

# 2025

Annual report



An integrated research programme  
to understand subsurface dynamics  
caused by human activities



## DeepNL annual report 2025

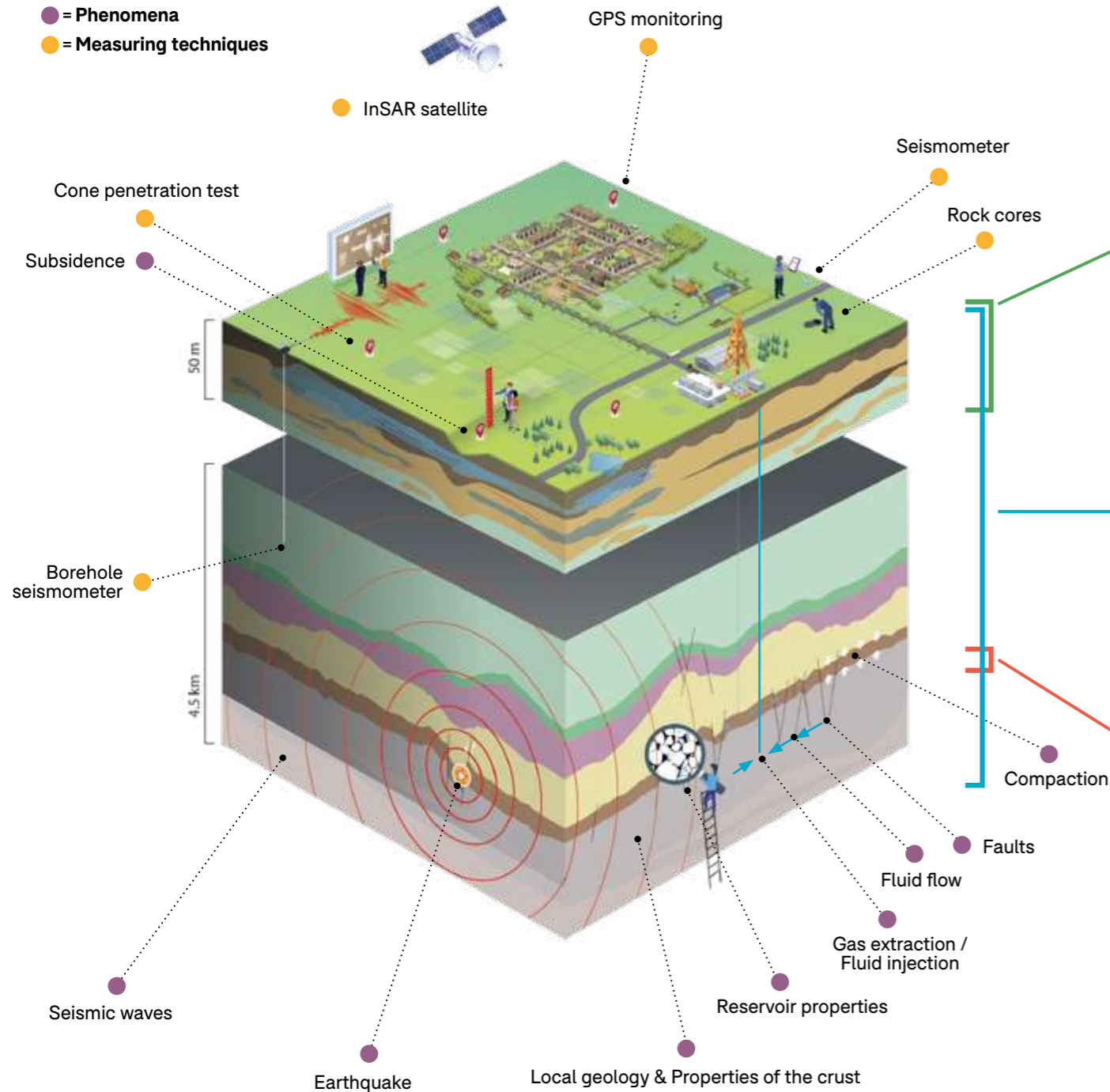


**The aim of the research programme DeepNL is to contribute to a better understanding of how the deep subsurface behaves under the influence of human interventions. In addition, the programme aims to strengthen and integrate the research community in the Netherlands around this theme.**



An integrated research programme to understand subsurface dynamics caused by human activities

● = Phenomena  
● = Measuring techniques



### Cluster 3

#### Subsidence and the response of the Earth's surface to earthquakes

How can we assess and model the impact of deep and shallow subsurface processes on ground motion at the surface?

**Research projects:** 5

**Researchers:** 9 (co-)project leaders, 11 PhDs and 3 postdocs

**Budget:** € 4,516,672,-

**Involved universities:** TU Delft, Utrecht University



### Cluster 2

#### Monitoring of physical conditions and forecasting

How can we monitor the subsurface conditions that could lead to seismicity, and forecast the occurrence of earthquakes?

**Research projects:** 8

**Researchers:** 22 (co-)project leaders, 18 PhDs and 5 postdocs

**Budget:** € 6,758,953,-

**Involved universities:** Eindhoven University of Technology, TU Delft, University of Twente, Utrecht University



### Cluster 1

#### Analysis of processes and conditions that lead to seismicity and subsidence

How can we constrain and model deep subsurface conditions and processes that can ultimately lead to earthquakes and subsidence?

**Research projects:** 13

**Researchers:** 28 (co-)project leaders, 34 PhDs and 10 postdocs

**Budget:** € 10,274,704,-

**Involved universities:** Eindhoven University of Technology, TU Delft, University of Groningen, University of Twente, Utrecht University

*This infographic gives an overview of the subsurface system and main processes that are studied within the DeepNL projects. It includes some of the measuring techniques that are used in conjunction with laboratory experiments and numerical models. The focus of the infographic, and most of the projects, lies on subsidence and induced seismicity due to gas extraction in the Groningen area. However, DeepNL also develops knowledge relevant for assessing the effects of geothermal energy production and subsurface storage of CO<sub>2</sub> and hydrogen in other areas of the Netherlands.*

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# Introduction

**The DeepNL programme committee is proud to present to you the 2025 DeepNL annual report. Besides updating you about the scientific progress, activities and other relevant information, this report also highlights a number of ongoing affairs.**

The 3.4 magnitude earthquake which occurred under Zeerijp on 14 November 2025 once again underscores the relevance of our work. This earthquake was one of the strongest ever measured in Groningen and it came, at least for some, as a surprise since it occurred well after the gas extraction was terminated. With the research in DeepNL we contribute to a better understanding of subsurface processes and to minimising risks of present and future subsurface activities.

Looking back, we are glad to see that all projects from DeepNL Call 1a have now been finalised and those of Call 1b and 2a are entering their final stages. In addition, all eight Call 2b projects are now fully operational and first ideas and results start reaching the community.

Together with the DeepNL community, the programme committee is taking further steps to ensure that the research results reach the professional stakeholders and society at large. Integrating the results and providing answers to the overarching questions of the DeepNL programme construct an important but challenging task, which requires commitment of the entire community. During the latest Scientific Meeting (21 November 2025, Utrecht), DeepNL researchers started defining the key outcomes of the programme and discussed in which forms these should be reported back to stakeholders and society. The programme committee is now working on next steps.

To improve the accessibility of the results of the projects and make them more usable for professional stakeholders and society, NWO has published the DeepNL Top-up Call for proposals 'Opportunities for Integration and Impact'. This Call provides financial support for small projects that build on previous DeepNL results and focus on integration, upscaling, application and outreach, thereby enhancing the value of our findings.

During the past year we also had a successful Stakeholder Meeting (15 April, Amersfoort) with 130 participants. In particular, I want to bring to mind the presentation and workshop on GeoKennisNL. This national umbrella programme for the coordination of knowledge development and sharing is initiated by the Ministry of Climate Policy and Green Growth and addresses the key issue of the coordination and continuation of subsurface research in the future. Universities and the fundamental research they execute, will be of key importance.

A variety of organisations, ranging from GeoKennisNL to provinces and local authorities, look at universities for input and answers to pressing questions. To be better positioned and to interact more efficiently with these organisations, and building on the exciting and strong community that DeepNL has built over the years, we have initiated a university platform, which hosts all Dutch universities working on issues related to safe and responsible use of the deep subsurface. The DeepNL University Platform came together for the first time during the 2025 Scientific Meeting in Utrecht and provided requested input to KEM (Knowledge Programme on the Effects of Mining) contributing to the definition of its research priorities. We hope the university platform can play an important role in ongoing discussions and national alignment.

I would like to thank the entire DeepNL community for its passion in developing science and projects, and the programme committee and the International Advisory Committee for the pleasant collaboration over the past year. Finally, I want to express a special thanks to the NWO team for their support. I very much look forward to the exciting years to come.

**Giovanni Bertotti**  
Chair programme  
committee DeepNL



# Events in 2025



## Netherlands Earth and Environmental Sciences Conference (NAC)

Researchers associated with DeepNL were actively engaged in the annual interdisciplinary Earth and Environmental Sciences (NAC) conference organised by NWO, contributing 15 oral presentations and poster presentations.



## DeepNL Stakeholder Meeting

This edition of the DeepNL Stakeholder Meeting brought together over 130 researchers and professionals for knowledge exchange on human-induced subsurface dynamics. The programme featured a diverse range of contributions, including insights from DeepNL researchers as well as perspectives from State Supervision of Mines and the Knowledge Programme Effects of Mining. In addition, the contours were sketched of the overarching knowledge programme GeoKennisNL. The meeting concluded with engaging parallel working sessions focused on the future use of the subsurface.



## Visit to Rijswijk Centre for Sustainable Geo-energy

Young DeepNL organised a visit to TNO's Rijswijk Centre for Sustainable Geo-energy. This is an open innovation lab where geo-energy projects can be tested at full scale, focusing particularly on geothermal energy and the subsurface storage of heat, hydrogen and CO<sub>2</sub>. The programme started with a tour of the facility, followed by presentations.



## DeepNL Scientific Meeting

What insights have the 26 DeepNL projects yielded so far? That question was central to the seventh edition of the Scientific Meeting. Around 65 DeepNL researchers gathered in Utrecht to share progress and results. In addition, early career researchers explored connections through speed dates and senior researchers discussed the DeepNL University Platform, a collaboration between six universities to coordinate focus areas, knowledge gaps and national developments in deep subsurface research. In the afternoon, participants split into thematic groups for a work session to identify key outcomes of the DeepNL programme.

# DeepNL research projects



The eight projects that received funding within the first DeepNL Call 1a form the basis under the DeepNL programme. In the subsequent three calls for proposals eighteen more projects were added to the programme. Together, these twenty-six DeepNL projects are grouped into three clusters, based on their research focus and the interfaces between projects. In 2025, the final two projects from the first call were finalised successfully.

**FINALISED PROJECT =** 

## Cluster 1 Analysis of processes and conditions that lead to seismicity and subsidence



### FAULTS

-  **Probing the micromechanics of small magnitude earthquake slip** - Niemeijer et al. - Call 1a - p44
-  **InFocus: An Integrated Approach to Estimating Fault Slip Occurrence** - Vossepoel et al. - Call 1a - p16

**μFAULT** - scaling friction from micro-contacts to faults at the reservoir scale - Mishra et al. - Call 1b - p20

**Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field** - Willingshofer et al. - Call 2a - p22

**FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity** - Niemeijer et al. - Call 2b - p26

**NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient natUre of iNDUced Seismicity** - Vossepoel et al. - Call 2b - p28

### RESERVOIR AND SEALS

-  **A multi-scale, multi-physics framework for modelling the geo-mechanical response of sandstone reservoirs to pore fluid extraction** - Hangx et al. - Call 1a - p46
-  **Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields** - Jansen et al. - Call 1a - p45

**The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs** - Míocic et al. - Call 1b - p30

**Making digital rocks a practical reality for energy storage within subsurface reservoirs** - Rücker et al. - Call 1b - p32



**Quantitative constraints on pre-production reservoir stresses in Groningen** - Govers et al. - Call 2a - p34

**Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoirs** - Hangx et al. - Call 2a - p36

**Constraining uncertainties across scales: From Groningen to future geoenergy applications (CrossScale)** - Geiger et al. - Call 2b - p38



## Cluster 3 Subsidence and the response of the Earth's surface to earthquakes



-  **Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension** - Hanssen et al. - Call 1a - p68
  -  **SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential** - Hicks et al. - Call 1a - p78
  -  **3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis** - Ghose et al. - Call 2a - p72
- DAMPINGSOIL: Providing the missing information of elastic damping ratio and strain-dependent modulus and damping curves for reliable, local site response analysis** - Ghose et al. - Call 2b - p74
- Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region** - Govers et al. - Call 2b - p76

## Cluster 2 Monitoring of physical conditions and forecasting



-  **DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity** - Barnhoorn et al. - Call 1a - p64
  -  **Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations** - Trampert et al. - Call 1a - p65
- PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling** - van Dinther et al. - Call 2a - p50
- Deep, deeper, deepestNL; Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM)** - Fadel et al. - Call 2a - p52
- LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data** - Niemeijer et al. - Call 2a - p56
- Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions (INTEGRATION)** - Van der Meijde et al. - Call 2b - p58
- SHAWave: Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach** - Van der Meijde et al. - Call 2b - p60
- A digital twin for modelling and forecasting induced seismicity** - Trampert et al. - Call 2b - p62

Progress  
**CLUSTER**

# 1



## Analysis of processes and conditions that lead to seismicity and subsidence

How can we constrain and model deep subsurface conditions and processes that can ultimately lead to earthquakes and subsidence?

## InFocus: An Integrated Approach to Estimating Fault Slip Occurrence

**Project leader:** Prof. Femke Vossepoel (TUD)  
**Associate project leaders:** Dr Ylona van Dinther (UU); Dr Andre Niemeijer (UU)  
**Postdoc:** Dr Mohsen Goudarzi (UU)  
**PhDs:** Hamed Ali Diab-Montero (TUD); Meng Li (UU)  
**Budget:** € 818,831,- (Call 1a)  
**Duration:** 2019 - 2025  
**WP1:** Development forward model for seismicity

and fluid flow in poro-viscoelasto-plastic media. (Goudarzi)  
**WP2:** Application of forward model and laboratory experiments to advance physical understanding of faults. (Li)  
**WP3:** Statistical analysis of seismological data and data assimilation experiments. (Diab-Montero)

### Research aim

To understand earthquake nucleation and recurrence in the Groningen gas field and assess data assimilation for estimating and forecasting fault stresses and motions using coupled earthquake, geomechanical, and fluid flow simulations.

### Highlighted outcomes 2025

The fundamental work on earthquake nucleation on velocity-strengthening faults was published in *Nature Communications*. Conventional thinking suggests that shallow faults cannot generate earthquakes because they become stronger as sliding accelerates. However, in practice, earthquakes do occur on these faults. The InFocus research explains this paradox. When faults are inactive for thousands to millions of years, they can slowly 'heal' and build up substantial strength. When human activities disturb that quiet subsurface, this stored strength can be released in a single earthquake. Crucially, once this long-term strength is released, no further earthquakes can occur on that fault segment. This strongly reduces the future seismic hazard, also because that segment will from then on act as a barrier to inhibit future earthquakes from growing larger.

The team moved on to address the central questions for seismic hazard assessment in Groningen: where do earthquakes start, how far can they rupture, and what physically limits their size? 2D earthquake models were used to simulate sequences of spontaneous seismic and aseismic slip events, while resolving fault physics from healing over millions of years to enhanced dynamic weakening on millisecond time-scales during earthquakes. Realistic geological layering was adopted, characterised by lithology- and juxtaposition-dependent frictional and elastic properties.

The team started from a conservative reference model (Figure B) pushed to criticality by e.g., neglecting stable stresses in the under-burden. They explored a wide and critical range of parameters by running 2000 simulations with widely varying fault and reservoir geometry, tectonic stresses, as well as frictional and elastic parameters. Of these 2000 simulations, only two percent of the models reach seismic slip rates before the Groningen gas reservoir is depleted (Figure A). Another ten percent could reach seismic slip rates, if more than double the amount of gas could be extracted. This means that the large majority of fault segments can slip, but not at rates that generate seismic waves. Many fault segments can host slow slip events, but only in four percent of the models before the gas present in the Groningen reservoir is depleted. From these simulations, it could be concluded that the large majority of fault segments can slip, but not at rates that generate seismic waves. Earthquakes always start inside the gas-producing Slochteren Sandstone layer, regularly near the top of the sandstone-sandstone juxtaposition. Generally, after initiation, slip may spread quickly across the reservoir, such that the largest earthquakes on a fault segment can regularly reach widths of about 75 up to 115 percent of the reservoir thickness. This shows that the largest ruptures can enter into the part of the fault, where reservoir rocks are juxtaposed to over- or under-burden rocks. However, ruptures readily arrest in there due to a comparatively large increase of normal stresses followed by a strong decrease in shear stresses below that. Together these stress changes significantly reduce fault criticality tens to few hundreds of meters below the reservoir-reservoir juxtaposition. This stress barrier ensures that only 1 out of 2000 simulations exhibits a rupture that runs away into the under-burden, albeit under highly unlikely conditions.

When mapping these simulation results onto the complex fault network in Groningen, only on a few tens of short fault segments in peripheral regions have a probability of runaway rupture of tens of a percent (Figure C). Since reservoir compaction and consequent fault loading is limited in these southern regions, one would not expect that the amount of gas depletion required for runaway earthquakes could arise.

These results demonstrate that lithological heterogeneity imposes strong physical constraints on rupture size. Earthquake confinement is facilitated by localised stress changes, heterogeneous materials, and an underburden with velocity-strengthening friction and no-to-low healing. This finding and the parameters that enhance rupture widths agree with earlier studies. However, taking into account processes incorporated in rate-and-state friction and heterogeneous properties distinctly reduce the likelihood of runaway ruptures. Mechanical heterogeneity strongly suppresses slip rates and thus limits rupture extent, while frictional heterogeneity removes large stress peaks (singularities) and thus plays an opposite though secondary role.

Meng Li is currently working as a postdoctoral researcher at Stanford University. Together with Paul Segall and Eric Dunham he works on numerical and analytical models for induced seismicity due to fluid injection.

### Data and method products 2025

The advanced earthquake sequence models with cross-scale fault physics and heterogeneous frictional and elastic parameters are made available to the public on [www.github.com/USustSub](https://www.github.com/USustSub). This website will host all developed products from connected DeepNL projects such as InFocus, PhysMmax and NEPTUNUS, to create

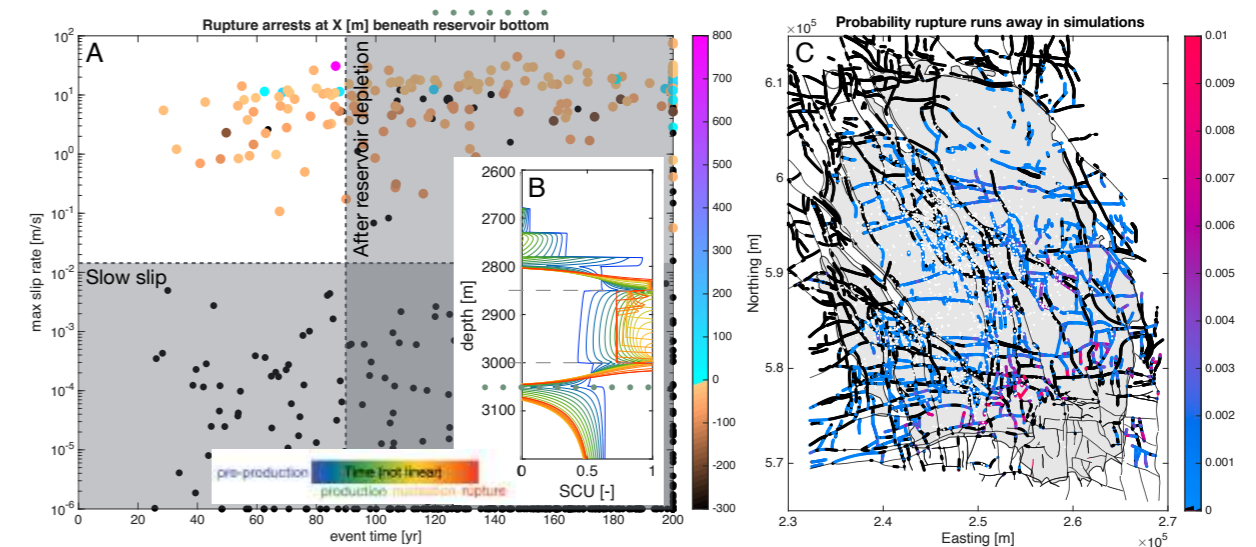
one go-to location for stakeholders who search for numerical models for induced seismicity.

### Collaboration and integration within DeepNL

PhysMmax and NEPTUNUS build on the methods, concepts and constraints provided by InFocus.

### Relevance for and knowledge exchange with stakeholders

The InFocus results provide a clear physical explanation for why earthquake magnitudes in Groningen remain limited: the geology itself constrains rupture growth. This robust, physics-based finding makes it possible to lower the estimated hazard of earthquakes on Groningen, because this hazard is largely influenced by the maximum magnitude of earthquakes. Fundamental outcomes and tools developed within the InFocus project are also applicable to sustainable subsurface applications, such as geothermal energy and energy storage. The publicly available models and methods could ultimately feed into the Seismic Hazard and Risk Analysis workflows for Groningen. Meng Li, Ylona van Dinther and André Niemeijer published their work in *Nature Communications*. This article received a large amount of attention from the news media. It has been published in at least 10 languages in over tens of articles and led to interviews with e.g. RTV Noord. The InFocus team organised a roundtable with stakeholders to gauge their interest in making DeepNL fault-slip models available to a wider audience. Inspired by this meeting, a project was initiated by TUD, TNO and UU. The project will be funded by EZK and will deliver a benchmark of existing fault-slip models and a web-based interface that allows operators and other stakeholders to access specific versions of fault-slip models developed within DeepNL and at TNO.

