geothermal systems. Simulations studies indicate that fractures which propagate due to a combination of fluid flow, transport of thermal energy, and rock mechanical effects, may form efficient pathways for fluid flow and transport of energy towards the shallower parts of the subsurface. This can be important not only in regimes where the temperature varies rapidly with depth, as are found in volcanic areas, but also in regions with relatively weaker temperature variations. These findings were reported in Halldorsdottir et al. (2023).

The project has also developed simulation techniques for reactive transport of water-borne chemicals in fractured porous media. This transport may change the chemical composition, leading to mineral dissolution and precipitation which both can alter the flow pattern. A methodology for non-isothermal reactive transport, considering equilibrium reactions only, was presented by Banshoya et al. (2023). Ongoing work aimed at extending this to kinetic reactions and realistic reaction systems, is in an advanced state.

The project has also contributed to the development of a new linear solver for calculating pressure fields in fractured porous media, as reported by Hu et al. (2023).



Left: Temperature profile in propagating fractures under cooling-induced tensile fracturing. Figure from Halldorsdottir et al. (2023). Right: Concentration of a precipitated mineral under non-isothermal reactive flow in a fractured porous media. Figure from Banshoya et al. (2023).

Quantifying the relation between Carbon Capture and Storage and earthquake risk (CCS-ER)

Duration	2021-2025
PI	Mathilde B. Sørensen
Team	Maren K. Karlsen, Mathilde B. Sørensen, Lars Ottemöller, Corbett Grainger

This project aims to quantify the relation between CCS and seismic hazard and risk, the likelihood of earthquakes, and the risk of these earthquakes causing damage. The project will include a field example, evaluating the hazard and risk for a planned storage site at the Horda platform, off the coast of western Norway. A thorough hazard and risk analysis will help inform industry and policy makers when making decisions towards the UN climate goals, as well as the strategic focus of the Norwegian government on CCS as a future industry.

The project started in October 2021. Since then, activity been focused on developing a baseline probabilistic seismic hazard model for Norway. This includes compiling and quality checking a homogeneous earthquake catalog for Norway, developing a model of seismic source zones, establishing earthquake activity rates for each source zone and identifying ground motion prediction models (describing the level of ground shaking as a function of e.g., earthquake magnitude and distance). The PhD candidate working on the project has been on maternity leave for most of 2023 and thus the hazard model is still under development. In the beginning of 2023, a workshop was arranged with colleagues from the neighboring Nordic countries working on national seismic hazard models, to assure that the models are consistent across national borders.

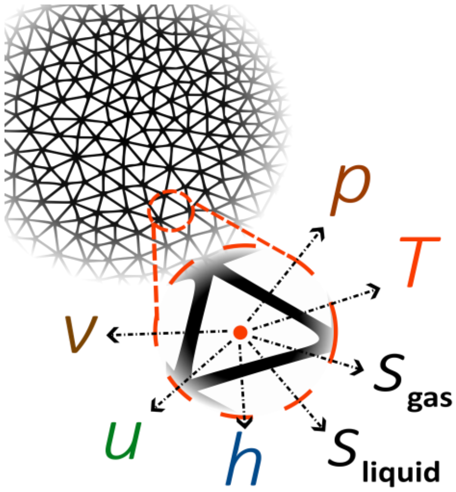
The seismic source zonation model to be used in the baseline probabilistic seismic hazard model for Norway. Figure: Maren Karlsen.

Mathematical and Numerical Modelling of Process-Structure Interaction in Fractured Geothermal Systems (MaPSI)

Duration	2021-2026
PI	Inga Berre
Team	Hau Trung Dang, Omar Duran, Ingrid Kristine Jacobsen, Jakub W. Both, Eirik Keilegalven, Veljko Lipovac, Jan Martin Nordbotten, Florin Radu, Ivar Stefansson

The goal of the MaPSI project is to provide mathematical models and simulation technology required to assess subsurface process-structure interaction in the context of hydraulic and thermal stimulation in development and production of high-temperature geothermal resources.

High-temperature geothermal systems involve multicomponent multiphase processes in porous rock. The model being developed in the project is based on a compositional formulation with pressure, mole fractions of the components and enthalpy as primary variables. A central part of the work is development of new, unified, methodology for the required isenthalpic flash calculations to find phase composition, temperature, and partial phase fractions (Lipovac et al., 2023). The unified formulation of the fluid phase equilibrium problem (flash) was also extended to the isenthalpic formulation, with analogous work done for isochoric or isoenergetic approaches. Due to local equilibrium assumptions, flash calculations are performed locally, and emphasis was placed on an efficient and parallel implementation for the equilibrium problem when coupled with flow and transport.



Fluid properties in a cell: The properties relate to each other via the fluid phase equilibrium problem. Illustration: Veljko Lipovac.

The fracture deformation model was extended to include normal elastic deformation. The interplay between this effect and cooling-induced rock contraction was studied using a thermo-poromechanical simulation model. Fluid injection into fractured subsurface rock might lead to seismic fracture slip. The elastic wave equation is relevant for modeling the seismic waves propagating through the rock due to the seismic slip, and for solving this problem we have worked on development of the FV-MPSA-Newmark (finite volume multi-point stress approximation-Newmark) method. Absorbing boundary conditions are included in the problem formulation to avoid artificial wave reflections from the domain boundaries.

The project has also investigated the potential of Cosserat continuum models for subsurface formations. This model includes micro-rotations and can accommodate the micro-structure of granular, layered and/or blocky materials, which is relevant in modeling of faults in the subsurface. From a macroscopic perspective, a fault gauge exhibits local rotations of fractured blocks, which result in an asymmetric stress field along the fault extension. Linearized Cosserat elasticity was employed to model such asymmetries in a mixed-dimensional format. As a result of this research, robust mixed finite methods for linear elastic Cosserat equations have been devised, including a transition from Cosserat elasticity to classical Cauchy media.

A central part of the project is integrated open-source software development based on the PorePy software and on the development of efficient coupling schemes and solvers. Work on the simulation framework has continued, the last year has seen a major refactoring to allow for flexible representation of general multiphysics processes in fractured porous media. This enhanced framework is currently being used for activities within this project and in other projects within CSD.

In 2023, work has started on the testing and comparison of various solvers for hydro-mechanical coupled processes and fracture contact mechanics. One considered approach is based on regularizing the equations of contact mechanics as well as on identifying characteristics of problems with convergence issues.

Gradient Flow Modelling of multi-phase flow in Deformable Porous media (GradFlowPoro)

Duration	2022-2023
PI	Jakub W. Both
Team	CSD: Omar Duran, Veljko Lipovac, Erlend Storvik; UiB: Peter von Schultzendorff; Inria Lille: Clément Cancès, Maxime Jonval; University of Nice Sophia Antipolis: Konstantin Brenner

The GradFlowPoro project falls under the Aurora Mobility Programme, ran by the RCN, aiming at establishing new international collaborations between Norway and France, as well as to strengthen European research collaboration under Horizon Europe. As such, short-term visits between the participating partners (with main locations in Bergen and Lille) lied at the heart of the project.

The primary scientific objective of the project has been 'the development of a novel, thermodynamically consistent mathematical model for multi-phase poromechanics with a natural gradient flow structure'. Such has been identified within the project period accompanied by a first-ever extensive well-posedness analysis addressing degenerate two-phase flow in linearly deformable media. The results are submitted for journal consideration and are currently under review. The developed theory is furthermore suitable for analyzing structure-preserving numerical schemes and the robust nonlinear solution, which remains a work in progress. With this, the project has successfully contributed to the mathematical theory of multiphase poromechanics.

The project has concluded in 2023 with final exchange between the two groups, in particular providing possibilities for the younger researchers to disseminate their own research in dedicated seminars and grow their network.

Network Inpainting via Optimal Transport (NIOT)

Duration	2023-2025
PI	Enrico Facca
Team	Enrico Facca, Jan M. Nordbotten

The precise digital reconstruction of natural networks such as blood vessels or plant roots is crucial to ensure the quality of simulation-driven predictions. However, these structures can often be accessed only via noninvasive techniques, leading to artifacts that compromise the reliability of the data and the derived simulations. No technological solution is currently able to recover digital reconstructions of "real" networks from corrupted images.

The NIOT (Network Inpainting via Optimal Transport) project aims to fill this technological gap by defining for the first time a robust mathematical formulation of the image network reconstruction problem. A major ambition of the project is to pair theoretical analysis with robust simulation tools that are capable of handling real data arising from MRI acquisition techniques.

In 2023, we achieved the first milestone of the project that consists in the development of the theoretical framework of the network inpainting method, together with a code to test it. We obtained a series of promising results in the reconstruction of 2d networks, that were presented during two international conferences. We plan to publish these results in the first part of 2024 and then focus on the problem of reconstructing corrupted vascular networks in MRI scans of human patients.