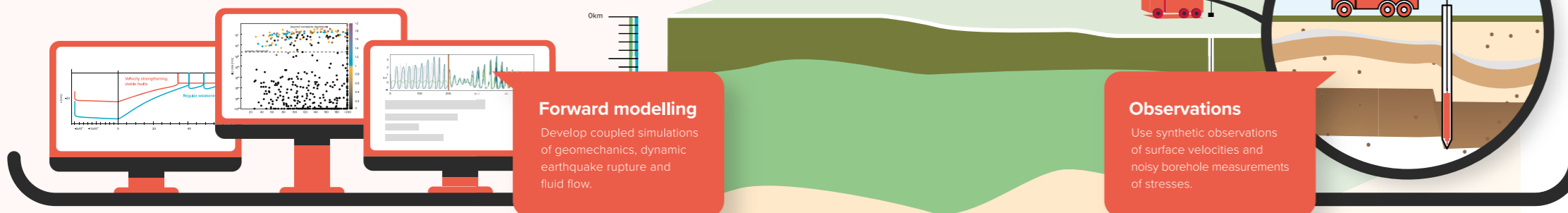


Data-constrained earthquake cycle results. (A) Each dot represents slip rate and timing of the largest event in each of the 2000 simulations. Only left top quadrant shows earthquakes occurring before gas reservoir is empty. (B) Criticality vs. depth for the reference model showing seismic slip until orange depth lines and the strong stress barrier below the lowest orange line showing why the rupture stops. (C) Map showing how many of the 2000 simulations show a runaway rupture for the geometries of each mapped segment.

# How can we understand and forecast earthquakes by combining models and observations?

## DEVELOPED PRODUCTS

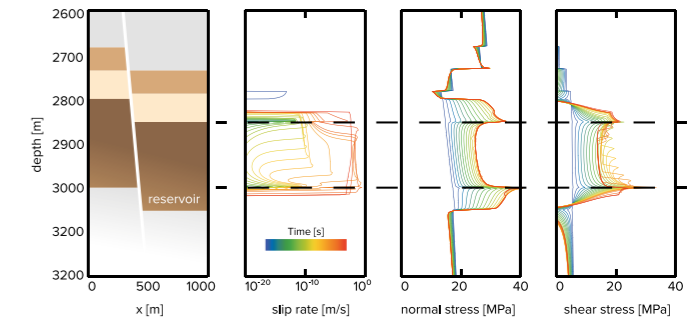
## APPROACH



Developed products available at:  
<https://github.com/USustSub>

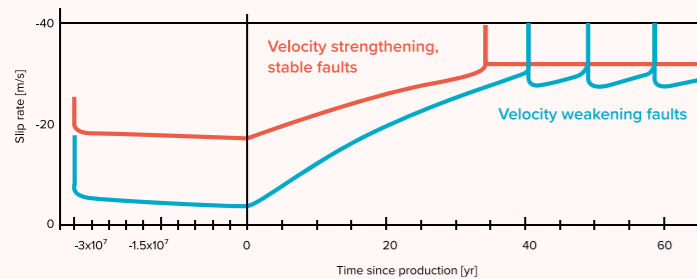


- Dynamic earthquake cycle models** with rate-and-state friction and fluid flow in 0D-3D.
- 2D model simulating sequences of seismic and aseismic slip** on a dipping normal fault in Groningen due to poro-elastic compaction.
- Regularised continuum models** for spontaneously evolving fault zones and earthquakes governed by rate-and-state friction.
- Ensemble Kalman Filter to estimate and forecast seismic and aseismic slip** in product 1.
- Three advanced ensemble-based data assimilation methods** connected to a 0D spring-block model to improve estimates of variable earthquake size and earthquake timing.



## KEY OUTCOMES

- The developed data assimilation methods provide very good fault stress estimation and forecasting potential for synthetic slow slip events and earthquakes.

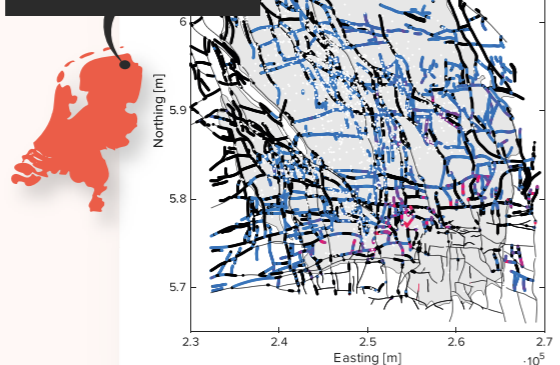


- In contrast to current understanding, a single earthquake can occur on typical shallow faults that strengthen with slip rate. Once their millions-of-years of healed strength is released, no further earthquakes can occur on that segment.

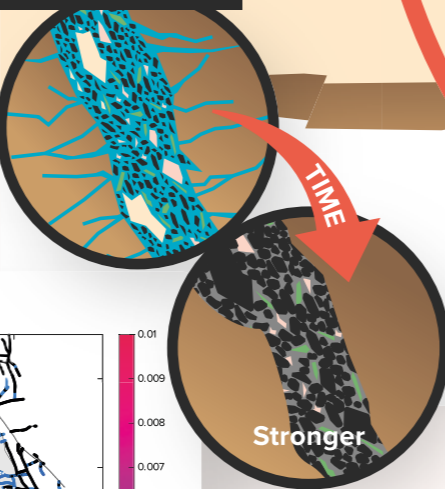
- Earthquakes start and stop within the reservoir, or just adjacent to it for a few extreme modelled cases. Earthquake confinement is facilitated by localised stress changes, heterogeneous materials, and an underburden with velocity-strengthening friction and no-to-low healing. This eliminates the possibility of triggering very large, runaway earthquakes within the observed parameter ranges.

- Since earthquake propagation is limited in depth (outcome 3) and along the fault (outcome 2) the maximum expected magnitude of earthquakes in Groningen should be reduced.

### PROBABILITY OF RUNAWAY EARTHQUAKES ON THE FAULT NETWORK OF GRONINGEN



### FAULT HEALING



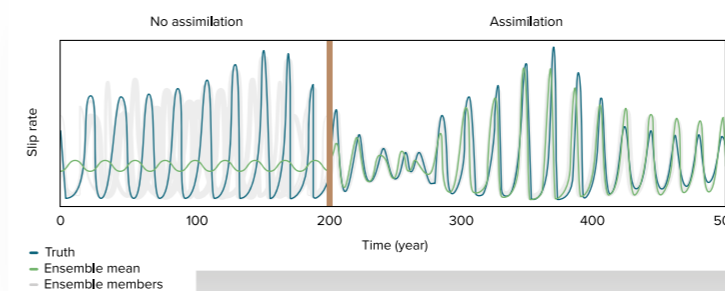
### Observations

Use synthetic observations of surface velocities and noisy borehole measurements of stresses.

### Data assimilation

Combine physics-based models and observations to estimate fault stress and slip rate.

### DATA ASSIMILATION FOR SEISMIC CYCLE ESTIMATION



## IMPACT

Earthquake models in which observations have been assimilated hold promise for earthquake forecasting. Infusing physics-based models with the latest laboratory observations suggests that seismic hazard in Groningen will be less than currently anticipated. The publicly available models and methods could ultimately feed into the Seismic Hazard and Risk Analysis workflows for Groningen. Fundamental outcomes and tools are also applicable to sustainable subsurface applications, such as geothermal energy and energy storage.



More information about this project:

*InFocus: An Integrated Approach to Estimating Fault Slip Occurrence (Vossepoel et al.)*

An integrated research programme to understand subsurface dynamics caused by human activities.



# μFAULT - scaling friction from micro-contacts to faults at the reservoir scale

**Project leader:** Dr Tanmaya Mishra (UT)  
**Postdoc:** Dr Atiyeh Adelinia (UT)  
**PhD:** Malek Jaran (UT)  
**Budget:** € 750,000,- (Call 1b)  
**Duration:** 2021 - 2027

## Research aim

To develop physics-based friction models for fault-gouge contacts following a bottom-up approach, to be able to compute slip in faults resulting in induced seismicity due to subsurface activities.

## Highlighted outcomes 2025

Malek Jaran decided to quit his position in the μFault project per 31 August 2025. Atiyeh Adelinia started on 1 November 2025 as a postdoctoral researcher on the project. Due to these changes in personnel, the research outcomes in 2025 have been somewhat limited. The main research related activities included: (1) Single-grain sliding experiments on the finalised high precision friction setup for quartz contacts (2) Development of the numerical model for fault gouge shear and implementation of grain-scale friction in the developed numerical model to study stick-slip events and (3) Experimental studies on time- and rate dependent contact and friction behaviour in grain-scale contacts using atomic force microscopy (AFM).

## Focus for 2026

The research focus for 2026 will be to:

1. Perform experiments to characterise the grain scale friction and contact forces for quartz and calcite specimens using the single-grain sliding setup. Effects of material anisotropy, contact heterogeneity, variable loads and sliding velocities on frictional behaviour at the grain scale will be investigated. This will be the main aspect of research for Atiyeh Adelinia.
2. The single-grain friction data generated from experiments will be implemented in the numerical DEM model developed to simulate (direct) shear in fault-gouge aggregates. The simulated shear behaviour,

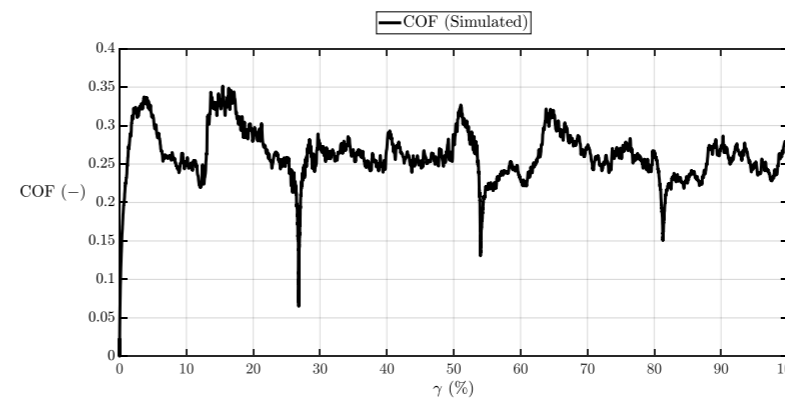
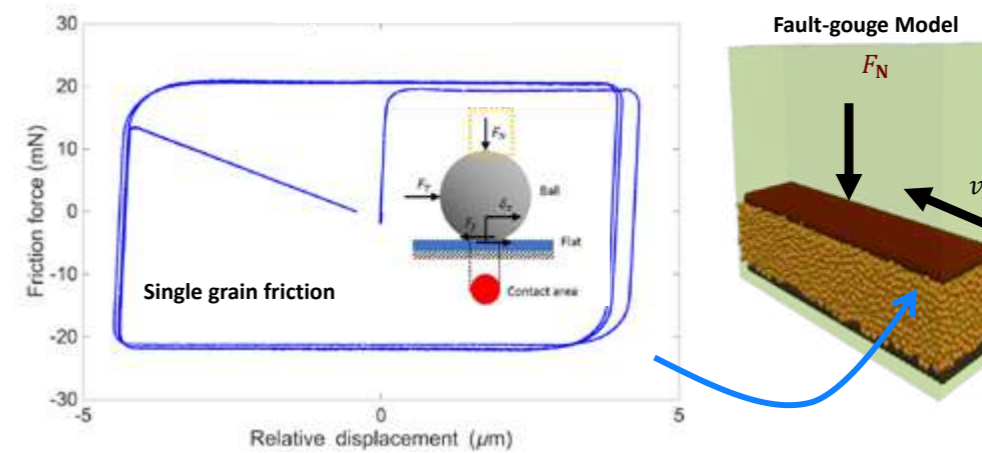
the stick-slip event distribution and the microstructure of the gouge aggregate will be then validated against the experimental data obtained from the gouge segments sheared using the direct shear apparatus at the HPT lab at Utrecht University.

3. The experimental studies on frictional ageing will be further used to validate the numerical model developed for frictional ageing due to effects of humidity in grain-grain contacts.

The aim is to disseminate the knowledge on grain scale friction and its upscaling to gouge scale in scientific journals by the end of the year.

## Collaboration and integration within DeepNL

There are strong links between the μFault project and the ongoing and completed projects of André Niemeijer. Both PI's are looking at fault friction under different conditions at different scales: Niemeijer's projects look at frictional heating in dynamic slip, while this project focusses on friction in quasi-static slip, resulting in nucleation of earthquakes. Nevertheless, the micro (grain)scale models and numerical gouge shear models will be mutually beneficial in constraining the forecasting of the magnitude of induced seismicity in Groningen and in future subsurface storage. The grain-scale contact models and the fault gouge DEM models developed in the μFault project will also be useful for understanding the role of granular contact mechanics in reservoir compaction, by Hangx et al. There has been active collaboration and joint research with Johannes Miocic on performing nano-indentation experiments on clay specimens to study the micro-mechanical properties of clay minerals with regard to their role in compaction in the gas reservoir.



Upscaling friction and slip from single grain to granular gouge assembly.



## Introduction DeepNL researcher Atiyeh Adelinia

Atiyeh Adelinia joined the μFault project as a postdoctoral researcher starting November 2025. She is currently finalising her PhD in the Surface Technology and Tribology group at the University of Twente. Adelinia has great expertise and experience in coating technology, wetting mechanisms, experimental methods, analysis and development of novel experimental setups. She will be characterising the frictional behaviour of microcontacts between grains (for example: quartz and calcite) in conditions replicating the subsurface fault gouge. She will focus on performing grain-scale sliding experiments in the high precision friction setup to measure contact (friction) forces and slip distances for different contact and loading scenarios, as well as for material (mineral) combinations.

# Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field

**Project leader:** Dr Ernst Willingshofer (UU)  
**Associate project leader:** Prof. Martyn Drury (UU)  
**PhD:** Job Arts (UU)  
**Budget:** € 357,328,- (Call 2a)  
**Duration:** 2021 - 2026

## Research aim

To constrain the structure, geometry and rheology of faults and fault zones in the Groningen reservoir at multiple spatial scales through an innovative integration of geological observations from the Groningen field with detailed (micro)structural analysis of field analogues, rock physics experiments and physical analogue modelling.

## Highlighted outcomes 2025

Outcrop-scale observations show that large offset faults typically consist of a fault core where most deformation localises, and an enveloping, less deformed damage zone. Although it is often assumed that fault mechanical behaviour is controlled by fine-grained material in the fault core, outcrop observations suggest that fault zones continue to grow with offset. This raises questions about how fault zones form and grow in space and time, whether this growth differs between seismic and aseismic faults, and hence how it is related to fault mechanical behaviour. Through physical analogue modelling using a newly developed shear apparatus, this project studies the coupling between fault zone structural development and fault mechanical behaviour. Based on a novel data acquisition approach that includes optical, mechanical and acoustic monitoring, five different stages can be distinguished in the structural evolution of fault zones in granular materials, from diffuse deformation, to incipient localisation, to the formation of a continuous fault zone. The results show that slip instabilities are always associated with shear localisation. With increased fault offset, the structural complexity of a fault zone decreases, and the slip instabilities or lab earthquakes become characteristic in size and inter-event time. The experimental work is linked to a multi-scale characterisation of faults and fault rocks from the Groningen field, which focuses on the composition and (internal) structure of faults, their rela-

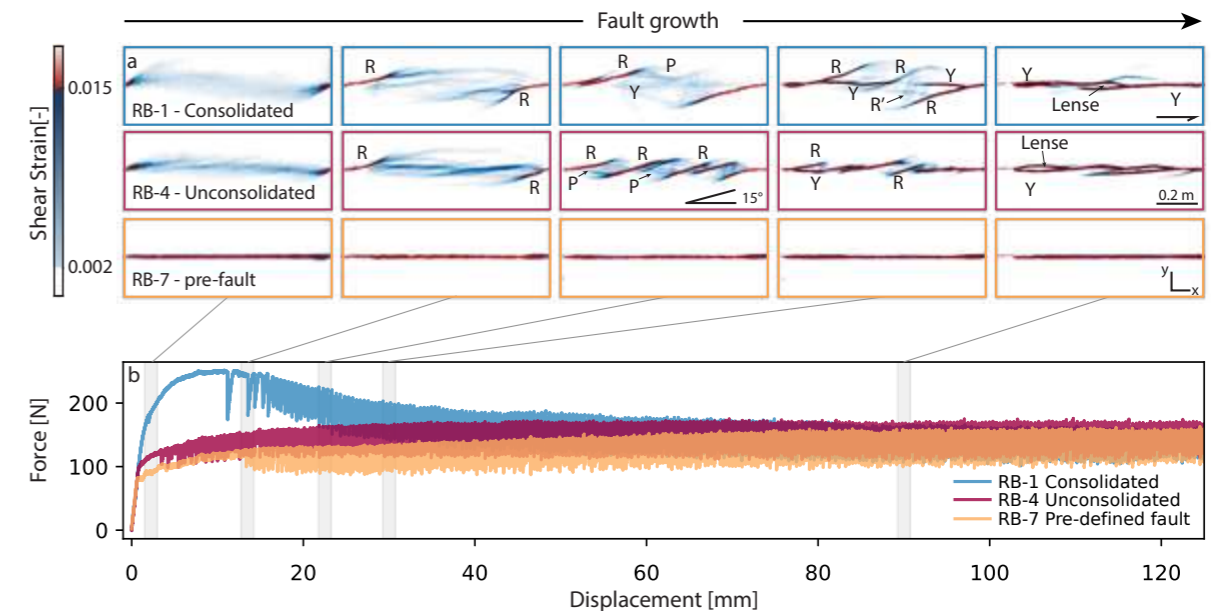
tionship with the complex multi-phase tectonic history, and the possible role of fault healing and cementation in the millions of years of tectonic quiescence. The mineralogy, porosity, diagenetic observations of fluid-rock interaction, and grain characteristics such as grain size distribution of natural samples derived from faulted samples from wells in the Groningen gas field were analysed. Based on the results, four main types of fault rocks encountered in the Groningen Rotliegend can be distinguished, based on their microstructural characteristics: (1) gouges consisting of quartz and feldspar grains embedded in a very fine clay matrix, (2) very fine-grained quartz-rich gouges, (3) quartz-cemented cataclasites, and (4) anhydrite-cemented cataclasites. Induced fault movement in the first two gouges is likely to occur by reactivation of the earlier-produced fault gouges, whereas reactivation of faults with cemented gouges probably occurs at the interface of the fault core to the damage zone, or within the damage zone leading to widening of the fault zone.

## Data and method products 2025

A data publication entitled 'Faulted samples from the Groningen gas field, the Netherlands' is available through the Utrecht University data portal. This dataset includes high resolution core images, sample images, full thin section digital scans, and optical and scanning electron microscope images. In addition, an overview report is provided that links the different images spatially. The dataset is the largest available microscopic dataset on faulted samples from the Groningen field and provides valuable insights for any Rotliegend and other sandstone reservoirs in the Dutch subsurface.

## Focus for 2026

Job Arts will focus on finishing his PhD thesis and transferring the up to now unpublished chapters of the thesis into publications in peer-reviewed journals.



Coupling between fault zone structural development and mechanical behaviour in physical analogue shear experiments. Different colours represent models with different initial grain packing distribution. a) Incremental shear strain. Note the various stages in structural development from distributed deformation to incipient localisation, Riedel shear (R) development and connection to form a throughgoing 'mature' fault. b) Associated shear force as function of displacement. Drops in shear force represent slip instabilities or 'labquakes'.

## Collaboration and integration within DeepNL

The results of the project provide constraints for friction experiments, microphysical models on fault frictional behaviour, and models that simulate fault reactivation, nucleation and seismic slip in the Groningen field. Within this framework, the published experimental results on heterogeneous gouges and the structural and compositional characterisation of faults and fault rocks from the Groningen field have already been implemented in geomechanical and dynamic rupture models as used by the PhysMmax and InFocus projects. Further knowledge exchange on the implications for fault frictional behaviour at different scales is anticipated with projects like  $\mu$ Fault and FastSlip. A collaboration with the project of Johannes Miocic to discuss diagenetic processes that occurred within the Groningen field and the role that faults have played in the fluid-rock interactions is ongoing. Combining their dataset on the intact reservoir rocks and this project's data on fault samples will paint a more complete picture of the distribution and relevance of authigenic mineral phases within the Groningen field.

## Relevance for and knowledge exchange with stakeholders

The relations between fault architecture, along-fault lithology distribution, fault healing and mechanical behaviour are directly relevant for improving the forecasting capabilities of advanced geomechanical and seismic wave field modelling approaches, and hence for improving risk assessment associated with reservoir depletion. This project also fuelled knowledge exchange and collaboration with stakeholders (TNO, EBN) on characterising deformation structures within faulted reservoirs in different stratigraphic levels of the Dutch subsurface. Data availability on faulted samples from the subsurface in the Netherlands is limited. This project contributes significantly to making such data available. Knowledge exchange with stakeholders has thus far been realised in the context of DeepNL stakeholder meetings and smaller workshops organised by stakeholders like <https://scanaardwarmte.nl/workshop-resultaten-scan-boring-amstelland/>. The team is planning an open day for stakeholders to visit the analogue and microscopy laboratories to showcase their results and show what research is possible with the new equipment.

Reflection by DeepNL  
PhD researcher  
**Job Arts**



Job Arts will defend his PhD thesis in the course of 2026 at UU

*'For me as a PhD researcher it was very valuable to be part of a large community with other PhD, postdoc and senior researchers and people from outside academia. I always enjoyed the scientific and stakeholder meetings and the Young DeepNL activities to strengthen this community. I am very proud that we were able to provide valuable qualitative and quantitative data on fault rocks from the Groningen gas reservoir. My most valuable experience was the fieldwork I conducted in the first year of my PhD. Seeing outcrop analogues of faults in the Groningen reservoir with all their complexities was important for understanding and interpreting my experimental results and microstructural observations in the context of the large Groningen gas field. The biggest challenge of my PhD was to bridge the various scales relevant for understanding fault mechanical behaviour, and the very broad range of methodologies to characterise faults and fault behaviour. In the future, I would like to work on similar topics related to the subsurface but in a non-academic environment, possibly for research institutes like TNO or Deltares, or local governments.'*

Job Arts and Ernst Willingshofer discussing experimental results on fault formation in the new share box.



# FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity

**Project leader:** Dr André Niemeijer (UU)  
**Associate project leaders:** Dr Hongyang Cheng (UT); Dr Tanmaya Mishra (UT)  
**Postdocs:** Dr Chien-Cheng Hung (UU); Dr Rafael Nazareth Lopez (UT); Dr Chengshun Shang (UU)  
**PhD:** Syukri Ainun Alfath (UT)  
**Budget:** € 1,021,627,- (Call 2b)  
**Duration:** 2024 - 2028

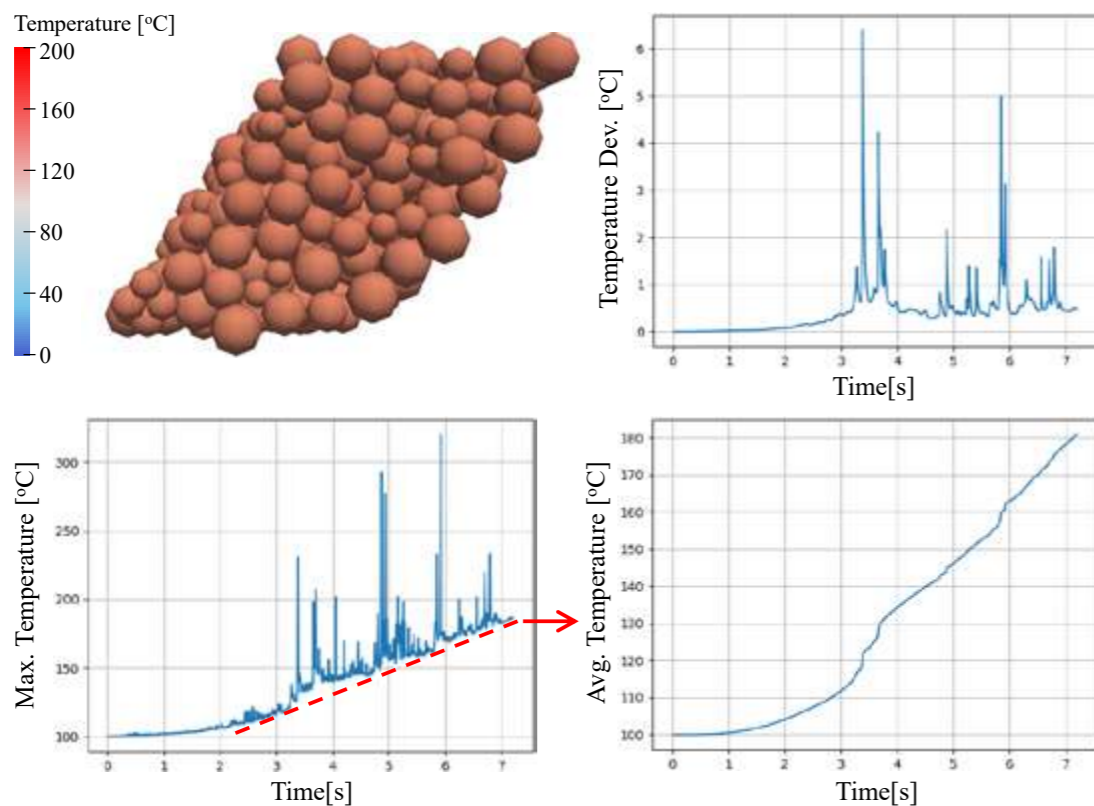
**WP1:** Microscale fast slip experiments to investigate and model the micromechanics of intergranular friction in seismogenic faults. (Alfath)  
**WP2:** Investigating the dynamic frictional behaviour of fault gouge under seismic slip using THM-DEM. (Nazareth Lopez)  
**WP3:** Coupling THM-DEM and fault reactivation models for induced seismicity. (Hung, Shang)

## Research aim

To characterise and simulate the thermo-hydro-mechanical processes that control the evolution of fault strength during seismic slip from the scale of a single contact to that of the entire reservoir fault. A key question that this project aims to answer is how variations in microscale processes affect the reactivation of faults at the reservoir scale.

## Highlighted outcomes 2025

Postdoctoral researcher Chien-Cheng Hung obtained a position in his home country Taiwan and quit his position in the FastSlip project per 1 May 2025. A new postdoc has been recruited: Chengshun Shang will start on 1 April 2026. Syukri Alfath has finalised the design of the high acceleration dynamic tribometer to measure grain scale friction at fast velocities.



DEM modelling results for fast sliding of fault gouges showing fast, short duration temperature rises ("flashes") as observed in experiments.

The design includes a detailed analysis to ensure accuracy, robustness and a wide range of samples and test conditions. The relevant parts for the tribometer are now being ordered and machined. Rafael Nazareth Lopez has developed a new thermal model to account for flash-heating mechanisms during grain shearing in fault gouges. The implementation has been completed within the open-source DEM code YADE. Initial benchmarks, including simple shear and biaxial compression tests, have been performed. Qualitative agreement is observed between the numerical predictions and experimental measurements obtained by Chien-Cheng Hung, former postdoctoral researcher at Utrecht University. In parallel, through an external collaboration with the University of Australia, Rafael Nazareth Lopez has developed a BEM-DEM coupling scheme to simulate one-dimensional heat transfer between the gouge and the surrounding rock phases.

## Focus for 2026

Syukri Alfath will focus on assembly and calibration of the dynamic, grain-scale tribometer in 2026. The aim is to obtain first results on grain-scale friction at high velocity and high acceleration sliding by the end of the year. Rafael Nazareth Lopez will first focus on calibrating and validating his DEM model with flash heating by reproducing experimental data at UU. He will then extend this work to investigate grain- and gouge-scale multiphysics by incorporating pore-fluid flow into the thermos-mechanical framework. The objective is to quantify how in-situ conditions, such as temperature, pore overpressure and shear rate, control dynamic weakening in fault gouges. In parallel, while continuing the collaboration with the University of Newcastle on BEM-DEM coupling, he will develop a multiscale FEM-DEM framework in which the host rock is modelled using FEM and the fault gouge layer using DEM. These approaches aim to integrate the rich physics previously captured in laboratory experiments currently from thermal DEM simulations into continuum-based numerical models, enabling large-scale modelling of heterogeneous fault system. This work will be in close collaboration with the newly hired postdoctoral researcher Chengshun Shang. He will first focus on fault slip modelling on the continuum scale, with laboratory scale validation.

## Collaboration and integration within DeepNL

Data and experimental techniques from the previous DeepNL 1a project of the PI will be used, as well as possibly data from the LabQuakeAI project. The experimental techniques and the relevant error contributions in measuring friction in the (quasi-static) friction setup

developed in the ongoing  $\mu$ Fault project will be considered in the design of the dynamic, high-speed friction setup. Additionally, the initial DEM model development for fault gouge assembly and relevant contact laws in the  $\mu$ Fault project can be also used in the current FastSlip project.

## Relevance for and knowledge exchange with stakeholders

Properties of fault gouge determine whether and how an earthquake accelerates and how it stops again. By understanding the fault mechanics better, we can better estimate the magnitude of the seismicity which has a strong control on the ground motion that is experienced at the surface.



## Introduction DeepNL researcher Chengshun Shang

Chengshun Shang has been a PhD researcher at CIMNE, Spain, since 2021, focusing on computational particle mechanics and sandstone mechanics. He holds a BSc in Mining Engineering (2018) and an MSc in Geotechnical Engineering (2021) from Shandong University of Science and Technology, China. During his PhD, Chengshun was a main contributor to the open-source Kratos Multiphysics DEMApplication and developed a numerical framework for modelling cemented sand with varying cementation levels. Part of his work on bio-cemented sand was carried out during a secondment at the University of California, Davis, supported by the Marie Skłodowska-Curie project LOC3G. In FastSlip, he will focus on continuum-scale fault slip modelling with laboratory validation, and later integrate his results with multiscale FEM-DEM approaches to investigate fault reactivation mechanisms.

## NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient nature of induced Seismicity

**Project leader:** Prof. Femke Vossepoel (TUD)

**Associate project leaders:** Dr Loes Buijze (TNO); Dr Ylona van Dinther (UU); Prof. Jan Dirk Jansen (TUD); Dr Bernard Meulenbroek (TUD); Annemarie Muntendam-Bos (TUD/SodM); Dr Henk van Waarde (RUG); Prof. Jan-Diederik van Wees (UU)

**PhDs:** Lada Dvornik (TUD); Jordan van Ekelenburg (TUD); Mhina de Vos (UU)

**Budget:** € 1,078,031,- (Call 2b)

**Duration:** 2024 - 2028

**WP1:** Evaluating the transient nature of induced seismicity through evaluation of the causal processes of the temporal and spatial variations in the Gutenberg-Richter parameters. (Dvornik)

**WP2:** Assessment and identification of crucial model parameters and state variables from a physics-based, process-oriented perspective. (de Vos)

**WP3:** Evaluation how observations can inform models in a data-assimilation framework using systems and control theory. (van Ekelenburg)

### Research aim

To provide constraints on the envelope for safe utilisation of the subsurface for conventional and new energy technologies, and to identify which variables need to be monitored to remain within the safe envelope during a project's lifetime.

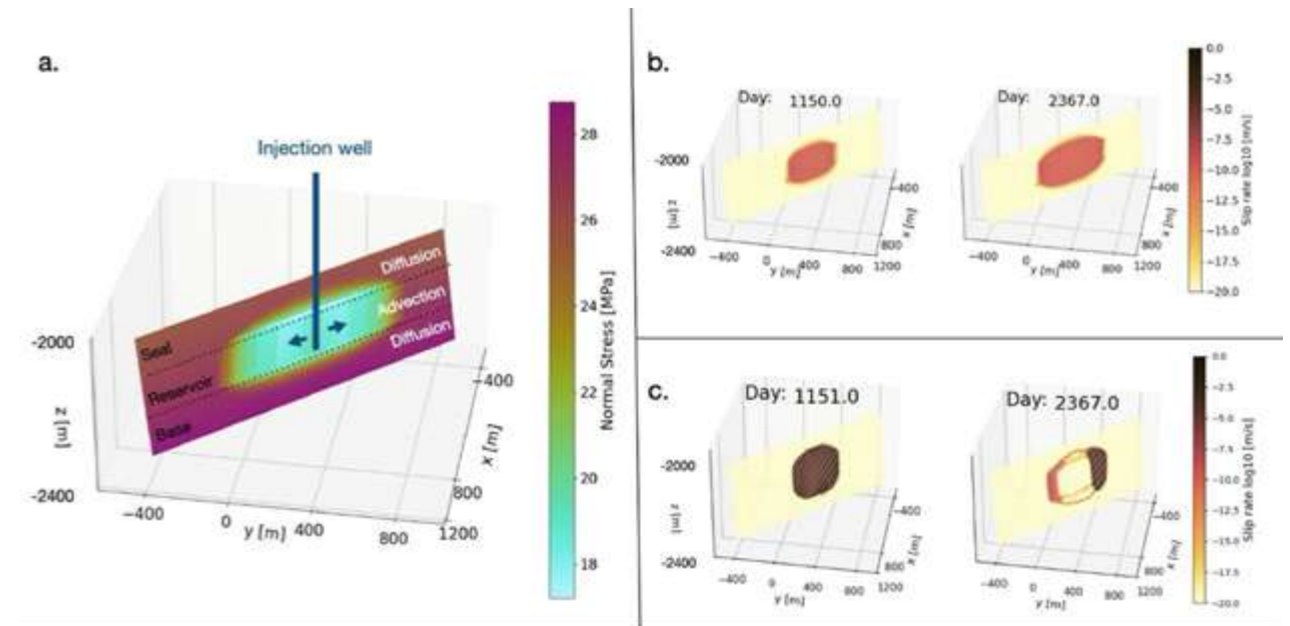
### Highlighted outcomes 2025

Using the TNO PANTHER programme as well as an in-house developed code, production-induced seismicity originating from faults in the Groningen gas field was modelled. A first synthetic earthquake catalogue was developed as a basis for comparison with measured earthquake data from the Groningen field. The dependency of earthquake nucleation on fault dip and offset was studied. While the fault offset showed a strong influence, as expected, the influence of dip was surprisingly small. This led the team to prepare for a further sensitivity analysis and Monte Carlo simulation, to account for the uncertainty resulting from a wider set of fault parameters. In the part of the research focusing on the stress changes and the expected seismicity in geothermal reservoirs in the Netherlands, the current tool developed by TNO to assess the risk posed by geothermal systems in the Netherlands was coupled with a more realistic earthquake simulation model. Combining these two models provides realistic pressure- and temperature-dependent stress distributions along with accurate frictional resistance accounting for weakening and strengthening slip rates, as well as evolution effects describing the state/age of the fault. This makes it possible to robustly simulate seismicity during and after geothermal production. A systematic

parameter study revealed a wide range of slip behaviour and showed that the most realistic models behave a-seismically. Based on a physical model and linear algebra, a conceptual framework was built that fully explains how the structure of physical modelling or how observations could, or could not, lead to different sets of physical parameters that explain the data. For earthquake models, the results state that observing the frictional state variable on the fault is essential for resolving multimodality. This indicates slip and slip rate measurements on the fault alone do not suffice to achieve unique estimators for rate and state parameters.

### Data and method products 2025

The open-source model framework PANTHER, developed by Loes Buijze from TNO, was used to obtain the first results, where a fault geometry table from NAM was taken as input. In parallel, an in-house code is being developed for simulation of induced fault slip using a semi-analytical approach assuming slip-weakening faults. The TNO tool SRIMA is used to assess the risk posed by geothermal systems in the Netherlands, which is accessible via the website of NLOG. In addition, the earthquake simulation model Quake-DFN is used. A new modelling framework combining the two models is available on GitHub (<https://github.com/USustSub>). All project-generated code in the three work packages is currently under development and therefore only suitable for in-house research purposes. Potential software tools for wider community use (together with the external tools PANTHER, SRIMA and Quake-DFN) will be made available through repositories by the end of the project.



Normal stress on the fault after 10 years of injection with cooled brine (a). Slip rate on the fault after 1151 and 2367 days in injection for a model with realistic friction parameters for the Dutch subsurface (b) and for a model with highly unstable/unrealistic friction parameters (c).

### Focus for 2026

While 2025 was very much a year to map out the research plan, familiarise with literature and software and produce first results, in 2026 the first journal papers will be produced. These will cover comparisons of synthetic and measured earthquakes catalogues from the Groningen field shedding light on the relevance of fault parameters; further qualitative and quantitative insights in the effects of temperature changes on the hazard of seismicity due to cold-water reinjection in geothermal reservoirs; and an assessment of the observability and identifiability of states and parameters governing fault slip under less-than-ideal conditions, i.e. involving measurement and model errors.

### Collaboration and integration within DeepNL

NEPTUNUS contributes first and foremost to the overall objective of the DeepNL programme, namely 'to successfully develop a quantitative, physics-based understanding of how the subsurface responds to activities of resource production and geological storage' through combining modelling and data assimilation. By quantitatively assessing the relationship between physical properties such as fault geometry and strength and the occurrence and magnitudes of induced seismicity in Groningen, this project primarily contributes to this call's objective of 'consolidation and optimal utilisation of the Groningen region as a study area'.

### Relevance for and knowledge exchange with stakeholders

The relevance of fault parameters, the effects of thermal stresses on the nucleation of fault slip, and the observability and identifiability of states and parameters governing such slip, are all important to assess the hazard and risk of geothermal energy production. Results of practical relevance will become available during the project. During the next DeepNL Stakeholder Meeting first results will be presented. Also, the direct contact with geothermal practitioners via the TNO involvement in the project (Loes Buijze, Jan Diederik van Wees) is an important avenue for knowledge exchange.

# The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs

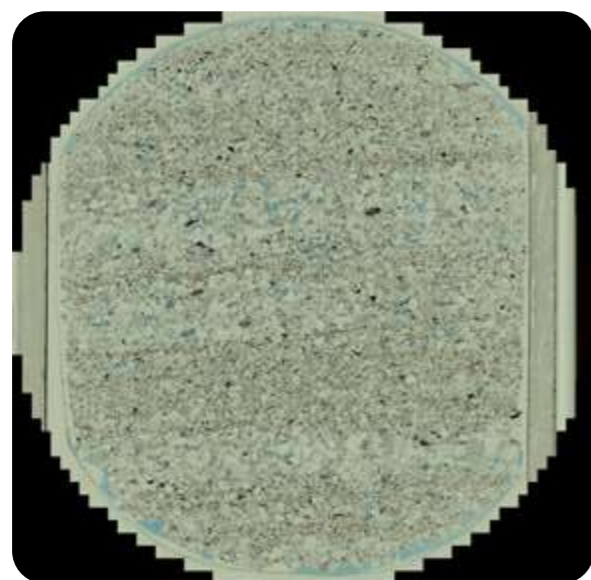
**Project leader:** Dr Johannes Miocic (RUG)  
**PhDs:** Dmitry Bublik (RUG); Sebastian Mulder (RUG)  
**Budget:** € 749,754,- (Call 1b)  
**Duration:** 2021 - 2026

## Research aim

To provide a compositional petrographic model of the Groningen gas field and its surrounding aquifers in order to help predict reservoir compaction and surface subsidence. The key question is: What is the sedimentary heterogeneity of the Groningen field like, can it be predicted, and how does it impact the geomechanical behaviour of the reservoir?

## Highlighted outcomes 2025

The team finished the analysis of the new, coherent, and high-quality petrographic dataset that details the composition of the Rotliegend reservoir rock in the Groningen gas field. They were able to identify spatial trends and patterns of various cements within the reservoir and link the occurrence of cements to depositional settings and the history of the sandstones since they were deposited 250 million years ago.



Thin-section scan of the Rotliegend sandstone reservoir of the Groningen field.

The researchers also undertook triaxial deformation experiments on samples with varying cementation at the HPT lab at Utrecht University. The results highlighted that sedimentary heterogeneity indeed impacts the geomechanical behaviour of the reservoir sandstones, with both clay minerals and pore filling cements such as Dolomite and Anhydrite playing an important role. To further understand this behaviour, microstructural analysis of the samples before and after the deformation experiments have been carried out.

## Data and method products 2025

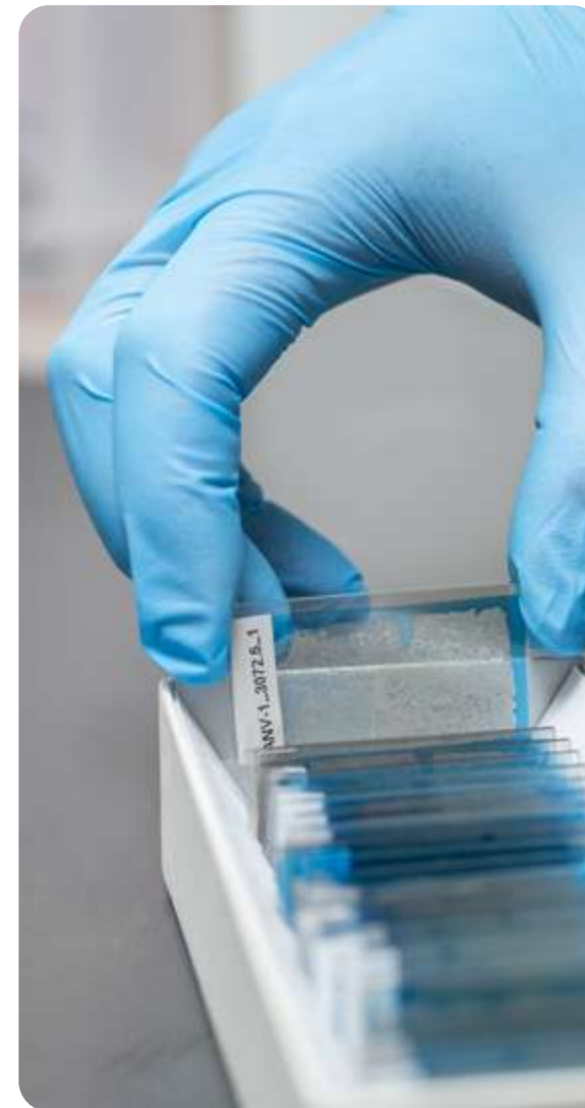
The petrographic dataset is a cornerstone of this project, enabling a data-driven analysis of the processes that shape the reservoir's composition and variability. By understanding these processes, predictive models for reservoir composition can be developed. The dataset has been published on the DataverseNL repository.

## Focus for 2026

In 2026, the project will be finalised by publishing the work and storing all data created in a reusable way on publicly available repositories.

## Collaboration and integration within DeepNL

Understanding the reservoir composition is relevant for several other projects within DeepNL. There are active collaborations with Willingshofer et al. (2a) regarding fault related cementation and with Geiger et al. (2b) regarding reservoir heterogeneity. Additionally, the team carried out geomechanical experiments at the HPT-lab in Utrecht, where they are strongly supported by expertise gained in other DeepNL projects (Hangx et al., 1a, 2a).



Thin-section samples.

## Relevance for and knowledge exchange with stakeholders

The petrographic database, along with the improved understanding of reservoir heterogeneity and the processes that influence it, is highly relevant for all subsurface utilisation projects targeting the Rotliegend formation. For stakeholders, this knowledge can enhance predictions of reservoir properties and its geomechanical response to subsurface activities. However, the team recognises the importance of receiving feedback from external parties on how best to share their findings with relevant stakeholders. This input would help them bridge the gap between purely academic research and its application in more practical, real-world scenarios.

Reflection by DeepNL  
 PhD researcher  
**Sebastian Mulder**



Sebastian Mulder will defend his thesis entitled 'Cementing the Sandstone Foundation: A Field-Scale Reconstruction from Depositional Fabric to Diagenetic Framework in the Rotliegend of the Groningen Gas Field' in the course of 2026 at RUG:

*'My project resulted in a large, complex dataset of petrographic properties of the Groningen gas field, with many interconnected aspects. Initially, I was concerned that the strong heterogeneity of the field would make it difficult to identify clear trends. However, the large sample set allowed us to demonstrate that some patterns do exist within this heterogeneity. I am most proud of the fact that our results show that commonly used regional diagenetic models and assumptions cannot simply be applied everywhere. This highlights the need to re-evaluate diagenetic processes in other Rotliegend areas and better understand how these processes actually operate. Being part of DeepNL was valuable to me because it clearly showed the societal relevance of my research and how my results could be integrated with those of other researchers in the programme, who formed a very pleasant and collaborative group. In the near future I hope to remain active in this field, whether in industry, a research institute, or academia, and contribute to the sustainable use of the subsurface.'*



Sebastian featured in an Instagram post of NTR Wetenschap, explaining why the earthquake from 30 July 2025 located between Russia and Japan was special.