Example of the preliminary results obtained in the network reconstruction problem (images from Facca, E., Nordbotten, Jan. M. and Hanson E. A. "Network Inpainting via Optimal Transport", manuscript in preparation for 2024). In the left image, the y-shaped network is corrupted within the three red rectangles. The second and third images show the networks obtained using standard inpainting algorithms. The rightmost picture shows the reconstruction obtained using NIOT-based tools.

VISTA CSD Researcher Training Program

As of 31 December 2023, 20 PhD students, post-doctoral fellows and early-career researchers have been affiliated with the VISTA CSD Researcher Training Program. The training program is progressing according to plan, and in 2023, the following activities have been organized

- the CSD Winter School 13-17 March 2023, https://www.uib.no/en/vista-csd/161430/csd-winter-school-13-17-march-2023,
- CSD mid-term meeting
- weekly CSD seminars at UiB

CSD Winter School

CSD Winter School participants. Photo: Inga Berre

The winter school concentrated on various aspects of modeling subsurface systems with multiple phases or components, such as soil, water, air and CO_2. The more than 60 attendees learned about various mathematical and computational techniques and challenges for simulating the behaviour of these systems, as well as how to apply these tools to solve practical problems in fields such as CO_2 storage, civil engineering, and geosciences.

> *"The winter school did fully meet (if not overfulfill) my high expectations in terms of providing opportunities for networking (and collaboration) with other participants and faculty."*
>
> Student response in evaluation.

The main lecturer at the winter school was Hamdi Tchelepi from the University of Stanford, who gave lectures on a several topics from contact mechanics including faults and fractures and simulation of CO_2 sequestration in the subsurface. There were also many other lectures delivered by renowned experts on different numerical methods for simulating subsurface dynamics, the connection between modelling and experiments, the monitoring of induced seismicity and energy storage. The school also included a hands-on tutorial of the simulation software PorePy and group discussions about the role of scientists in society by debating ethical issues related to subsurface energy extraction and storage.

> *"I have learned how science/mathematics can be utilized to solve big scale problems and how likeminded people can effectively collaborate and aim for united goals"*
>
> Student response in evaluation.


Main lecturer Hamdi Tchelepi (Stanford University). Career Panel lead by Kundan Kumar (left) consisting of Hamdi Tchelepi (Stanford Unviversity, Kenneth Ruud (Norwegian Defence Research Establishment), Sarah Gasda (Norce) and Mathilde Sørensen (CSD/University of Bergen)

During the day, when not attending lectures, the participants enjoyed downhill or cross-country skiing. Some even tried skiing for the very first time with significant improvement during the week. On Wednesday evening we were lucky enough to see northern lights. It was quite spectacular. Overall, the CSD winter school 2023 was a huge success. Participants left with a better understanding of subsurface modeling in theory and in practice, as well as new connections to fellow students and experts in the field.


Northern lights in Myrkdalen and skiing during the Winter School. Photo: Florin A. Radu (left) and Inga Berre (right)

CSD Mid-term meeting

On November 8th and 9th, 2023, the VISTA CSD center had a midterm meeting at Solstrand Hotel in Os, Norway. International collaborators, industry partners, and the scientific advisory board (consisting of Paola Antonietti, Insa Neuweiler, and Stefan Buske) participated in the meeting. On the first day, seven presentations were given on the two main research pillars of the CSD Vista center: groundbreaking modeling concepts for deformation in porous rocks and fundamentals of induced subsurface deformation. The keynote speaker, Ruben Juanes from MIT, gave an exciting talk on mitigating the risk of induced seismicity related to the underground storage of carbon dioxide. He discussed various models and how they could be utilized to forecast seismic risk when applied to real injection sites.

The MaPSI project's progress was discussed in detail on the second day of the meeting. Presentations were given on various research topics, including unified flash calculations and solving the contact mechanics problem by regularization. Additionally, affiliated research projects like SiGIS, GradFlow, FracFlow, and NIOT presented their current work, covering a wide range of topics from image analysis to the optimal transport problem. The final presentation of the day was given by Gunnar Gunnarson from Orkuveita Reykjavikur, who talked about the current and upcoming geothermal extraction wells in Iceland. The meeting ended with closing remarks from the director of CSD, Inga Berre.

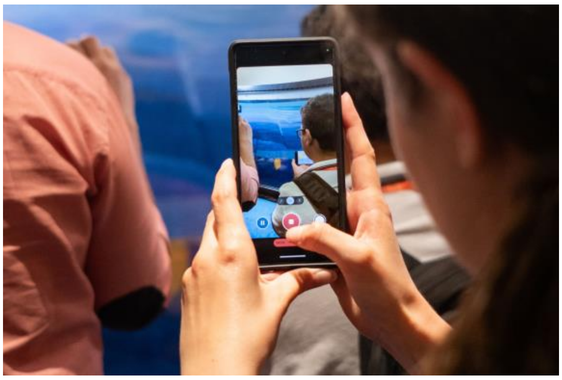
CSD Mid-term Meeting participants. Photo: Solstrand

SIAM Geosciences conference in Bergen

Over four days in June 2023, Bergen was host for the Society of Industrial and Applied Mathematics Conference on Mathematical Issues in the Geosciences (SIAM Geosciences), with CSD members as co-chair of the conference and filling roles in both the scientific as well as local organizing committees. The conference was a big success, and with more than 350 participants was likely the biggest mathematical conference organized ever in Bergen.

Among the highlights of the conference were invited lectures from leading international scientists and SIAM award winners. Moreover, with support from CLIMIT and Wintershall DEA, we were able to showcase the FluidFlower experiment – with live subsurface CO2 injection taking place during a Monday evening icebreaker.

The program also included two excursions – both fully booked – to the Northern Lights facility in Øygarden, where participants had the chance to see the onshore development of one of the world's first commercially viable CO2 storage operations. Keeping with the theme of Geosciences, the conference dinner took place at the Bergen Aquarium, among inhabitants from all of the world's oceans.

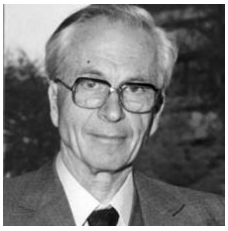


Onsite experiments showing CO2 storage with the FluidFlower rig during the SIAM Geosciences conference in Bergen. Photo:private (left), Jin Mæland (right).

Honors and awards

Inga Berre named Argyris Visiting Professor 2023

The SimTech Cluster of Excellence at the CSD partner institution University of Stuttgart appointed Professor Inga Berre as the Argyris Visiting Professor for the year 2023. This position reflects the recognition of Professor Berre's contributions to the field of simulation technology and her impact on advancing research in the domain.

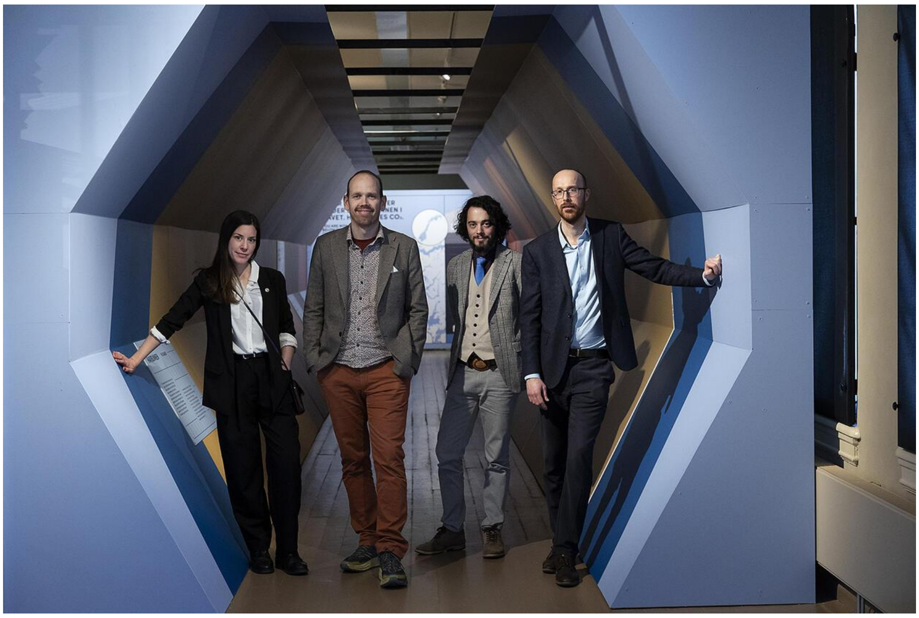


Since 1959 John Argyris was a professor at the University of Stuttgart, then the Technische Hochschule Stuttgart. Photo: SimTech

"With the Argyris Visiting Professorship, SimTech reminds of Professor John Hadji Argyris, one of the most internationally respected pioneers in the field of simulation technologies. John Argyris was a professor at the University of Stuttgart (which was then known as Stuttgart University of Technology) and an important co-founder of the finite element method, with which a multitude of physical processes are still simulated today."