# Making digital rocks a practical reality for energy storage within subsurface reservoirs

**Project leader:** Dr Maja Rücker (TU/e)

**Postdoc:** Dr David Rieder (TU/e)

**PhDs:** Mohammad Hossein Khoeyini (TU/e); Gijs Wensink (TU/e)

**Budget:** € 1,076,055,- incl. € 350,000,- co-funding (Call 1b)

**Duration:** 2021 - 2026

**WP1:** Systematic study on the influence of

Minkowski functionals on dissolution and precipitation phenomena in porous rocks. (Wensink)

**WP2:** Minkowski functional based evolution equations for structural alteration processes during multiphase flow in porous rocks. (Rieder)

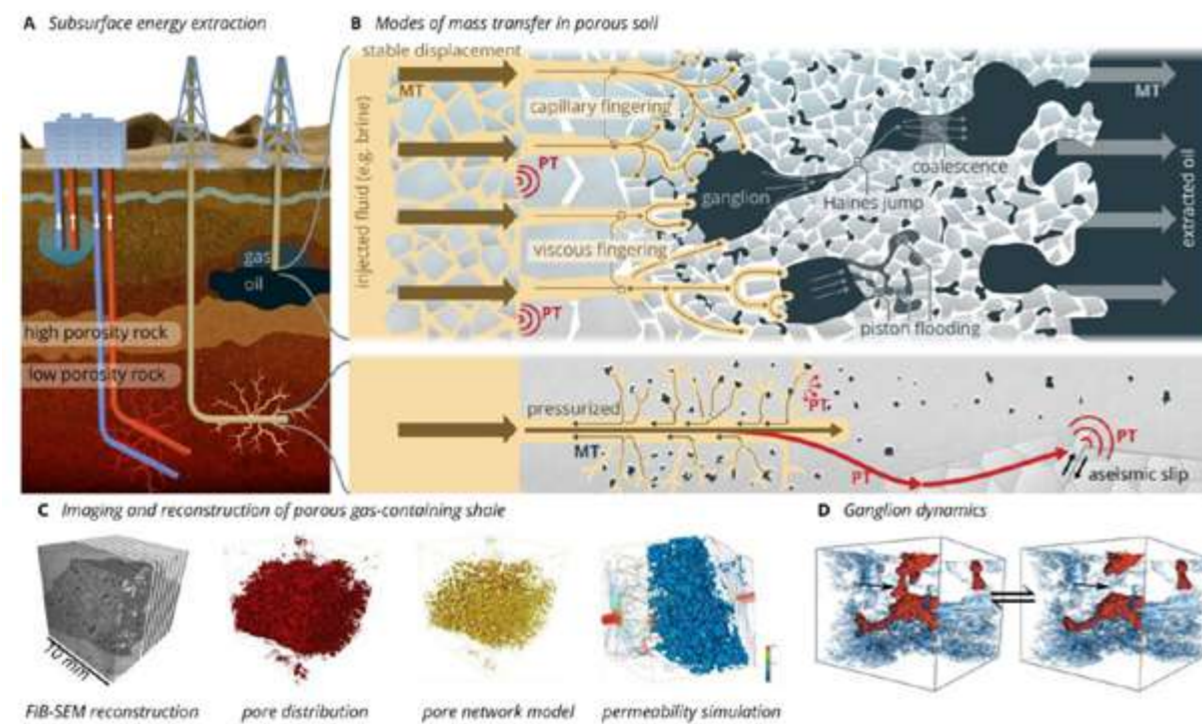
**WP3:** Upscaling dissolution and precipitation processes during multiphase flow in porous rocks (Rücker, Khoeyini)

## Research aim

To develop upscaling approaches and digital predictive tools that address the structural alteration of porous rocks accompanying multiphase flow processes, as they occur, for instance, during subsurface hydrogen storage.

## Highlighted outcomes 2025

A comprehensive understanding of the application of inverse Gas Chromatography for characterising the surface properties of porous media has been achieved, and methodologies have been developed to relate



Energy extraction from porous sub-surface reservoirs. (A) Extraction of oil, gas, or geothermal heat, with or without hydraulic fracturing of the rock. (B) Modes of mass transfer: stable viscous flow of injected and extracted fluids (such as brine and oil, or cold and hot water in geothermal extraction), in parallel with complex dynamics of fluid pockets (ganglions) inside the pores, including corner flow due to capillary forces, Haines jump leading to ganglion coalescence, or piston-like flooding. (C) Focused ion beam-scanning electron microscopy imaging and 3D reconstruction of a shale core, allowing for pore network analysis and permeability simulations (6). (D) Micro-CT imaging of ganglion dynamics in multi-phase flow (7). Taken from Farber et al. 2025.

the measures to existing data. Heterogeneity effects challenge data interpretation, necessitating a more complex analytical solution. Chemical heterogeneity can be differentiated through competitive adsorption measurements. However, information on spatial distributions remains unresolvable.

The acquisition of imaging data to link multiphase flow and reactive transport process across length scales has been completed. Pinning of fluid-fluid interfaces on solid features turns out to contribute to the seeding and growth of crystals across the internal surface of the rock. This means that macroscopic properties describing reactive transport in multi-phase flow conditions are multifactorial, requiring a large amount of input data.

The team contributed to a review paper on porous materials published in *Science* covering fluid transport and mechanics of porous rocks alongside synthetic materials used in energy applications. The review highlights joint challenges of porous materials across fields, being the relation of the porosity and the processes it facilitates to the macroscopically observed properties. The knowledge gained on this topic in subsurface engineering is thereby highlighted as a cornerstone for the development of new materials.

## Data and method products 2025

The data sets produced show fluid film motion and precipitation processes in porous rocks with unprecedented resolution. Within the project, this data are used as visual reference to the quantitative data collected with iGC. For the DeepNL project and beyond, this data provides a benchmark for computational modelling of fluid flow and precipitation processes, as they may occur during geothermal and subsurface hydrogen-storage applications.

## Focus for 2026

To address how small effects of interfacial processes can be incorporated into digital models, and how these new methodologies can be applied in a subsurface energy storage scenario. Furthermore, the team plans to write a review on the advances of digital rock physics made in the last year and showcase the use of iGC in a precipitation experiment. Gijs Wensink will defend his PhD on 16 January 2026 at TU/e.



Team at the Advanced Lightsource research facility at Lawrence Berkeley National Laboratory for beamline experiments.

## Collaboration and integration within DeepNL

Collaborations have been planned; however, due to delays in establishing the iGC research infrastructure, the exploration of the utilised techniques beyond the scope of the described project was prohibited. Ideas included using iGC with its great sensitivity to detect small-scale deformations.

## Relevance for and knowledge exchange with stakeholders

Currently, the interplay between geochemical processes and multi-phase flow across length scales and the associated change in structural and chemical attributes of the material are insufficiently understood. Yet, these processes may impact the mechanical properties of the material, leading to increased potential for the failure of its structural integrity. Digital Rock Technology tools for petrophysical assessment as developed in this project are therefore crucial to assessing the risks of new energy applications.

## Quantitative constraints on pre-production reservoir stresses in Groningen

**Project leader:** Dr Rob Govers (UU)  
**PhD:** Renato Gutierrez Escobar (UU)  
**Budget:** € 291,328,- (Call 2a)  
**Duration:** 2022 - 2026

### Research aim

The natural stress field is a critical ingredient for earthquake models and other geomechanical studies, but it is not known in the Groningen gas field area. This project evaluates these natural stresses using high resolution mechanical models of the Eurasian tectonic plate, which are constrained by observations of stress directions and geodetic velocities.

### Highlighted outcomes 2025

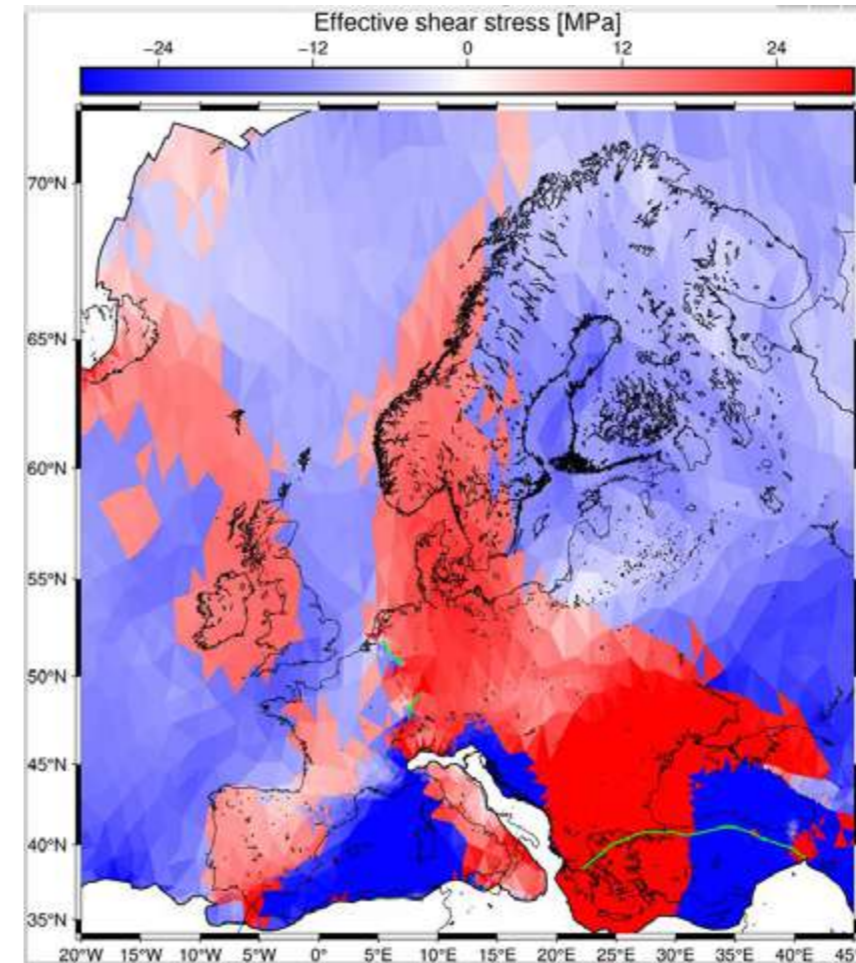
By using Bayesian sampling of the posterior probability of the model parameters, useful constraints were identified on resistive shear tractions on most model faults, on viscosities of most geological regions, on the magnitudes of driving forces, and on overall torque balance. Some parameters cannot be constrained because the observations are not sensitive to them. Horizontal gravitational tractions (HGT), as described by Nijholt et al. (submitted 2026), are prime drivers of the observed lithospheric velocities and stresses. Predicted velocities of the median model match Global Navigation Satellite System velocities reasonably well in many regions, including the Alps-Dinarides, Makran-Anatolia-Aegean, central Tibet and Japan-Taiwan-Philippines-Banda region. The model also reproduces observed stress orientations well. However, the agreement is poor around the East Himalayan syntaxis and requires further improvement in the United Kingdom and Scandinavian Peninsula. Ongoing work involves modifications of the forward lithospheric model of Hasterok et al. (2022) in line with more recent publications.

### Data and method products 2025

The numerical codes underlying new calculations of horizontal gravitational tractions (HGT) have been submitted as *Gutierrez Escobar, R., Nijholt, N., Wouters, N., Govers, R., (2026). Public release of horizontal gravitational traction code [Software]*. The publication facilitates other researchers to redo, extend or modify the calculations and compute lithospheric stresses from them. The horizontal gravitational tractions and other global data produced for the publication of Nijholt et al. (submitted to *Geophysical International* 2026) have also been submitted. This publication promotes the verification and reuse of the acquired data in the context of lithospheric stresses for any tectonic plate.

### Focus for 2026

1. Complete the sampling of model parameters, fault slip, and stress.
2. Write and submit the manuscript about the Eurasia stress field to a peer review journal.
3. Develop a 3D finite element model specifically for the Groningen gas field region.
4. Compute natural stresses in the Groningen gas field region.
5. Submit the manuscript about the Groningen stress field to a peer reviewed journal.
6. Develop a 3D model to compute Glacial Isostatic Adjustment induced stresses in northern Netherlands.
7. Write the PhD thesis.



First, preliminary estimates of effective shear stress magnitudes in Western Europe. Positive values correspond with predominantly tensile stresses, and negative values with compressive stresses. Green lines show model fault zones and black lines show coastlines and plate boundaries.

### Collaboration and integration within DeepNL

Quantitative constraints on the natural stress field are critical for currently running DeepNL studies like those of Vossepoel et al. (InFocus, NEPTUNUS) and Trampert et al (1a project). Since shear tractions on faults are sensitive to the total stress field, this project is relevant for all rock mechanical experiments aimed at constraining friction properties such as those conducted within the projects led by André Niemeijer (1a project and FastSlip) and Jan-Dirk Jansen (Science4Steer), and essentially for all DeepNL projects studying activation of faults within the reservoir.

### Relevance for and knowledge exchange with stakeholders

Developing a stress model is anticipated to be critical for assessing the potential impact of future subsurface activities such as gas production, geothermal energy

production, geological storage of CO<sub>2</sub>, geological storage of energy reserves, and salt mining. As such it is an essential component in applying quantitative hazard risk analysis tools to the regional situation of Groningen. Preliminary results for material stresses across the entire Eurasian plate suggest final results that will be relevant to stakeholders. Knowledge transfer so far has been carried out through peer review journal publications with all data, software and developed codes publicly available following open science and FAIR principles. In addition, the researchers involved in the project organised a scientific session at the EGU general assembly 2025 where they shared and discussed the project results with the European community that works on stress and geodetic observations. In addition, the researchers would like to collaborate with national and international partners in geotechnical engineering. At the moment, there are no concrete ideas on how to approach this.

## Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoir

**Project leader:** Dr Suzanne Hangx (UU)

**PhD:** Mike Sep (UU)

**Budget:** € 330,328,- (Call 2a)

**Duration:** 2021 - 2026

### Research aim

Field measurements from the Groningen gas field have demonstrated that besides the compaction of the reservoir sandstone, there is an additional significant amount of compaction in the overlying Ten Boer claystone and the underlying Carboniferous shales. This project aims to improve our understanding of the grain-scale deformation mechanisms in these clay-rich formations.

### Highlighted outcomes 2025

An extensive set of XRD-measurements on different clay-rich rocks from the Groningen gas field was done to determine the heterogeneity in mineralogical content. A total of 13 samples covered the metre-scale heterogeneity in the overburden Ten Boer claystone, a clay-rich part of the Slochteren sandstone reservoir, and the underburden Carboniferous shales. Within these 13 samples, an additional 32 measurements on individual centimetre-scale layers were done to further investigate the mineralogical heterogeneity in these clay-rich formations. The results show that the type of minerals throughout the samples is constant, but that the amount of each mineral changes drastically between centimetre-scale layers. For example, on the scale of one centimetre, the amount of clay minerals can differ up to 30 percent.

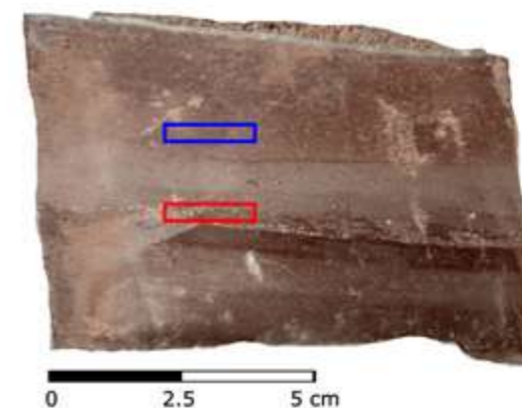
To investigate the effect of the centimetre-scale mineralogical heterogeneity on the mechanical behaviour of clay-rich rocks in the Groningen gas field, rock mechanical experiments were performed on individual layers from Ten Boer claystone samples. From these individual layers, small discs of relatively homogenous mineralogy were constructed for mechanical testing. The results demonstrate the effect of the amount of clay on the

mechanical behaviour. For example, a sample with a relative low amount of clay (38 percent clay minerals) compacted twice as much as a clay-rich (67 percent clay minerals) sample under dry conditions when loading to 60 MPa. Under wet conditions, this effect is reversed and the clay-rich sample compacts twice as much as the low-clay sample, with creep rates twice as fast as well. Upon releasing stress under wet conditions, time-dependent expansion of the samples occurred, where the clay-rich sample expanded 50 percent more than the sample low in clay minerals. The team is currently determining the main deformation mechanism for each of these thin samples, each roughly representing a single depositional environment.

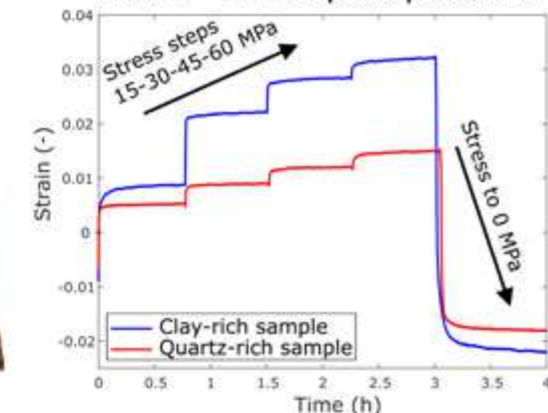
### Focus for 2026

The extensive dataset of XRD-measurements on the mineralogical heterogeneity in the Groningen clay-rich rocks will be finalised and will be complemented with analyses of thin sections of the samples. This will create a full petrographic understanding of the Groningen clay-rich rocks, covering heterogeneities from metre- to millimetre-scale. These results will be further coupled to the results of the disc experiments on the individual layers of the Ten Boer claystone. The mechanical results of these disc experiments are compared to an experiment on a larger sample that contains the same four layers as the discs, sampled from the same block of material. The experiment forms the step of upscaling in lab-scale, from millimetre-size samples with a homogeneous mineralogy to a centimetre-size sample with a heterogeneous mineralogy. The results will help gain a better understanding of the effect of small scale heterogeneities on the mechanical behaviour of clay-rich rocks.

Ten Boer claystone, 2859m depth



Disc experiment results  
100°C - 5 MPa pore pressure



Left: Ten Boer claystone sample used to retrieve two thin discs of material with a relatively homogeneous composition. One sample has more clay (blue), while the other has more quartz (red). Right: Results from two compaction experiments on these two thin discs, highlighting the difference in compaction behaviour, as a result of the mineralogical composition.

In addition, mechanical experiments will be performed on samples from the underburden Carboniferous shales formation of the Groningen gas field. As the previous analyses demonstrate that these samples are more homogeneous in mineralogical composition, triaxial compression experiments will be performed on centimetre-scale samples to investigate the dominant deformation mechanisms active under conditions relevant for the Groningen gas field.

### Collaboration and integration within DeepNL

This project's results show that the mineralogy of the mostly layered claystones has a clear influence on how the material deforms. However, the material that was investigated, originates from one specific location, in the middle of the field. Interactions will be sought with the group of Johannes Miocic to link these findings to the lateral variation in the mineralogy of the claystones across the entire area covered by the gas field, which they are examining and correlating to subsidence behaviour.

### Relevance for and knowledge exchange with stakeholders

The work on typical Dutch clay-rich caprock material is relevant for stakeholders working on modelling ongoing compaction in the Groningen region, but also for those working on alternative uses of the Dutch subsurface. Clay-rich caprocks form the sealing formation for many potential storage sites for CO<sub>2</sub> and H<sub>2</sub>. Therefore, the knowledge obtained in this project is used to build upon further in projects such as DeepNL CrossScale, ACT RETURN (CO<sub>2</sub> storage in depleted gas fields capped by clay-rich rocks), and GroenvermogenNL HyTROS (integrity of clay-rich caprock during hydrogen storage). Notably the impact of mineralogy on deformation behaviour, specifically sorption-induced swelling, is of key importance here. At present no collaborations with stakeholders have been identified yet. The team is keeping an eye out on this potential once the research has been consolidated more.

## Constraining uncertainties across scales: From Groningen to future geenergy applications (CrossScale)

**Project leader:** Prof. Sebastian Geiger (TUD)

**Associate project leaders:** Dr Hemmo Abels (TUD); Dr Auke Barnhoorn (TUD); Dr Aad Correljé (TUD); Dr Alexandros Daniilidis (TUD); Dr Johannes Miocic (RUG); Dr Anne Pluymakers (TUD); Dr Gerdien de Vries (TUD)

**Postdocs:** Helena Schmidt (TUD); t.b.d (TUD)

**PhDs:** Jesse Steinvooort (TUD); Ailsa Tucker (RUG)

**Budget:** € 1,058,984,- (Call 2b)

**Duration:** 2024 - 2028

**WP1:** Characterising sedimentary heterogeneities across scales. (Tucker)

**WP2:** Geological modelling and numerical simulations. (Steinvooort)

**WP3:** Validation of REV scales and upscaling methodology. (Tucker, Steinvooort)

**WP4:** Analysing the impact on reservoir scale predictions. (t.b.d.)

**WP5:** Developing communication strategies with the societal actors (Schmidt)

### Research aim

To establish a generic, geologically-informed, and validated upscaling methodology that is based on accurate representative elementary volume (REV) scales for the geological heterogeneities within the Rotliegend. The project also aims to develop a Q&A strategy with stakeholders from industry, regulators, and the broader society to inform a more balanced and trusted decision-making process for future geo-energy applications.



Ailsa Tucker and Jesse Steinvooort during fieldwork at a Rotliegend quarry in Germany, photo taken by Johannes Miocic with a drone.

### Highlighted outcomes 2025

Jesse Steinvooort identified and classified the main geometries that characterise the geological heterogeneities inherent to the Rotliegend, using information from the field campaigns and core store visits that took place in 2024 and early 2025. This provided generic geometry templates for which REV scales are being identified. Based on these geometries, first models were created in the open-source Rapid Reservoir Modelling software and REVs for permeability and porosity were calculated. To expedite the REV analysis, an automated workflow was designed based on the open-source Matlab Reservoir Simulation Toolbox.