Faculty of Mathematics and Natural Sciences' Communication Award

CSD members Martin Fernø and Jan Nordbotten received, together with Atle Rotevatn, the Faculty of Mathematics and Natural Sciences' communication award for 2023. In the jury's reasoning for why Fernø, Nordbotten, and Rotevatn were awarded this year's prize, MatNat Dean Gunn Mangerud highlighted, among other things, the project's innovative thinking. "Through the research infrastructure, or perhaps I should rather say the communication infrastructure FluidFlower, and not least the exhibition Our Porous World, Martin Fernø, Jan Martin Nordbotten, and Atle Rotevatn have blurred the boundaries between research, teaching, communication, and innovation. They demonstrate how we can rethink our core activities. Together, they show how communication is not just something done in addition to or on the side of everything else, but how communication can be an integrated part, said Mangerud."



Åshild S.F. Thorsen (University Museum of Bergen), Atle Rotevatn (Dept. Earth Science, University of Bergen), Jan Martin Nordbotten (CSD), Martin Fernø (CSD). Photo: Silje K Robinson

Organization of the Center

The Board is CSD's formal decision body. The Center Director is supported by the Center Management Team (MT) and the Industry Reference Group. The Scientific Advisory Board (SAB) reports to the CSD Board and gives advice to the Center Director. An overview of the organization structure of CSD is provided in the chart below.

CSD PIs and project leaders

CSD Principal investigators and project leaders. From left: Jan M. Nordbotten, Jakub W. Both, Helge Dahle, Einar Iversen, Inga Berre, Kundan Kumar, Eirik Keilegavlen, Mathilde Sørensen, Morten Jakobsen, Florin Radu. Enrico Facca and Volker Oye were not present.

The CSD Board

Kenneth Ruud (Chair)

Director General at The Norwegian Defence Research Establishment (FFI)

Anne Marit Blokhus

Professor, Department of Chemistry, University of Bergen

Antonella Zanna Munthe-Kaas

Professor and Head of Department, Department of Mathematics, University of

Atle Rotevatn, Professor and Head of the Department of Earth Science, University of Bergen

Unni Olsbye

Professor, Department of Chemistry, University of Oslo

Roger Sollie, Academia
Program manager at Equinor

Scientific Advisory Board

The task of the CSD Scientific Advisory Board (SAB) is to contribute to realizing the center's main goals and give advice to the center director and host institution. The CSD board has appointed the following Scientific Advisory Board for CSD:

- Prof. Paola Francesca Antonietti, Politecnico di Milano
- Prof. Stefan Buske, TU Freiberg
- Prof. Insa Neuweiler, University of Hannover

Industry reference Group

The CSD industry reference group has eight members

- Geir Terje Eigestad, Wintershall Dea
- Ketil Hokstad, Equinor
- Leo Eisner, Seismik
- Gunnar Gunnarsson, Orkuveita Reykjavíkur
- Guðjón Helgi Eggertsson, HS Orka
- Lilja Magnúsdóttir, HS Orka
- Anette Mortensen, Landsvirkjun

Hilmar Már Einarsson, Landsvirkju

Center Management Team

The center management team consists of Prof. Inga Berre (Center Director), Prof. Morten Jakobsen (P1 Coordinator), Assoc. Prof. Kundan Kumar (P2 Coordinator) and Prof. Jan Martin Nordbotten (P3 Coordinator).