Ailsa Tucker delivered key new insights into the nature and scale of sedimentary heterogeneity in the Rotliegend reservoir of the Groningen Field. Reservoir heterogeneity is shown to occur at small vertical scales, while laterally continuous sedimentary units vary strongly in thickness over relatively short distances. This finding has important implications for upscaling core-scale measurements to well and field scales. Detailed analysis of cores from the Zeerijp-3A and Slochteren wells showed that existing lithofacies classifications were not correctly capturing the observed sedimentological variability. As a result, a revised, higher-resolution facies framework is being developed, revealing a greater influence of fluvial deposition relative to aeolian processes in parts of the Groningen field.

Helena Schmidt conducted a scoping literature review and interviews with DeepNL and other researchers to identify both what is already known about communicating subsurface data and the main knowledge gaps. Building on this, she developed a comprehensive stakeholder analysis that maps the key organisations and the roles they fulfil in subsurface governance, infrastructure, knowledge development, and advocacy in the Dutch subsurface sector. This overview also highlights who produces and uses subsurface information, and which websites and online databases are available for data dissemination.

### Data and method products 2025

A major methodological breakthrough in 2025 was the fully automated workflow to generate models representing small-scale geological heterogeneities, compute effective properties for them, and analyse the corresponding REV scales as well as the key geological heterogeneities that control them. This approach is based on the open-source Matlab Reservoir Simulation Toolbox. The code is planned to be released in 2026.

The most detailed dataset of vertical grain-size heterogeneity of the Rotliegend to date was generated for ZRP-3A with a vertical resolution of five millimetres. Additionally, new, high-resolution sedimentary logs were created for cores from the Slochteren well-swarm, together with logs for ZRP-3A. These data will be incorporated into a publication in 2026 and made publicly available on a repository.

The project also delivered an extensive stakeholder report on the Dutch subsurface sector. It maps key organisations and their roles and identifies which actors should be surveyed about communication needs and challenges.

### Focus for 2026

Jesse Steinvooort will apply his workflow across the entire geometry template that was identified for the Rotliegend and commence the multi-scale upscaling for single- and two-phase flow properties. During 2026, the second postdoc will be appointed to simulate reservoir-scale fluid flow processes, using traditional reservoir modelling approaches as well as the effective single- and two-phase flow properties from Jesse's work.



Lab set up with a Rotliegend rock plug to measure the acoustic wave velocity.

Ailsa Tucker will continue working on analysis of the Slochteren well cluster data, integrating geophysical well logs data with the detailed sedimentological logs to develop conceptual (sedimentological) models on Rotliegend lateral variability. This concept will then be tested in another well-swarm to validate our understanding of heterogeneity on a kilometre scale, which will be an important input for the reservoir-scale modelling.

Helena Schmidt will finalise and roll out a large-scale survey among professionals in science, industry, and government to map their concrete communication needs and challenges related to subsurface data and uncertainties. Based on the survey insights, a communication strategy will be developed and, if time allows, possibly piloted to evaluate usability and effects.

Ailsa Tucker and Jesse Steinvoort during fieldwork at a Rotliegend quarry in Germany, photo taken by Johannes Miocic with a drone.



Core from Slochteren 9 well

### Collaboration and integration within DeepNL

CrossScale investigates the fundamental issue of up-scaling of reservoir behaviour across multiple scales, which is not yet studied at detail in the DeepNL programme. CrossScale will also tackle another gap within the current DeepNL projects by explicitly addressing and communicating the uncertainties and risks associated with subsurface operations to different stakeholders and societal actors. CrossScale is hence a crucial link between a considerable number of the ongoing DeepNL projects, integrating and utilising the valuable data and results generated by these impactful projects at different spatial scales.

### Relevance for and knowledge exchange with stakeholders

CrossScale focuses on improving upscaling, reservoir modelling, and uncertainty assessment of reservoir behaviours by developing a generic methodology to identify REV scales that drive upscaling strategies for low-carbon geoenergy applications. Failure to upscale properly has been shown to change uncertainty quantification and project economics, and hence can undermine the assessment of production risks as well as the trust that low-carbon geoenergy technologies benefit the wider public. CrossScale will provide valuable knowledge with respect to transparently communicating how research programmes such as DeepNL can reduce uncertainties in future geoenergy projects. This will help to improve transparency and trust in the wider public when developing future low-carbon geoenergy projects.



### Introduction DeepNL researcher Helena Schmidt

Helena Schmidt joined CrossScale in October 2025 as a postdoctoral researcher. She is a social scientist with a PhD in Energy Acceptance (TUD) and MSc degrees in Environmental Psychology (RUG) and Clinical Psychology (LU). In CrossScale, she studies how subsurface data and uncertainties can be communicated so stakeholders can better understand, trust, and use the information in decision-making. She collaborates with researchers, industry, and government to co-develop communication strategies and translate findings into actionable recommendations for practice and policy. More broadly, Helena is interested in using social science to make the energy and climate transition more effective and just, building on her extensive experience working in interdisciplinary teams that bridge technical and social perspectives.



TUD Geoscience and Engineering part of the CrossScale team. From left to right: Dr Alexandros Daniilidis, Dr Anne Pluymakers, Prof. Sebastian Geiger, Jesse Steinvooort, Dr Hemmo Abels.

## Probing the micromechanics of small magnitude earthquake slip

**Project leader:** Dr André Niemeijer (UU)  
**Associate project leader:** Dr Mark Dekkers (UU)  
**Postdocs:** Dr Qiang Fu (UU); Dr Annika Greve (UU);  
 Dr Marcel Mizera (UU); Dr Michael Volk (UU)

**PhD:** Chien-Cheng Hung (UU)  
**Budget:** € 725,576,- (Call 1a)  
**Duration:** 2019 - 2024

### Research aim

How hot and weak do faults get during small magnitude earthquake slip?

### Update

The research in this project addressed the fundamentals of fault behaviour during rapid, short-lived displacement. While the experimental and numerical results give insights into the processes that are relevant, they are not suitable for direct use. There have been frequent interactions with researchers from UU, TNO and TUD to explain how the results might be used to constrain the input of large numerical models of fault reactivation. Chien-Cheng Hung has now returned to Taiwan as a postdoc and aims to secure a faculty position in the near future.

He mentions that engaging with this vibrant international research community was his most valuable experience. Qiang Fu reflected that his postdoctoral research was challenging, stimulating, and rewarding. He is most proud of the findings demonstrating the critical role of fluids in controlling magnetic property modification during frictional slip, a process that had not been systematically investigated before. These results provide important implications for applying rock magnetic methods to infer thermal and chemical processes during natural earthquakes. Qiang Fu plans to remain in academia.

**For a summary and output see:**



Quantum diamond magnetometer (QDM) at Utrecht University.

## Science4Steer – a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields

**Project leader:** Prof. Jan Dirk Jansen (TUD)  
**Associate project leaders:** Dr Auke Barnhoorn (TUD); Prof. Hadi Hajibeygi (TUD); Dr Suzanne Hangx (UU); em. Prof. Chris Spiers (UU); Dr Denis Voskov (TUD)  
**Postdocs:** Dr Jianye Chen (UU); Dr Pavan Cornelissen (TUD); Dr Mark Jefferd (UU); Dr Mohammad Hadi Mehranpour (UU)

**PhDs:** Milad Naderloo (TUD); Aleksei Novikov (TUD); Sara Shokrollahzadeh Behbahani (TUD)  
**Budget:** € 1,451,531,- (Call 1a)  
**Duration:** 2019 - 2024

### Research aim

To understand the effects of time-varying pressures, stresses and strains resulting from gas production and (re-)injection in the Dutch

subsurface as a basis for operational strategies to minimise the seismic hazard of human activities in the subsurface.

**For a summary and output see:**



Large-scale fault reactivation experiments, using a 30x30x30cm block as a reservoir analogue with a displaced fault.

## A multiscale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction

**Project leader:** Dr Suzanne Hangx (UU)  
**Associate project leaders:** Prof. Martin Drury (UU); Dr Helen King (UU); Dr Oliver Plümper (UU); Dr Cedric Thieulot (UU)  
**Postdocs:** Dr Mark Jefferd (UU); Dr Mohammad

Hadi Mehranpour (UU)  
**PhD:** Takahiro Shinohara (UU)  
**Other staff:** Hannah Vogel (UU)  
**Budget:** € 915,331,- (Call 1a)  
**Duration:** 2019 - 2024

### Research aim

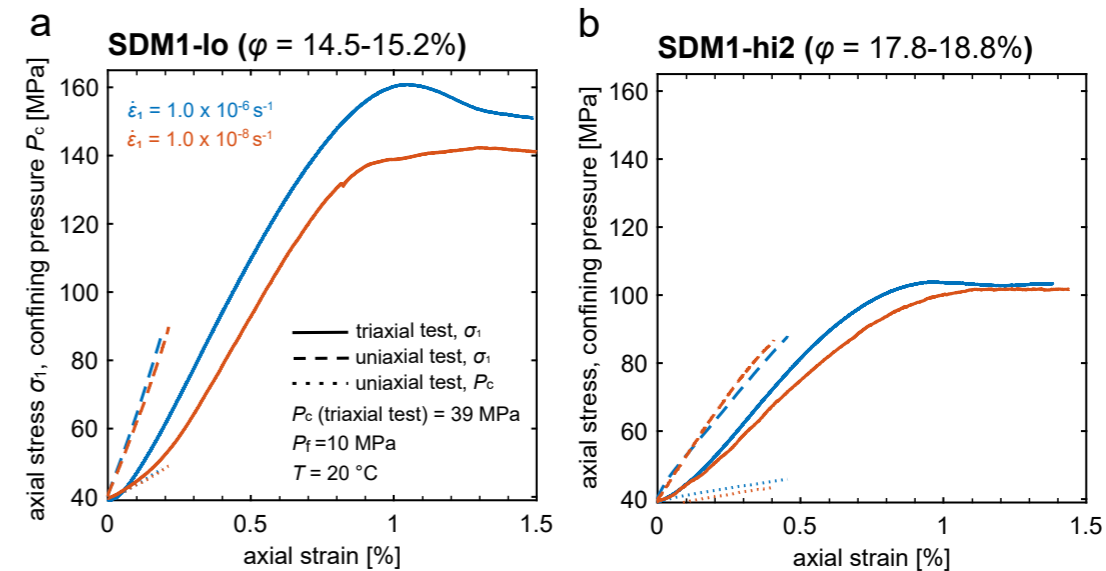
To develop a physics-based model for time-dependent, inelastic compaction of sandstones by including the relevant grain-scale mechanisms that operate under realistic in-situ conditions.

### Update

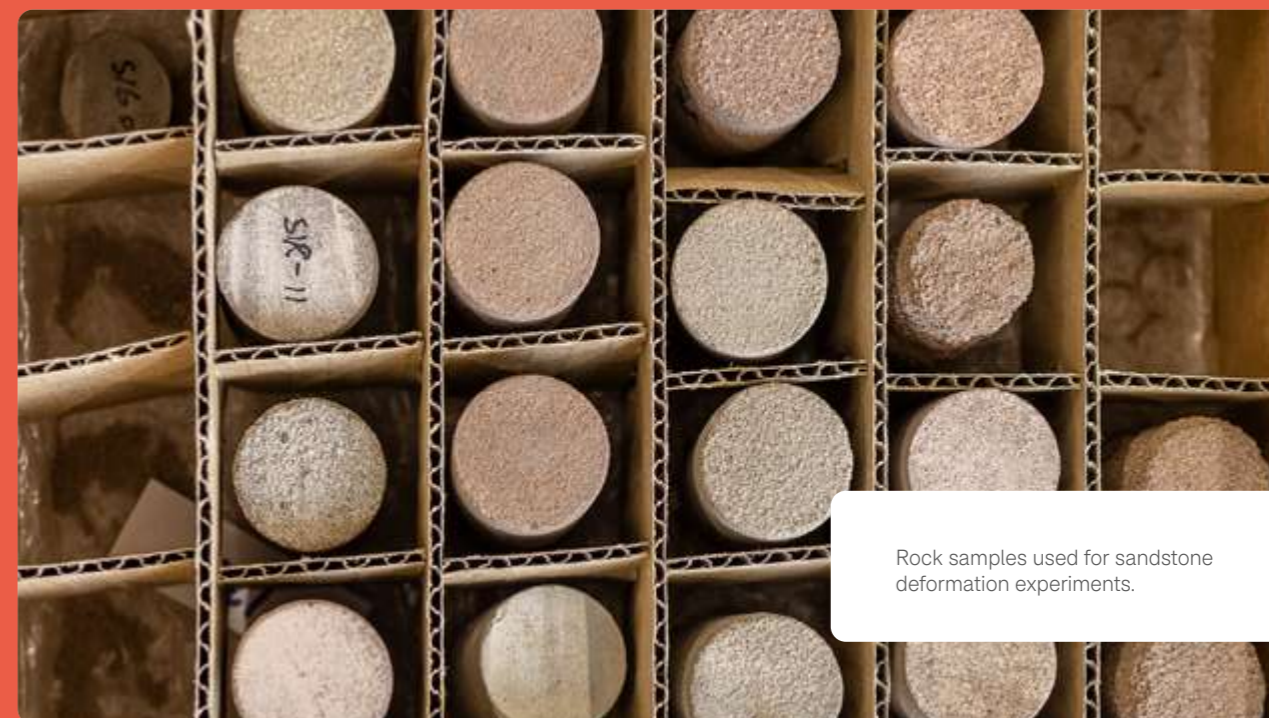
Two more chapters of Taka Shinohara's PhD thesis were published. The last chapter will be published early 2026. The two published chapters concern work done on the Slochteren sandstone from the Groningen gas field, and the finite element modelling done to predict the local stresses on grain contacts and in grain bodies. Together with the already published first chapter on rate-dependent deformation of porous sandstone and the upcoming paper on the analytical description of deformation in such rocks, this series of publications forms the basis to further extend existing numerical models. This is done in collaboration with Frans Aben at TNO. The knowledge gained in this project has formed the basis for other projects to build on, such as the ACT RETURN project on CO<sub>2</sub> injection in depleted gas fields. This DeepNL project showed that slow deformation

due to time-dependent crack growth, combined with grain rearrangement, plays a significant role on the longer term (beyond active gas production). In the ACT RETURN project, PhD researcher Sahar Amiri has been building on that insight to see how changes in the chemical environment, temperature and/or pore fluid pressure further impact this time-dependent compaction behaviour during injection and long-term storage of CO<sub>2</sub>. For this project there is a collaboration with modellers at UU (Wenzhuo Cao) and TNO (Peter Fokker), to see how these mechanisms can be incorporated into models predicting the near-wellbore behaviour in a CO<sub>2</sub> storage site. In 2025, a collaboration was initiated with Frans Aben from TNO to incorporate the observed time-dependent and time-independent deformation mechanisms into existing numerical models aimed at predicting subsidence and induced seismicity. To accelerate this collaboration, the team is currently exploring the option to obtain additional funding through the DeepNL Top-up Call.

**For a summary and output see:**



Results of two constant strain rate experiments on water-saturated Slochteren sandstone deformed at 20°C. Samples have a porosity of (a) 14.5-15.2% (SDM1-lo) or (b) 17.8-18.8% (SDM1-hi2). The strain rate in each experiment was either  $1.0 \times 10^{-6} \text{ s}^{-1}$  (blue curves) or  $1.0 \times 10^{-8} \text{ s}^{-1}$  (red curves), as indicated. Note the difference in behaviour between conventional triaxial (solid lines) and uniaxial strain (dashed lines) conditions.



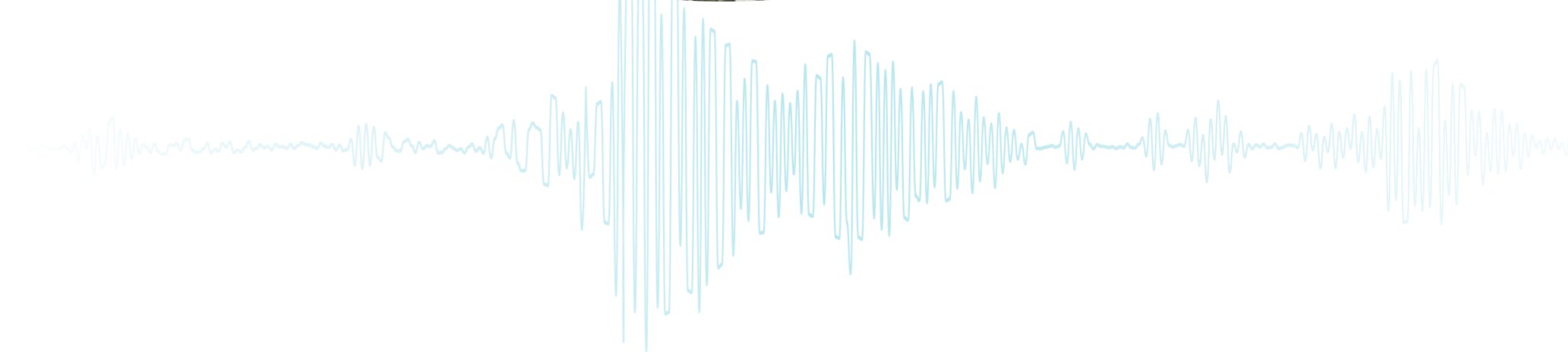
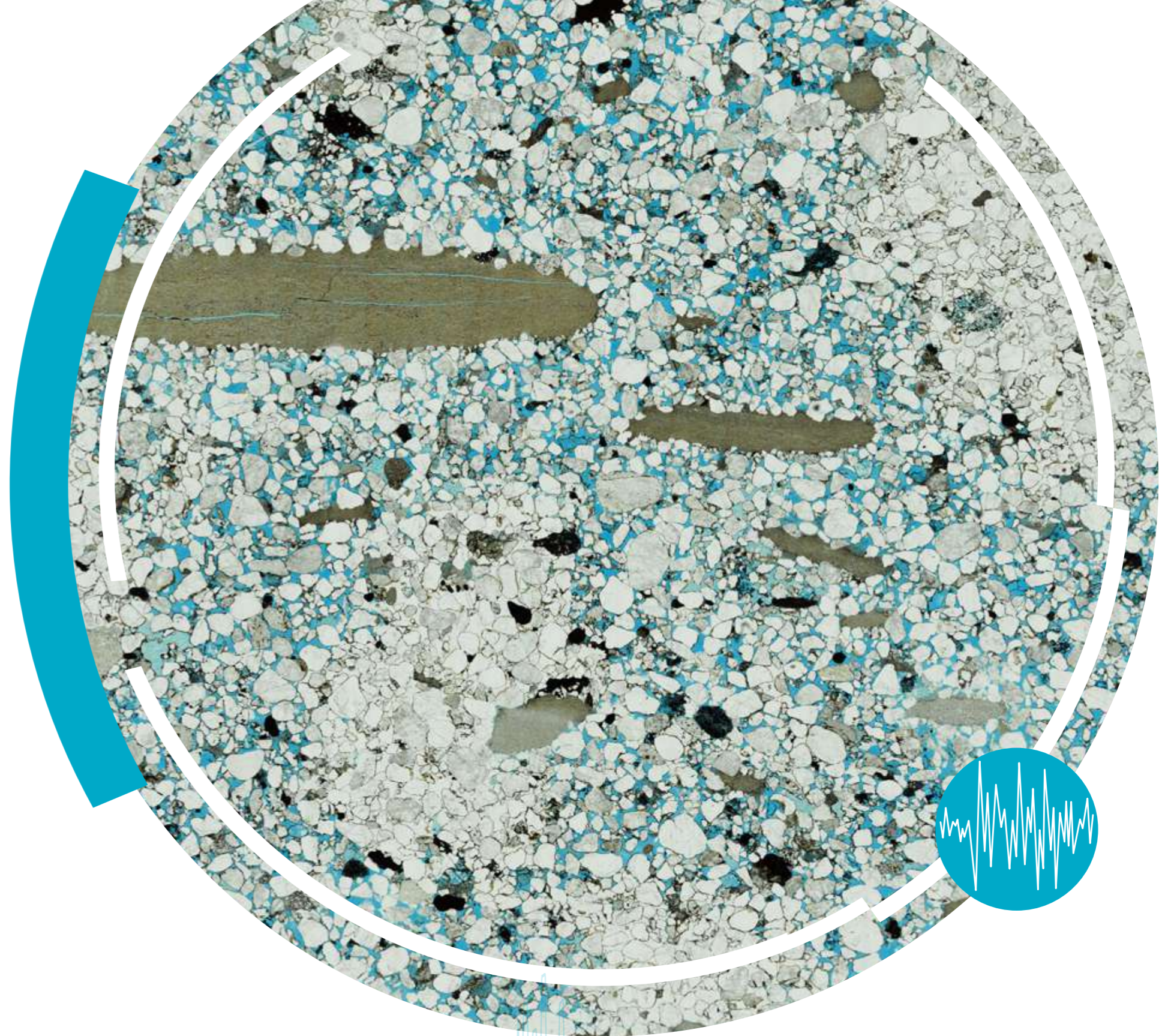
Rock samples used for sandstone deformation experiments.

Progress  
**CLUSTER**

# 2

## Monitoring of physical conditions and forecasting

How can we monitor the subsurface conditions that could lead to seismicity, and forecast the occurrence of earthquakes?



# PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling

**Project leader:** Dr Ylona van Dinther (UU)

**Associate project leaders:** Prof. Jan-Diederik van Wees (UU/TNO); Dr Loes Buijze (TNO/UU)

**PhD:** Vincent van der Heiden (UU)

**Budget:** € 358,228,- (Call 2a)

**Duration:** 2022 - 2027

## Research aim

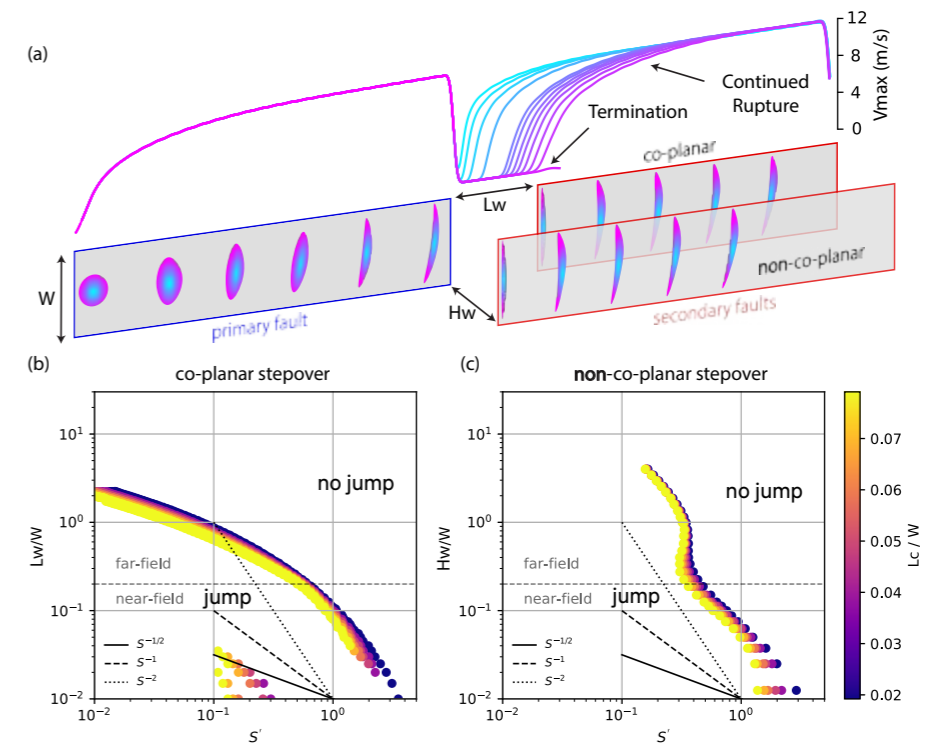
To generate physics-based, data-driven probabilistic constraints on the maximum earthquake magnitude ( $M_{max}$ ) in Groningen. These constraints should also account for interactions between faults in Groningen's complex fault network.

## Highlighted outcomes 2025

The results regarding the simulations of the Wirdum earthquake sequence were finalised, consolidated and summarised in two papers. The researchers were able to hindcast the sequence of nine earthquakes since 2018 through poro-elastic loading of a fault with laterally strong variability in fault dip and strike. Earthquake locations can be identified through an interplay of increased relative reservoir throw ( $>=0.25$ ) combined with a fault dip-angle below  $72^\circ$ . In terms of depth, most earthquakes nucleate at the top of the reservoir, but a significant number also nucleates in the centre or at the bottom of the reservoir, where the faults dips less steep. Spontaneous nucleation and arrest on observed locations allowed the researchers to constrain key parameters, as described in both papers. These simulations also revealed that a dynamic friction coefficient of 0.05 is needed to rupture the underburden and thereby generate a  $M>4$  earthquake. However, laboratory experiments subjecting Carboniferous shales to seismic slip rates reveal dynamic friction values between 0.2 and 0.4 (Chen et al., JGR, 2023). Values lower than 0.2 are deemed extremely unlikely, i.e., chances of less than 0.1 percent. These results again suggest that it will be very unlikely that earthquakes can propagate outside of the width-limited reservoir. That means that rupture widths will be limited to values slightly larger than the thickness of the reservoir of 50 - 280 metres.

With limited width of the rupture, the only way to generate a very large earthquake is by increasing the along-strike rupture length. The largest theoretical rupture lengths could be constrained by the largest along-strike length of faults. However, from natural earthquakes it is known that a fully dynamic rupture is very energetic, such that its stress increase ahead of the rupture could also trigger rupture on neighbouring fault segments. Since the Groningen fault network has many neighbouring and cross-cutting faults, it is critical to evaluate whether ruptures can jump from one fault to the next, thereby potentially increasing the rupture length significantly. To be able to account for rupture jumping as well as large uncertainties in parameters, the researchers are developing an extension to a semi-analytical rupture tip equation of motion. Almost 3000 2.5D dynamic rupture simulations were run to determine how the critical distance for rupture jumping across stepovers depends on the prestress level on both fault segments and seismogenic width. Two jumping criteria were developed for jumping within the same plane or to a neighbouring fault. These rupture jumping criteria are of crucial importance in seismic hazard analysis for both natural and induced seismicity earthquakes.

Applying the universal results to Groningen revealed that faults with small widths need to be highly critically stressed to jump over even short distances. For example, assuming a 300 metres wide rupture across a wide Groningen reservoir, a second fault should be more than 94 percent stressed to allow the rupture to jump over 300 metres. Such highly critically stressed faults can on average not be reached, because fault slip would have already happened and released fault stresses. These findings imply that rupture jumping in induced seismicity settings with small widths is extremely unlikely, unless faults are very close.



Results from simulations of elongated ruptures for (a) varying stepover distances  $L_w$  and  $H_w$  normalised by seismogenic depth  $W$ , and varying prestress levels  $S'$ , on co-planar and non-co-planar fault systems. The maximum slip rate  $V_{max}$  indicates continued rupture for small  $L_w$  and  $H_w$  and rupture termination for large  $L_w$  and  $H_w$ . (b) 2700 critical co-planar stepover distances  $L_w/W$  were identified (scatter), and (c) 192 non-co-planar stepover distances  $H_w/W$  were identified (scatter), revealing scaling relationships of  $H_w/W \sim 1/S'$  (dashed line). The colour of each scatter point represents the static process zone size  $L_c$ .

The fault geometry of the most hazardous M1 fault was re-interpreted. This individual fault in the NAM model turns out to constitute a system of multiple faults, which transfer their offsets to each other.

## Data and method products 2025

All developed modelling tools and data sets are or will be made available at <https://github.com/USustSub>. These tools are useful for any induced seismicity setting, but might need tuning of the fault loading mechanism.

## Focus for 2026

In 2026, three papers and a PhD thesis will be published. The rupture jumping theory will be finalised, dynamic rupture simulations on the M1 fault will be run, and their integration to the Groningen fault network will be achieved. That integration, writing a paper about it, and integrating the physics-based distribution of  $M_{max}$  into the Seismic Hazard and Risk workflow for Groningen is envisioned using the funds from the final DeepNL Top-Up call.

## Collaboration and integration within DeepNL

Collaboration and integration mainly occur via four PhD students working on different DeepNL projects, who share(d) one DeepNL office at Utrecht's Earth Simulation Laboratory. Additionally, several induced seismicity

integrative meetings were held to share experimental and modelling findings. Job Arts (2a. Willingshofer) delivered laboratory measurements for friction on bi-material faults to PhysMmax models. Mhina de Vos (NEPTUNUS) transfers DeepNL's findings from the Groningen gas field to understanding induced seismicity in relation to geothermal energy.

## Relevance for and knowledge exchange with stakeholders

The findings for the Wirdum fault suggest that ruptures nucleate and arrest within the reservoir depth interval, such that rupture widths will remain bounded and mostly below M4. Findings for rupture jumping suggest that ruptures with such small widths can not jump over large or relevant distances. This limits the maximum length ruptures can reach. Together, these results suggest that rupture area (width times length for elongated faults) can likely not grow enough to reach the largest sizes denoted in the  $M_{max}$  logic tree. Hence, the weights on the largest magnitudes in the  $M_{max}$  tree could be reduced.

Through its connections with TNO, the team is planning to integrate this physics-based information for  $M_{max}$  into the Seismic Hazard and Risk workflow for Groningen using the Top-Up Call.

# Deep, deeper, deepestNL: Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM)

**Project leader:** Dr Islam Fadel (UT)  
**Associate project leader:** Prof. Mark van der Meijde (UT)  
**PhD:** Stephen Akinremi (UT)  
**Budget:** € 358,328,- (Call 2a)  
**Duration:** 2021 - 2026

## Research aim

To develop new high-resolution subsurface models of the Dutch crust and upper mantle down to 200 kilometres depth using data from a new densified broadband seismological network integrated with the freely available high-resolution potential field data.

## Highlighted outcomes 2025

The network densification has been achieved, and the temporary network has been deployed and removed in 2025. A total of 20 seismometers has been in operation for on average two years, delivering the data needed to generate the proposed subsurface models, doubling the resolution of the previously existing ones. One station remained at Terschelling and was integrated within the KNMI network to cover a seismological gap at that part of the Netherlands. Another station in the Wadden Sea, at two metres water depth near the NIOZ harbour, has also remained operational to continue the work on developing a permanent seismological monitoring technology in the Dutch shallow waters. The network deployment and design were published in a peer-reviewed article.

Within this project, a new method was developed for imaging sedimentary and crustal thicknesses, overcoming the challenges associated with reverberation signals. The method was published in two papers describing the technique and the software package associated with it, and was used to develop a high-resolution model of the basement depth and crustal thickness of the Netherlands. This model has been described in a paper which is to be submitted in 2026. Moreover, the newly developed crustal model was integrated with seismological surface wave observations from the densified network to develop a

3D shear wave velocity model of the Netherlands with almost double the resolution compared to the latest existing model.

In 2025, together with stakeholders, two real-time seismological monitoring systems were deployed at the Porthos site for CO<sub>2</sub> storage in the North Sea near the P18-A platform. Following successful testing in 2024 and 2025, a collaboration agreement was established with Porthos to secure the continued development of the system, with support from KNMI and EBN.

## Data and method products 2025

The seismological data generated from the temporarily deployed network is freely available through the KNMI web service. The data collection was completed and is being documented and organised to be published in collaboration with KNMI in the coming few months. The generated data can be further used for future projects in the Netherlands and for regional or global studies. Furthermore, the data, methods, and models developed during the PhD work have been documented and published on the DANS server for use in future studies in the Netherlands.

## Focus for 2026

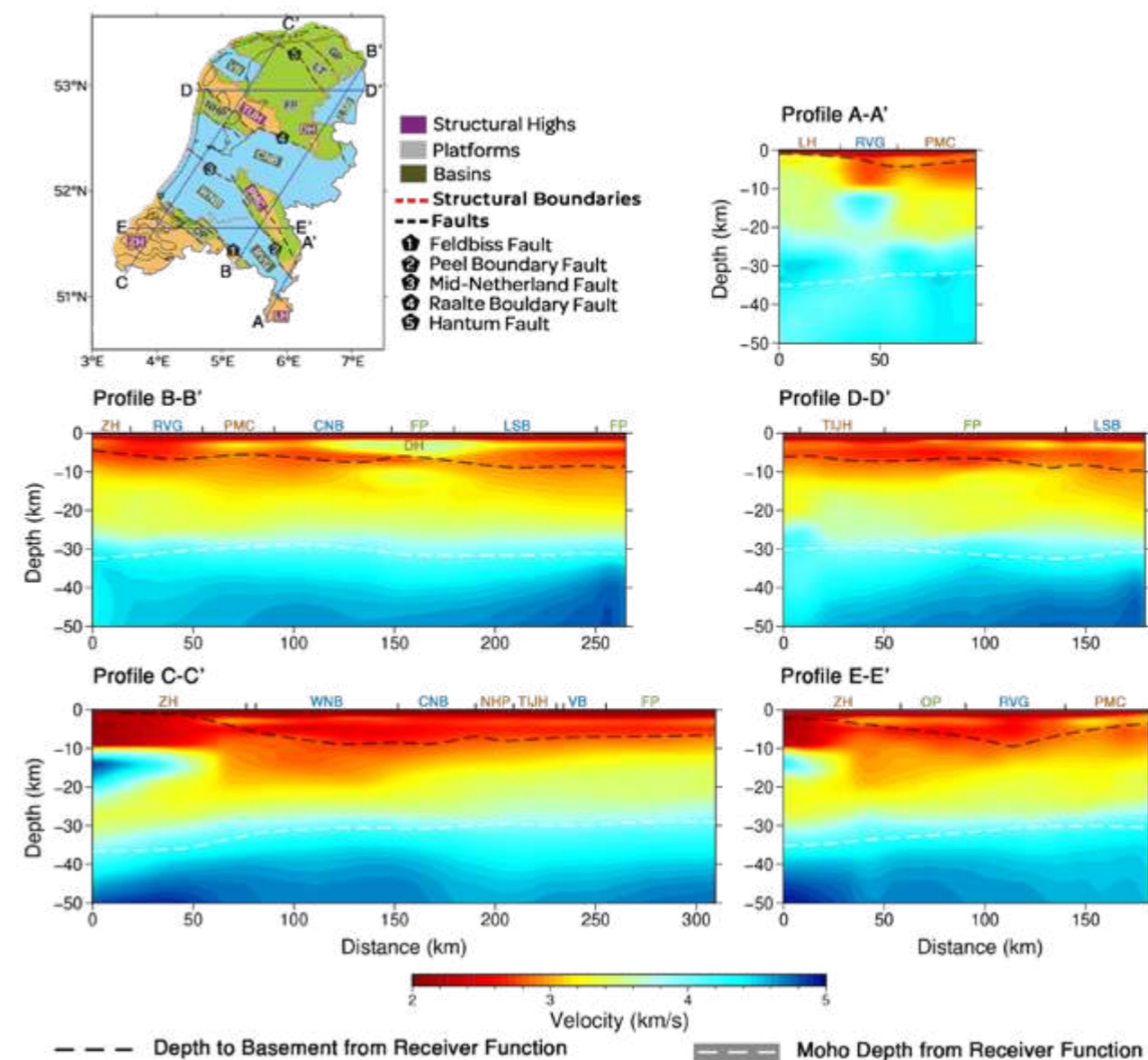
The main aim for 2026 is to publish the two papers related to the seismological crustal models of the Netherlands. Also, the multi-observables regional model of the Netherlands in terms of seismic velocities, density, and magnetic susceptibility is being built, by integrating the seismological observations with gravity and magnetic data. A free-open-source tool will be developed to integrate these datasets. Finally, the first stand-alone sea-bottom seismometer will be installed in the Wadden Sea with real-time data streaming to KNMI.

## Collaboration and integration within DeepNL

The products from the DICTUM project, including the basement depth and crustal thickness maps, the seismological observables, and the 3D velocity model, could be directly used in other DeepNL projects. For example, the crustal thickness map could be a crucial input for the projects dealing with the quantitative constraints on pre-production reservoir stresses in Groningen. Moreover, the new seismological data and extracted observables will be used in the INTEGRATION and the SHAWave projects.

## Relevance for and knowledge exchange with stakeholders

The regional 3D seismological model could be relevant for KNMI to improve the 3D velocity models used in local earthquake characterisation. The newly developed seismological system for the Dutch North Sea has attracted attention and is currently being implemented in three ongoing projects. As the first system that can be used for real-time seismological monitoring activities in the North Sea, the system has been proposed to be deployed at the Porthos site, the first



3-D shear-wave velocity model of the Netherlands presented as cross-sections along selected transects.

carbon capture and storage site in the Netherlands. Further collaborative efforts are currently ongoing to submit proposals that could establish a permanent long-period seismological network in the Netherlands. KNMI has identified the new North Sea seismometer system as a potential solution for the long-term existing seismological coverage gap in the North Sea. Through KNMI, a collaboration agreement and Horizon Europe projects have been established and granted in collaboration with Porthos and EBN, among other partners, to further develop and test the system. Furthermore, the new system will also be used within a new funded project by the Ministry of Climate Policy and Green Growth through TNO for seismological monitoring in the Dutch North Sea.



Reflection by DeepNL  
PhD researcher  
**Stephen Akinremi**

Stephen Akinremi defended his PhD thesis entitled 'Deep, Deeper, Deepest-NL – Imaging the Crust and Upper Mantle Structure of The Netherlands' on 9 December 2025 at UT

*Stephen developed a new method for crustal imaging in the presence of sediment reverberation – an outcome he is proud of. Exploring the complicated problem of sediment reverberations in seismic signals in the Netherlands and developing a new method to address it was very valuable. The biggest challenge during the PhD project was the substantial delay in data collection due to factors outside the project's control. Stephen completed his PhD and has started a new position as a post-doctoral researcher in the DeepNL SHAWave project at the University of Twente.*



Stephen Akinremi presenting during his PhD defence ceremony.

# LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data

**Project leader:** Dr André Niemeijer (UU)  
**Associate project leader:** Dr Ivan Pires de Vasconcelos (Shearwater GeoServices)  
**Postdoc:** Dr Chong Liu (UU)  
**PhD:** Rens Elbertsen (UU)  
**Budget:** € 358,358,- (Call 2a)  
**Duration:** 2022 - 2026

## Research aim

How do we use machine learning techniques on acoustic measurements of complex analogue fault experiments to uncover information about the state of the fault, and how does this method inform predictions of the time to failure?

## Highlighted outcomes 2025

The direct shear apparatus is now fully operational. A few preliminary experiments were conducted with a total of eight acoustic emission sensors capturing signals from a direct shear experiment at a constant velocity. These experiments clearly show acoustic signals in the 'interseismic' period, that is the time when shear stress is building up on the fault. This information can be used in machine learning techniques to predict the timing of the event. There is no further progress to be reported due to personal circumstances of the PhD researcher, who left the project. The new postdoc Chong Liu will continue the research and starts at 1 May 2026.

## Focus for 2026

1. Detailed analyses of acoustic emission signals of already acquired data on glass beads and application of existing machine learning and artificial intelligence techniques to these.
2. Further experiments using different analogue materials to answer the question what physical mechanism is responsible for the precursory signal(s) that can be used to predict lab earthquakes.

## Collaboration and integration within DeepNL

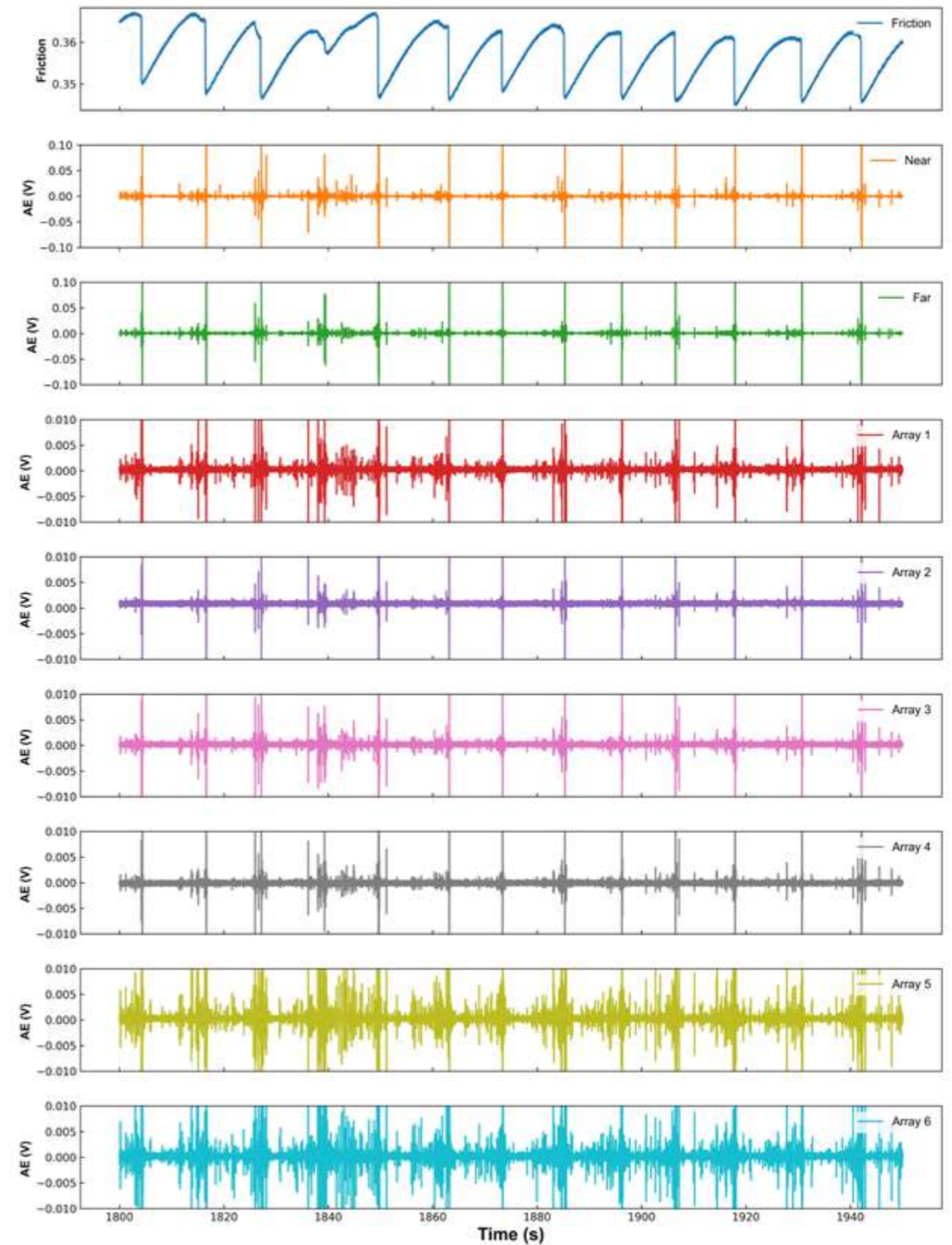
A few initial experiments were performed with the fast infrared thermal camera used in the PI's previous 1a project, but these require some further development and fine tuning. Some of the data may be used to validate or calibrate the large scale fault reactivation

models developed within the FastSlip-project. Since the planned testing of the new method to different materials that are more relevant to the subsurface of the Netherlands has not yet happened, there have not yet been interactions with other DeepNL projects beyond general discussions of seismicity with the people from the PhysMmax project.



Introduction DeepNL researcher  
**Chong Liu**

Chong Liu will start as a postdoctoral researcher on the project on 1 May 2026. Chong obtained his PhD in Civil Engineering at the University of Hong Kong in 2024. He brings in expertise in numerical simulation, deep learning, and laboratory earthquake experiments, having served as a teaching assistant for direct shear tests and having contributed to AI-driven analysis of pattern-forming processing. He will focus on analysing acoustic emission data from analogue fault experiments using machine learning to identify precursory patterns and physical mechanisms that enable time-to-failure prediction. His work will directly advance the project's core aim of linking lab-scale seismic precursors to real-world fault behaviour, contributing robust data-driven forecasting tools relevant to induced seismicity in the Dutch subsurface.



Evolution of friction and acoustic signals during a direct shear experiment at constant velocity. Besides the periodic labquakes, which generate a large output on all acoustic emission sensors, a clear signal is visible in the time leading up to the labquake.

## Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions (INTEGRATION)

**Project leader:** Prof. Mark van der Meijde (UT)  
**Associate project leaders:** Dr Islam Fadel (UT); Dr Suzanne Hangx (UU); Dr Bart Root (TUD); Dr Juan Carlos Afonso (formerly University of Tasmania)  
**Postdocs:** Dr Mark Jefferd (UT); Dr Janneke de Laat (UT)  
**PhD:** Mahsa Ashraf Navir (UT)  
**Budget:** € 903,601,- (Call 2b)

**Duration:** 2024 - 2028  
**WP1:** Data collection, pre-processing and analysis. (De Laat, Ashraf Navir, Jefferd)  
**WP2:** Integration of 3D conduction-convection solvers within multi-observable probabilistic Inversions. (De Laat, Ashraf Navir)  
**WP3:** A multi-parameter model of the subsurface for the Groningen region and on-shore Netherlands. (De Laat, Ashraf Navir)

### Research aim

To develop an integrated, physics-based and internally consistent model of the Dutch subsurface, with a particular focus on the Groningen region. The project seeks to optimally combine the large variety of geophysical, geochemical, petrophysical and geodetic datasets that have been acquired in the Netherlands over the past decades.

### Highlighted outcomes 2025

A key outcome in 2025 was the development of a multi-scale, multi-observable probabilistic inversion method, which allows different types of subsurface data to be integrated consistently across spatial scales while preserving uncertainty quantification. This methodology addresses one of the central objectives of the project and has been tested successfully. The resulting work has been accepted for publication in *Geophysical Journal International*, pending minor revisions. In parallel, a multi-parameter geological model of the Dutch subsurface was developed and is nearing completion. This model integrates current knowledge on temperature, lithology, major structures, seismic velocity models, and new constraints on deep basement and whole-crustal structure derived from receiver functions and tomography. Part of this information originates from the DICTUM project, demonstrating strong collaboration and effective reuse of results within the programme. The model forms the main input for the planned large-scale multi-scale inversions, which are a core objective of the project. The development of an initial AI-based workflow for the selection of relevant seismic phases from seismological datasets was further developed. This workflow generates site-specific, phase-labelled synthetic waveforms. The created realistic

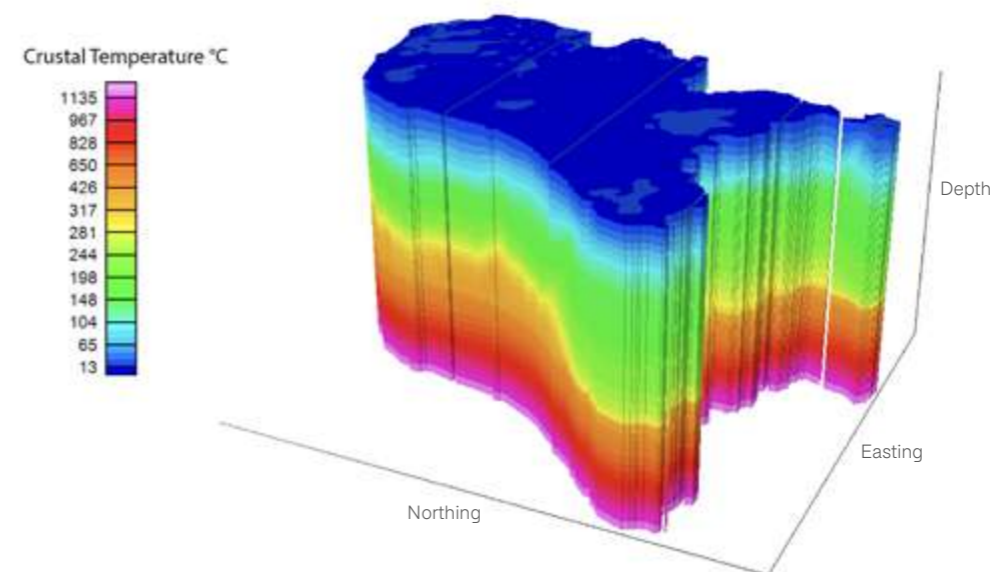
synthetic dataset is being used to retrain existing AI models, thereby improving the performance of phase extraction from raw seismograms. In parallel, a tomographic workflow has been developed, in which the derived phase picks can be used to construct a tomographic model of the lithosphere beneath the Groningen region.

### Data and method products 2025

The project developed the first dataset of P- and S-wave arrival times from local and regional earthquakes based on freely available broadband seismological data. This dataset can be used to construct regional seismic velocity models, which are relevant for improving subsurface imaging in the Netherlands and for supporting other DeepNL projects. The dataset also has potential value for regional and global seismological studies and for future updates of higher-resolution subsurface models. In addition, a new multi-scale, multi-observable probabilistic inversion method was developed and tested. The method enables the consistent integration of heterogeneous datasets across spatial scales while preserving uncertainty quantification. It forms a reusable methodological framework that can be applied within DeepNL and in other data-intensive subsurface studies, supporting reproducibility and long-term reuse.

### Focus for 2026

The project will focus on preparing the final components required for the large-scale multi-observable probabilistic inversions. A primary activity will be the completion of the reference multi-parameter subsurface model of the Netherlands. Where feasible, a first large-scale refinement of this model will be explored



Preliminary temperature model based on subsurface data integration for the Netherlands.

using potential field data within a simplified inversion framework. At the same time, the nationwide dataset of P- and S-wave arrival times will be finalised and used to construct three-dimensional seismic tomographic models. These models will provide improved constraints on crustal structure and will form an important input for the integrated inversions. In parallel, the systematic assessment and pre-processing will begin of all datasets that are to be combined in the final inversion, including seismic, gravity and thermal data. Finally, development will start on the FORTRAN implementation of the newly developed multi-scale inversion approach, enabling its integration with existing multi-observable probabilistic inversion software. This will allow the initiation of the multi-scale, multi-observable inversions, which represent a central outcome of the project.

### Collaboration and integration within DeepNL

The INTEGRATION project is designed to act as an integrative platform across multiple research clusters. The project builds directly on data, results and insights generated in previous and ongoing DeepNL projects, particularly those focusing on seismic imaging, monitoring, induced seismicity and subsidence. The multi-parameter subsurface models developed in this project provide essential structural, thermal and mechanical context for other DeepNL studies. In particular, the results support projects in the seismic imaging and monitoring cluster by providing improved constraints on crustal structure, stress distribution and physical properties at depth.

### Relevance for and knowledge exchange with stakeholders

By developing integrated, physics based subsurface models, the project provides stakeholders with quantitative insight into key properties that control subsurface behaviour, including temperature gradients, stress fields, lithological contrasts, fluid pathways, and permeability distributions. A central contribution of the project is its ability to combine seismic, gravity, magnetic, borehole, and geochemical datasets into a single internally consistent framework. This integration significantly reduces the uncertainty, inconsistencies, and interpretational biases that typically arise when datasets are analysed in isolation. As a result, stakeholders gain access to models that support evidence based decision making for spatial planning, licensing, risk mitigation, and long term energy transition strategies. The methodology also provides transparent uncertainty estimates, enabling regulators and industry partners to better evaluate operational envelopes and safety margins. Several stakeholders have already been involved in the ongoing activities of the project. The project team plans targeted dissemination through workshops, presentations and communication articles aimed at both scientific and non-scientific stakeholders. In addition, the project includes the development of a dedicated website to communicate objectives, progress and key outcomes to a broader audience. The final integrated datasets and models will be made available through established national infrastructures, enabling reuse by governmental agencies, research institutions and industry partners.

## SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach

**Project leader:** Prof. Mark van der Meijde (UT)  
**Associate project leaders:** Dr Islam Fadel (UT); Dr Joris Remmers (TU/e); Prof. David Smeulders (TU/e); Dr Clemens Verhoosel (TU/e)  
**Postdoc:** Stephen Akinremi (UT)  
**PhDs:** Maarten Hodzelmans (TU/e); Tarlan Khoveiledy (UT)  
**Budget:** € 1,059,127,- (Call 2b)  
**Duration:** 2024 - 2028

**WP1:** Full elastic waveform ground motion modelling in Groningen. (Khoveiledy)  
**WP2:** Poromechanical near-surface ground motion modelling. (Hodzelmans)  
**WP3:** Full scale demonstration of waveform modelling based probabilistic seismic hazard assessment for future exploration activities in NL. (Akinremi)

### Research aim

To understand how complex subsurface structures influence the surface effects of shallow, induced earthquakes in the Netherlands by using waveform based approaches to better predict local variations in seismic intensity.

### Highlighted outcomes 2025

To investigate how variations in the deep and shallow subsurface influence the way seismic waves travel and how strongly the ground shakes at the surface, extensive 3D full waveform simulations were carried out using the Salvus modeling framework. These simulations covered a broad range of frequencies. This allowed the optimisation of mesh resolution and achieving a practical balance between computational efficiency and physical accuracy. Using a synthetic velocity model representative of the Groningen subsurface, multiple earthquake scenarios were modelled with different source mechanisms and the resulting Peak Ground Acceleration (PGA) was calculated. To assess the role of subsurface complexity, these results were compared to simulations based on a simplified, homogeneous subsurface model. This comparison led to the production of detailed amplification factor maps, highlighting where geological structure leads to stronger or weaker ground shaking. By systematically varying factors such as source frequency content, the depth and thickness of velocity layers, velocity inversions, and the shape of subsurface interfaces, the individual contributions of each process to observed amplification patterns were identified. Better models of the shallow subsurface are needed to understand how seismic waves interact with water bearing layers. To support efficient and accurate

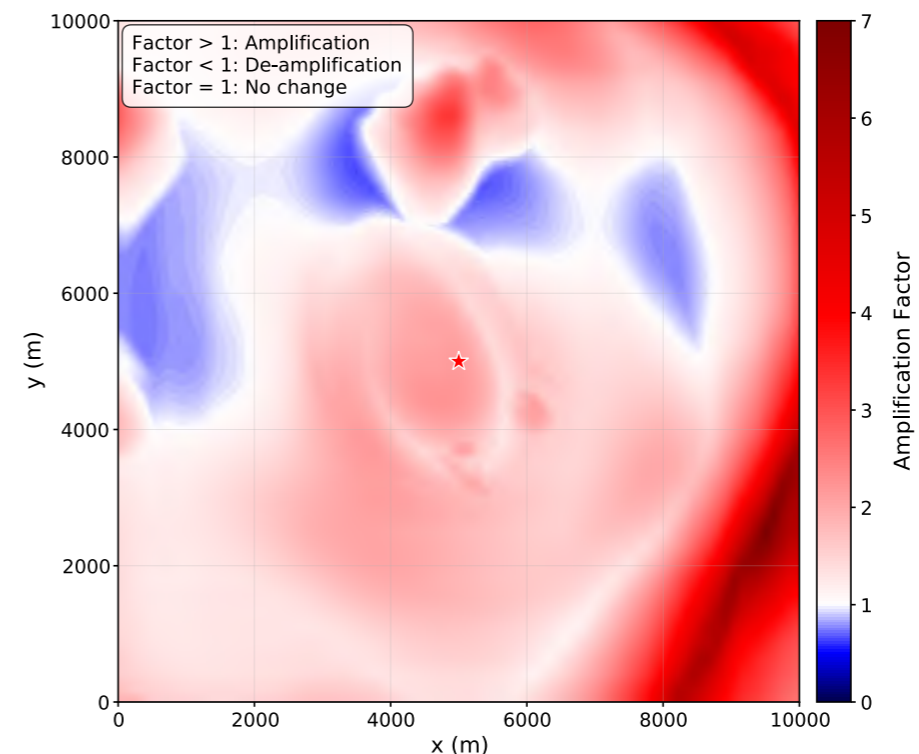
large scale simulations, the potential of IsoGeometric Analysis (IGA) was evaluated as an alternative to traditional higher order finite element or spectral element methods. The results demonstrate that several key advantages of IGA, which well established in elastic modelling, translate directly to poroelastic problems. These include:

- Higher order accuracy with minimal computational overhead,
- Eigenfrequency spectra that remain fully physical, avoiding spurious modes,
- The ability to use relatively large timesteps without compromising stability or accuracy.

These findings show that IGA is a promising approach for future large scale simulations of the shallow subsurface. A scientific manuscript describing these results is currently in the final stages of preparation. In parallel, efficient software tools are developed to ensure that these advanced numerical methods can be applied to realistic, computationally demanding subsurface models.

### Data and method products 2025

3D subsurface models were developed to simulate induced seismicity ground motion. Both the modelling framework and the resulting amplification factor maps are applicable to other DeepNL projects, and transferable to regions outside DeepNL with induced seismicity or complex geological settings. The code will be published to facilitate reproducibility and reusability by other researchers. The analysis of IGA is entirely reproducible through the accompanying package. This code will be of limited interest for other DeepNL projects, since it is more suitable for method analysis than method usage.



Example of the complicated spatial surface amplification pattern as a result of subsurface inhomogeneous structure.

### Focus for 2026

The team will transition from synthetic to realistic velocity models representing the Groningen subsurface. Ground motion from significant recorded earthquakes within the region will be simulated to compare the results with those from homogeneous half-space models. This addresses how subsurface heterogeneity affects ground motion amplification in realistic scenarios and contributes to developing region-specific amplification factor maps. Constitutive modelling will be another main topic of interest. Does the attenuation inherent in poroelasticity accurately capture what is observed, or is an extension to viscous or plastic models required? This contributes to accurately resolving the anelastic part of the subsurface. In parallel, the work on efficient software will be continued. A start will be made with the final work package for which the postdoctoral researcher joined the team in January 2026. Focus in the first year will be the application to the Groningen area to fully understand the effects of different subsurface features and necessary modelling resolution (model dimensions and frequency content).

### Collaboration and integration within DeepNL

SHAWave links to several earlier DeepNL projects that have provided insight into composition and structure in the Groningen area. The researchers have been in contact to get access to their database and support to transfer these models into formats that SHAWave can use. There is an active collaboration on this matter with the DeepNL INTEGRATION project since both projects need the highest resolution possible models for their upcoming activities. Regional data will be obtained from the DeepNL DICTUM project.

### Relevance for and knowledge exchange with stakeholders

The modelling framework (both elastic and IGA) provides physical explanations for the spatial variability of observed ground motions. These insights are directly applicable to current and future exploration activities and associated seismic hazard, providing stakeholders with improved hazard understanding and more robust, risk-informed decision-making. The project team hosted a meeting with their stakeholders in 2024. In 2025, the team hosted a workshop on modelling for the shallow subsurface at the DeepNL Stakeholder Meeting. It is their intention to host another project specific stakeholder meeting in 2026 to introduce the latest results and the startup of the final work package.

## A digital twin for modelling and forecasting induced seismicity

**Project leader:** Prof. Jeannot Trampert (UU)  
**Associate project leader:** Prof. Federico Toschi (TU/e)  
**Postdoc:** t.b.d. (UU)  
**PhDs:** Naud de Boeij (TU/e); Zach McBrearty (UU); Thomas Muhren (TU/e)  
**Budget:** € 1,077,489,- (Call 2b)  
**Duration:** 2024 - 2028

**WP1:** Modelling statistics of induced seismicity. (Muhren)  
**WP2:** Modelling the spatial distribution of seismicity. (De Boeij)  
**WP3:** Machine learning model to forecast seismicity. (McBrearty)  
**WP4:** Production scenarios. (t.b.d.)

### Research aim

To develop a numerical model capable of predicting timing, location and size of observed seismicity based on the Groningen fault geometry and forcing due to gas production. The project focusses on three complementary approaches: the Lattice Boltzmann modelling of stick-slip in soft glasses, an elasto-plastic theoretical model of stick-slip, and a data driven approach aimed at discovering the governing equations.

### Highlighted outcomes 2025

The Lattice Boltzmann modelling code is ready to run on a large GPU cluster and allows upscaling to metre-resolution. An elasto-plastic model, where fluidity (inverse viscosity) can be used as a proxy for the rate of plastic events, allows simultaneously accounting for shear banding (local flow) and stick-slip behaviour (local plastic events). The equations involved in seismicity are stochastic. The next step is to infer drift and diffusion from time series of fluidity and stress using an earlier proposed Langevin regression.



From left to right: Zach McBrearty, Thomas Muhren, Naud de Boeij, Roberto Benzi, Federico Toschi and Jeannot Trampert.

### Focus for 2026

Naud de Boeij's project, using Lattice Boltzmann, will focus on changing the spatial distribution of droplets in the soft-glass to mimic fault lines. He will also investigate how to model injection and extraction of fluids as a driving force. Thomas Muhren's elasto-plastic model is currently in 0D (spatially averaged quantities). He will focus on extending the model to 2D. In parallel he will be writing a paper on the statistical properties of the 0D model, which are remarkably similar to earthquake statistics. Zach McBrearty is currently writing a paper on the successful recovery of the stochastic differential equation of the 0D elasto-plastic model using fluidity time series generated with constant stress. He is also extending the approach to include varying stress. In the real world, we rarely observe stress and fluidity, but ground acceleration instead. Zach will investigate the information content of such data for equation recovery.

### Relevance for and knowledge exchange with stakeholders

This project models the macroscopic response of a medium in terms of seismicity due to fluid movement, which is a major DeepNL goal that is relevant for anybody who intends to move fluids around in the subsurface. The synthetic seismic catalogue and machine learning tool to forecast seismicity that are intended deliverables of this project, are relevant for applications like geothermal energy, underground water drainage, CO<sub>2</sub> sequestration or H<sub>2</sub> storage.



Project leaders Jeannot Trampert and Federico Toschi in from of their 3D soft-glass model.

### Collaboration and integration within DeepNL

Since this an entirely new angle on earthquake physics, there is no immediate connection yet with other DeepNL projects. Of course, over time results will be compared with those of other projects that approach forecasting of seismicity in a more classical way, such as InFocus, Science4Steer, DeepImage, PhysMmax, and LabQuakeAI.



### Introduction DeepNL researcher Thomas Muhren

Thomas completed his undergraduate degree in Applied Physics at TU/e and his master's degree at RU, with a focus on theoretical physics. He enjoys trying to understand physical systems by employing analytical and computational methods. In his PhD research, he will extend an elasto-plastic model that shows the same statistical behaviour as earthquakes. Extending this model will lead to a better understanding of plasticity in emulsions, which can be used to model the seismicity observed in practical applications.

## DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity

**Project leader:** Dr Auke Barnhoorn (TUD)  
**Associate project leaders:** Dr Deyan Draganov (TUD); Dr Ranajit Ghose (TUD); em. Prof. Kees Wapenaar (TUD); Dr Kees Weemstra (TUD/KNMI)  
**PhDs:** La Ode Marzujriban Masfara (TUD);

Jingming Ruan (TUD); Faezeh Shirmohammadi (TUD); Aukje Veltmeijer (TUD)  
**Budget:** € 1,053,152,- (Call 1a)  
**Duration:** 2019 - 2023

### Research aim

To develop an integrated methodology for seismic imaging and monitoring of the Groningen subsurface and its induced seismicity based on innovative, scaled rockmechanic experiments, advanced geomechanical and seismic

modelling, and advanced seismic imaging and inversion techniques.

**For a summary and output see:**



## Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations

**Project leader:** Prof. Jeannot Trampert (UU)  
**Associate project leaders:** Prof. Marie-Colette van Lieshout (UT/CWI); Dr Hanneke Paulssen (UU); Dr Kathrin Smetana (Stevens Institute of Technology, USA)  
**Postdocs:** Dr Adam Candy (UU); Dr Rhys Hawkins (UU)

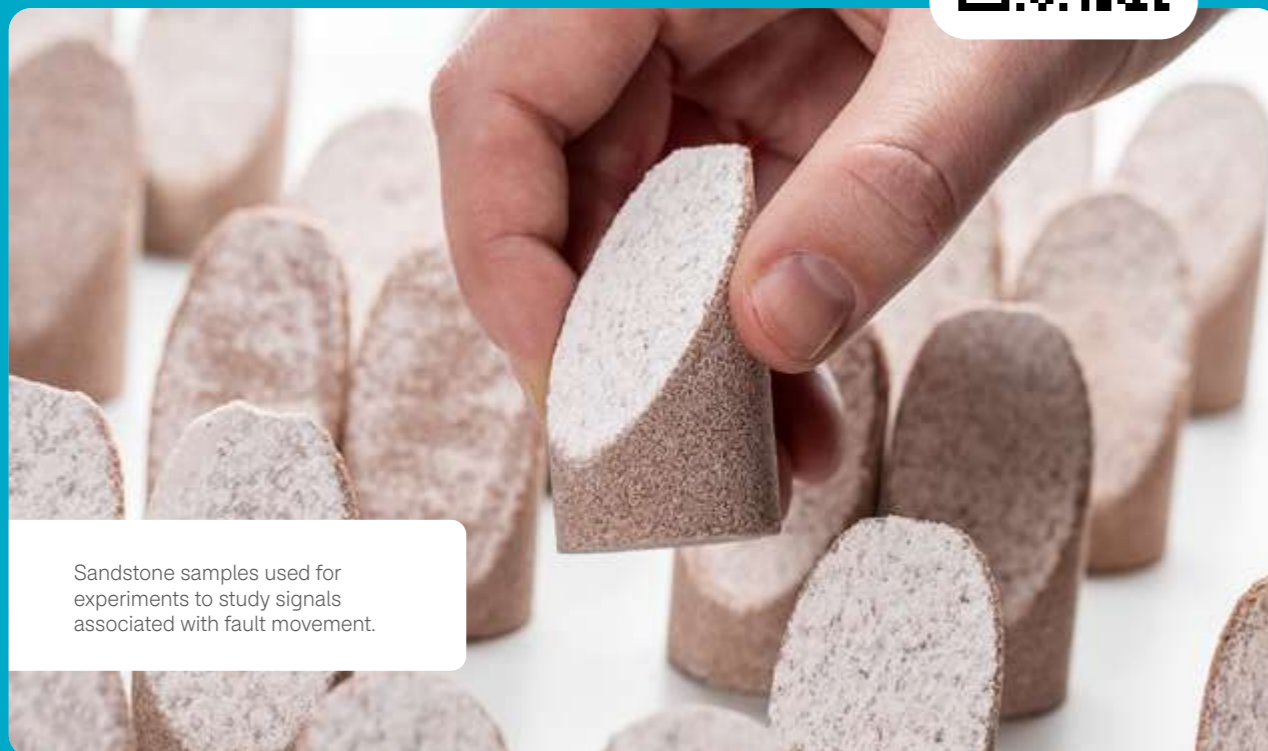
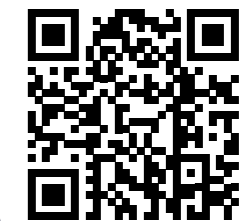
**PhDs:** Zhuldyzay Baki (UT); Thomas Cullison (UU); Eldert Fokker (UU); Janneke de Jong (UU); Muhammad Hamza Khalid (UT)  
**Budget:** € 1,590,670,- (Call 1a)  
**Duration:** 2019 - 2024