Journal Publications 2023

1. Almani, T., Kumar, K., and Wheeler, M. F. (2023). Convergence analysis of single rate and multirate fixed stress split iterative coupling schemes in heterogeneous poroelastic media. *Numerical Methods for Partial Differential Equations*, 39(4):3170–3194. https://doi.org/10.1002/num.23004
2. Banshoya, S. I., Berre, I., and Keilegavlen, E. (2023). Simulation of reactive transport in fractured porous media. *Transport in Porous Media*, 149:643–667. https://doi.org/10.1007/s11242-023-01946-0
3. Boon, W. M. and Nordbotten, J. M. (2023). Mixed-dimensional poromechanical models of fractured porous media. *Acta Mechanica*, 234(3):1121–1168. https://doi.org/10.1007/s00707-022-03378-1
4. Flemisch, Bernd, Nordbotten, Jan. M., Fernø, M., Juanes, R. Both, J. W.,Class, H., Delshad, M., Doster, F., Ennis-King, J., Franc, J., Geiger, S., Gläser, D., Green, C., Gunning, J., Hajibeygi, H., Jackson, S. J., Jammoul, M., Karra, S., Li, J., Matthäi, S. K., Miller, T., Shao, Q., Spurin, C., Stauffer, P., Tchelepi, H., Tian, X., Viswanathan, H., Voskov, D., Wang, Y., Wapperom, M., Wheeler, M. F., Wilkins, A., Youssef, A. A. and Zhang, Z., (2023). The FluidFlower Validation Benchmark Study for the Storage of CO_2, *Transport in Porous Media,* 1573-1634. https://doi.org/10.1007/s11242-023-01977-7
5. Halldórsdóttir, S., Berre, I., Keilegavlen, E., & Axelsson, G. (2023). Crustal conditions favoring convective downward migration of fractures in deep hydrothermal systems. *Geophysical Research Letters*, 50(22), e2023GL105380. https://doi.org/10.22541/essoar.169111788.82179301/v1
6. Hu, X., Keilegavlen, E., and Nordbotten, J. M. (2023). Effective preconditioners for mixed-dimensional scalar elliptic problems. *Water Resources Research*, 59(1):e2022WR032985. https://doi.org/10.1029/2022WR032985
7. Jakobsen, M., Xiang, K., and van Dongen, K. W. (2023). Seismic and medical ultrasound imaging of velocity and density variations by nonlinear vectorial inverse scattering. *The Journal of the Acoustical Society of America*, 153(5):3151–3151. https://doi.org/10.1121/10.0019563
8. Keilegavlen, E., Fonn, E., Johannessen, K., Eikehaug, K., Both, J. W., Fernø, M., Kvamsdal, T., Rasheed, A., and Nordbotten, J. M. (2023). Porotwin: A digital twin for a fluidflower rig. *Transport in Porous Media*, pages 1–20. https://doi.org/10.1007/s11242-023-01992-8
9. Lipovac, V., Duran, O., Keilegavlen, E., Radu, F. A., & Berre, I. (2023). Unified flash calculations with isenthalpic and isochoric constraints. *Fluid Phase Equilibria*, 113991. https://doi.org/10.1016/j.fluid.2023.113991
10. Nordbotten, J. M. and Mossige, E. J. L. (2023). The dissolution of a miscible drop rising or falling in another liquid at low Reynolds number. *Physics of Fluids*, 35(1). https://doi.org/10.1063/5.0133025
11. Nordbotten, J. M., Benali, B., Both, J. W., Brattekås, B., Storvik, E. and Fernø, M. A. (2023). DarSIA: An Open-Source Python Toolbox for Two-Scale Image Processing of Dynamics in Porous Media. *Transport in Porous Media,* 1573-1634 https://doi.org/10.1007/s11242-023-02000-9.
12. Saló-Salgado, L., Haugen, M., Eikehaug, K., Fernø, M., Nordbotten, J. M., and Juanes, R. (2023). Direct comparison of numerical simulations and experiments of CO_2 injection and migration in geologic media: Value of local data and forecasting capability*. Transport in Porous Media*, pages 1–42. https://doi.org/10.1007/s11242-023-01972-y
13. Shekhar, U., Jakobsen, M., Iversen, E., Berre, I., and Radu, F. A. (2023). Microseismic wavefield modelling in anisotropic elastic media using integral equation method. *Geophysical Prospecting*. https://doi.org/10.1111/1365-2478.13416

14. Stefansson, I. & Keilegavlen, E. (2023). Numerical treatment of state-dependent permeability in multiphysics problems, *Water Resources Research* 59, e2023WR034686. https://doi.org/10.1029/2023WR034686
15. Stokke, J.S, Mitra, K., Storvik, E., Both, J.W., and Radu, F.A. (2023). An adaptive solution strategy for Richards' equation. Computers & Mathematics with Applications 152, pp. 155-167. https://doi.org/10.1016/j.camwa.2023.10.020.
16. Storvik, E., Both, J. W., Nordbotten, J. M., and Radu, F. A. (2023). A robust solution strategy for the Cahn-Larché equations. *Computers & Mathematics with Applications*, 136:112–126. https://doi.org/10.1016/j.camwa.2023.02.002
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