### Research aim

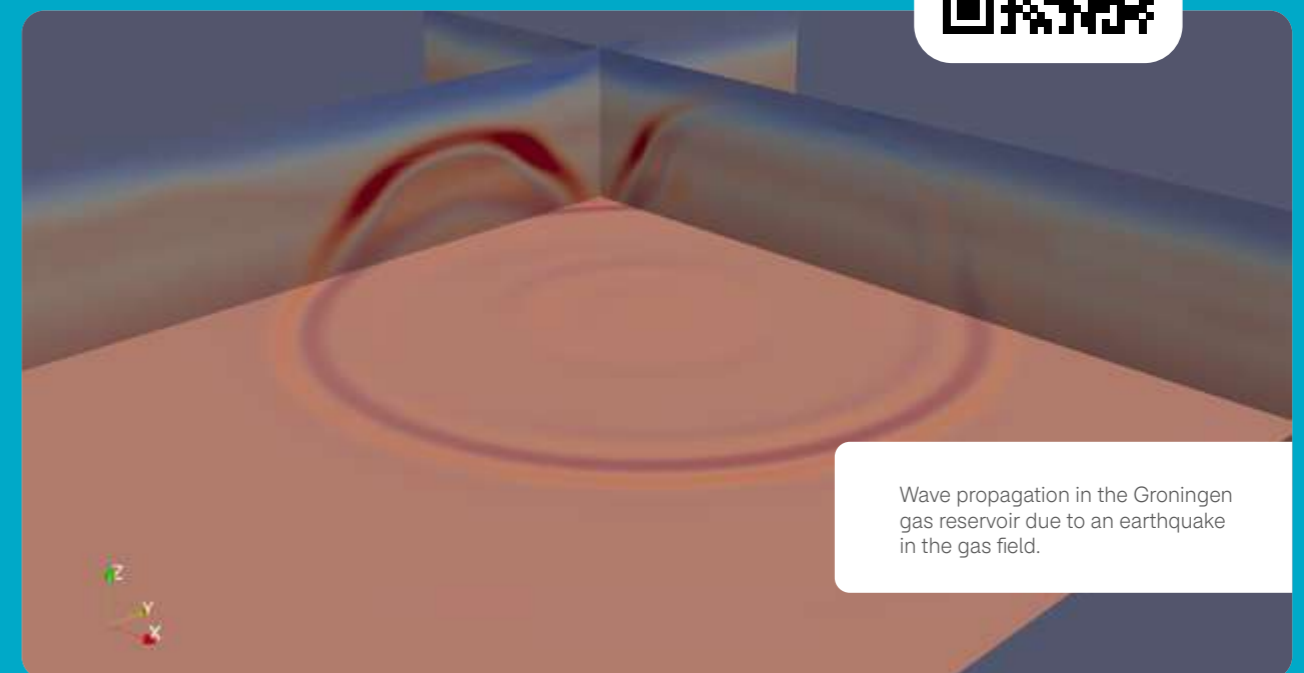
To understand the causal relation between gas production, subsidence, and seismicity by using physics based numerical modelling of seismic waves to monitor changes in seismicity, elastic parameters, induced stress and compaction.

This information was used to forecast seismic hazards of production scenarios based on advanced statistics.

**For a summary and output see:**



Sandstone samples used for experiments to study signals associated with fault movement.



Wave propagation in the Groningen gas reservoir due to an earthquake in the gas field.

Progress  
**CLUSTER**

**3**

**Subsidence and the response of  
the Earth's surface to earthquakes**

How can we assess and model the impact of deep and shallow subsurface processes on ground motion at the surface?



## Monitoring and Modelling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension

**Project leader:** Prof. Ramon Hanssen (TUD)

**Associate project leaders:** Dr Rob Govers (UU); Prof. Esther Stouthamer (UU); Prof. Femke Vossepoel (TUD)

**PhDs:** Wietske Brouwer (TUD); Chayenne Janssen (UU); Samantha Kim (TUD); Marius Wouters (UU)

**Other staff:** Marc Bruna (TUD)

**Budget:** € 1,233,808,- (Call 1a)

**Duration:** 2019 - 2025

**WP1:** Improvement of geodetic models and parameter estimation: InSARdata. (Brouwer)

**WP2:** Improvement of geophysical models at sub-Holocene depths: reservoir and overburden. (Wouters)

**WP3:** Improvement of geophysical models at Holocene and Pleistocene depths: soils, hydrology and water management. (Janssen)

**WP4:** Data assimilation: analysis of model data differences to help quantify model uncertainties. (Kim)

**WP5:** Advancement of numerical data processing techniques. (Bruna)

### Research aim

To significantly improve the accuracy of geodetic subsidence estimates, and to better constrain the model parameters that control physical processes in the subsurface.

### Highlighted outcomes 2025

Major progress was achieved in separating deep, shallow, and autonomous contributions to surface deformation in the Groningen region, culminating in the successful isolation of the deep, gas-production-related signal. A new InSAR-based methodology was developed to estimate the full three-dimensional surface displacement field by first separating reservoir-induced deformation from shallow and local surface motion and subsequently applying a strapdown decomposition to derive vertical and horizontal displacement components. The approach provides robust displacement estimates with propagated uncertainties and reveals maximum subsidence rates of approximately 6.5 millimetres per year, together with significant inward horizontal motions reaching about 1.8 millimetres per year, particularly near reservoir boundaries. These results demonstrate that horizontal deformation plays a substantial role and must be considered alongside vertical subsidence to properly understand and mitigate the long-term impacts of gas extraction in the Groningen region.

A further milestone was the development of a geomechanical model that balances computational efficiency

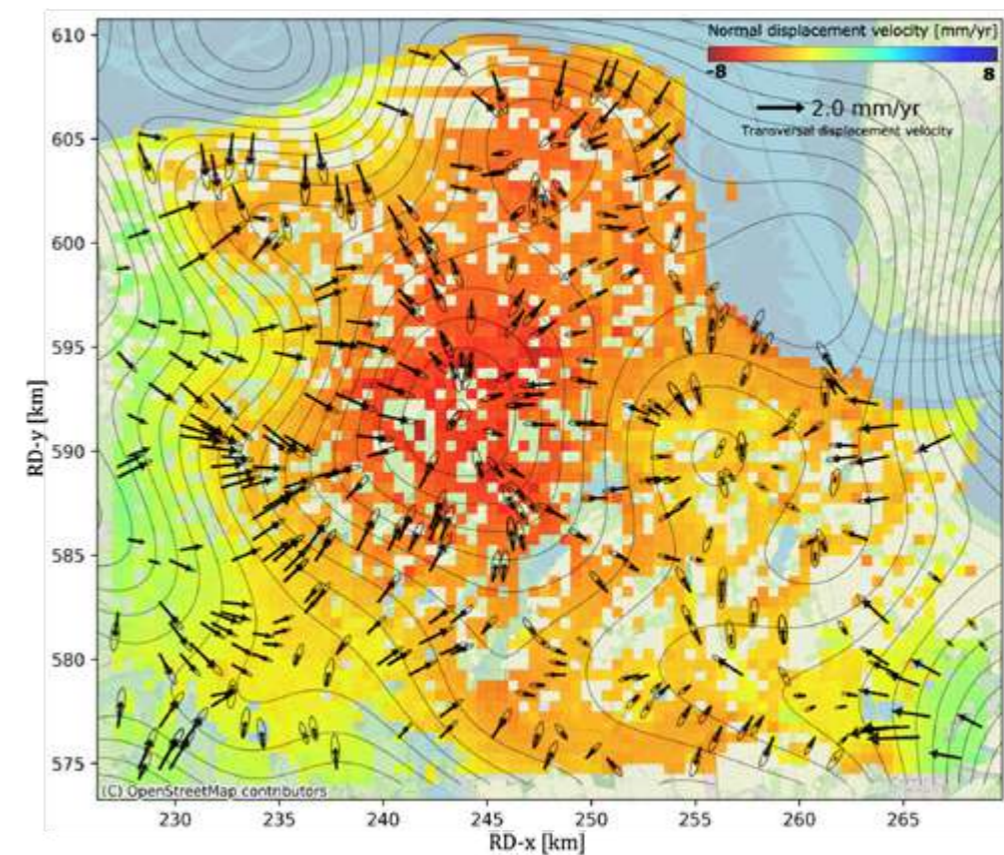
and physical realism, enabling practical integration of geomechanical simulations into data assimilation workflows – one of the central goals of the project. Previous models were either too simplified to capture relevant deformation processes or too complex to be computationally feasible for repeated assimilation cycles. The new model simplifies reservoir geometry and elastic layering by removing subsurface details unlikely to generate surface signals detectable in geodetic observations, resulting in a model that is both efficient and suitable for large-scale assimilation applications.

In parallel, a multi-scale data assimilation framework was established, integrating physics-based subsurface models with geodetic observations to attribute observed subsidence to reservoir processes and other deformation sources. Central to this framework is the application and evaluation of importance sampling (a type of particle filter) methods, which explicitly account for the spatially correlated nature of subsidence signals. The study demonstrates that neglecting prior information about the spatial smoothness of the expected displacement signal can lead to weight collapse in particle-filter approaches and unreliable parameter estimates. By incorporating smoothness constraints and applying information-theory-based criteria, such as entropy measures, to guide ensemble design and sampling strategies, the framework improves estimation of reservoir compaction contributions while maintaining reliable uncertainty quantification.

Research on shallow deformation processes also progressed through continued analysis of measurements from the DeepNL monitoring site in Nieuwolda, Groningen. Extensometer observations, which record relative movement between shallow subsurface layers, provide valuable insights into the mechanisms controlling surface motion. A clear relationship is observed between surface deformation and variations in phreatic groundwater levels driven by atmospheric conditions such as precipitation and evaporation. Measurements from a satellite radar transponder installed at the same location show strong agreement with the in-situ extensometer data, demonstrating that radar transponders provide an efficient, cost-effective, and minimally invasive method for monitoring surface motion at additional locations of interest.

### Data and method products 2025

Input, output and scripting files that were used in the geophysical modelling part of the project are digitally stored in the Yoda repository of Utrecht University (<https://doi.org/10.24416/UU01-W3PCRY>). A public dataset containing three-dimensional ground displacement velocities derived from InSAR observations was released. For each 500 × 500 metres Region of Uniform Motion (RUM), displacement velocities in east, north, and vertical directions are provided along with associated variances and covariances, enabling uncertainty-aware analyses and visualisation through confidence ellipses. The dataset is distributed in .csv format, accompanied by metadata and example scripts for reading, visualisation, and interpretation, and is freely accessible to the community.



Subsidence in Groningen is not one-dimensional but three-dimensional, as there are both vertical and horizontal displacements associated with the subsidence. The significant horizontal displacements are shown as vectors, and the vertical displacements in colour. The ellipses show the 95 percent confidence regions.

The data and methods developed in the geodetic part of the study have been made available in publications, as well as on GitHub and the 4TU data repository:

- <https://doi.org/10.31223/X5775W>
- <https://github.com/TUdelftGeodesy/3D-Groningen>
- <https://doi.org/10.1007/s00190-024-01918-2>
- <https://surfdrive.surf.nl/index.php/s/mjERLrRs5ajm5b>

### Collaboration and integration within DeepNL

There is a strong and natural connection to follow-up DeepNL project SubsApp that aims to capitalise on the methods developed in this project. In addition, there have been strong research collaborations with other NWO projects, such as the NWA-project Living on Soft Soil, the Regiodeal-project, and the NOBV-project.

### Relevance for and knowledge exchange with stakeholders

The project has produced several new insights, methods, and datasets that are directly relevant for stakeholders involved in monitoring, managing, and modelling the Dutch subsurface. These stakeholders include governmental agencies, research institutions, operators, regulators, and the wider public concerned with subsidence and its societal impacts. In the geodetic domain, the entire InSAR parameter estimation workflow has been redesigned, leading to improved methods for resolving datum defects, quantifying estimate quality, and deriving

displacement parameters. Regarding deep subsurface processes, the project demonstrated that existing geomechanical models are not optimally aligned with the resolution capabilities of geodetic observations, as they are often either too simplistic or computationally too demanding for efficient use in data assimilation workflows. A new geomechanical model was therefore developed that is more suitable for operational subsidence analysis and future assimilation applications. In the area of data assimilation, significant progress was made in defining both conceptual and computational boundary conditions required to integrate geomechanical modelling with geodetic observations. The developed methods have been successfully demonstrated using synthetic datasets. In follow-up DeepNL research, improved handling of real-world datasets will be further investigated in close collaboration with stakeholders. For shallow subsurface processes, unique multi-year time series of compaction and extension have been collected within the Groningen region that provide valuable insight into shallow deformation mechanisms and their relation to environmental drivers. The results, products, and findings are shared with stakeholders, such as water management boards, by on-site presentations, (inter)national conferences, and NAM. There are plans to propose separate information sessions to SodM and to local interest groups in Groningen, in particular at Norg and Grijpskerk.



TUD PhD researcher  
Yuqing Wang.

## 3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis

**Project leader:** Dr Ranajit Ghose (TUD)  
**Associate project leader:** Prof. Michael Hicks (TUD)  
**PhD:** Eddy Revelo Obando (TUD)  
**Budget:** € 358,991,- (Call 2a)  
**Duration:** 2021 - 2025

### Research aim

To derive the lateral soil variability in between cone penetration testing locations through innovative use of high-resolution seismic data. The overarching goal is to end up with realistic, local site response analysis for Groningen through incorporation of soil spatial variability in a data-driven manner.

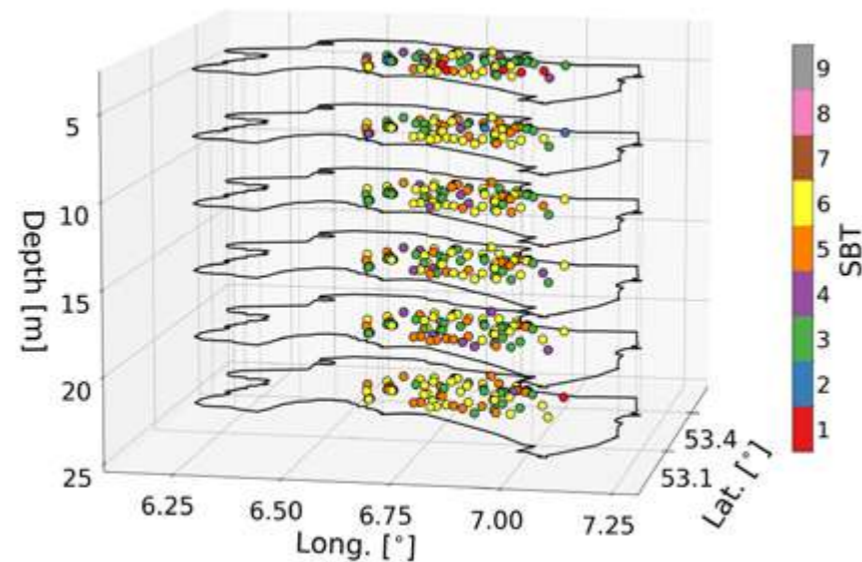
### Highlighted outcomes 2025

A hybrid deep learning architecture is successfully designed and tested on the Groningen seismic cone penetration test database. Through smooth, differentiable mapping in the multidimensional feature space, this architecture presents very accurate subsoil properties and their lateral variability information, even when

the training dataset is not very dense. In addition, the accuracy of the estimated void ratio and the soil behaviour type index derived from seismic shear-wave velocity is excellent. These soil mechanical parameters are essential inputs to analyse site response to seismic ground motion and evaluate liquefaction potential.

### Data and method products 2025

An edited database of seismic cone penetration tests is compiled for Groningen, homogenising quality, data sampling, and penetration depth. Six different machine learning and deep learning models are implemented, and a new hybrid deep learning architecture is designed and tested.



Spatial variability of soil behaviour type (SBT) captured from S-wave velocity ( $V_s$ ) using a hybrid deep learning (DL) architecture designed in this research and the SCPT database of Groningen. SBT 1=sensitive fine-grained soil, 2=organic material, 3=clay to silty clay, 4=clayey silt to silty clay, 5=silty sand to sandy silt, 6=clean sand to silty sand, 7=gravelly sand to sand, 8=very stiff sand to clayey sand, and 9=very stiff fine-grained sand, after Robertson (1990). This DL architecture is used next to obtain the lateral variability in soil parameters from the high-resolution VS field derived from surface-seismic data.

### Focus for 2026

Eddy Revelo Obando will finish writing his PhD thesis and then defend it.

### Collaboration and integration within DeepNL

The collaboration between the 3DSOIL and SOFTTOP projects has resulted in initial estimation of the effect of lateral variability of soil stiffness on the local site response. The PhD researchers in the DAMPINGSOIL project are maintaining a close contact with the PhD researcher on the 3DSOIL project. In addition to the seismic dataset, the CPT/SCPT dataset, the estimated stiffness variability, and the methodology, the deep learning architecture designed in 3DSOIL will be useful in the nonlinear site response calculations to be performed in the DAMPINGSOIL project. These outcomes are directly relevant to the goal of the DeepNL programme, which is understanding how anthropogenic activities in the subsurface, such as the extraction of natural gas, geothermal energy and salt, and underground storage of energy, CO<sub>2</sub>, and waste, affect the earth's surface.

### Relevance for and knowledge exchange with stakeholders

It is important to know the distribution of very soft and weak peat and clay layers for seismic site response analysis, and the distribution of the sand layers for evaluating liquefaction potential. This is especially true for the Dutch subsoil. The outcome of 3DSOIL, when integrated with the work being done in DAMPINGSOIL, will enable quantitative elucidation on field data about the effect of lateral variability of soil properties on the local, seismic site response. This will enable more safe and reliable site response analysis. It is now widely accepted that the spatial variability of soils (especially horizontally) has an important influence on the performance of a structure. This has serious implications for large infrastructure like dykes, rail embankments, or offshore wind farms, where closely spaced CPTs are impossible but where construction and maintenance costs can be enormous in the face of large uncertainties. New knowledge acquired within the various DeepNL projects will enable both a reduction in over-conservatism and in costs, thereby benefitting stakeholders and society.

The evaluation of the effect of spatially varying stiffness of soil as derived in this research was done in collaboration with Jose Leon Gonzalez. This former postdoc researcher in the SOFTTOP project is now employed by TNO. Continued collaboration with him is anticipated in the future, where more recent results, including spatially varying, accurate geomechanical properties of soil will be incorporated in site response analysis. Also, discussions with KNMI colleagues are ongoing for future use of the recent results in this research.

Reflection by DeepNL  
 PhD researcher  
**Eddy Revelo Obando**



Eddy Revelo Obando will defend his PhD thesis in the course of 2026 at TUD

*'The DeepNL programme provided me with extremely valuable experiences. I could learn from the top scientists and could connect with researchers on a global scale. Regarding my own work, I am proud of the new workflow for high-resolution FWI of shallow seismic data that I came up with, and the deep learning architecture to predict accurate soil properties from seismic shear waves. My most valuable experience was presenting in my first international conference, receiving positive feedback, and interacting with so many people. The biggest challenge for me was to succeed in the civil/geotechnical engineering field that was completely new for me. In the future, I want to pursue a career integrating geophysics, civil engineering, and machine learning, to make a positive impact on society. I am open to a career either in industry or in academia.'*

# DAMPINGSOIL: Providing the missing information of elastic damping ratio and strain-dependent modulus and damping curves for reliable, local site response analysis

**Project leader:** Dr Ranajit Ghose (TUD)

**Associate project leader:** Dr Karel van Dalen (TUD)

**PhD:** Fan Wang (TUD), Lukas Huber (TUD)

**Budget:** € 816,167,- (Call 2b)

**Duration:** 2024 – 2028

## Research aim

To improve the accuracy of seismic site response analyses by incorporating reliable estimates of damping or loss of energy in the shallow soil layers for different levels of strain that represent the seismic ground motion.

## Highlighted outcomes 2025

Fan Wang has developed a new method involving determinant-based multimode inversion of Rayleigh waves, and has shown on preliminary, synthetic models that this inversion can provide more accurate and stable damping ratio estimates than fundamental-mode-only approaches. Sensitivity analysis confirms that higher modes carry independent information on the deeper structures. Lukas Huber has introduced a nonlinear dynamic framework to enhance the accuracy of the results of widely used resonant column tests (RCT) to obtain strain-dependent stiffness and damping. Existing and new experimental results show that the nonlinear soil behaviour is not only observable in the measurements but can also be reproduced numerically, providing a new approach for parameter estimation. This will lead to an integrated approach toward a significantly improved constitutive modelling of soil behaviour at varying strain levels, and more accurate nonlinear site response prediction.

## Data and method products 2025

An extensive experimental (RCT) dataset is generated. In addition, a new, nonlinear dynamic analysis framework for RCT is introduced. Finally, initial success is achieved with the development of a new method to derive a 1D small-strain damping factor profile by inversion of multimode Rayleigh-wave data, and with testing the sensitivity of multimodal inversion. These datasets and approaches will be useful to other DeepNL projects

where seismic ground shaking is of importance. The developed scheme for in-situ appraisal of the damping parameters will be useful in a wide variety of geotechnical and structural engineering site investigations.

## Focus for 2026

Fan Wang will work on improving the new, multimodal inversion approach to obtain reliable, small-strain damping factor profiles and small-strain stiffness profiles on realistic synthetic data and field data. In addition, he will perform field experiments in Groningen. Lukas Huber will concentrate on extending the nonlinear viscoelastic model based on MRDI curves to a model that considers plasticity and loading history. He will also conduct a field campaign collecting soil samples from Groningen and then perform lab experiments on those samples. Finally, he will perform a preliminary nonlinear site response analysis. These outcomes will directly contribute to enhancing the accuracy of the nonlinear site response analysis, which so far fails to correctly incorporate the effect of damping and stiffness at different strain levels.

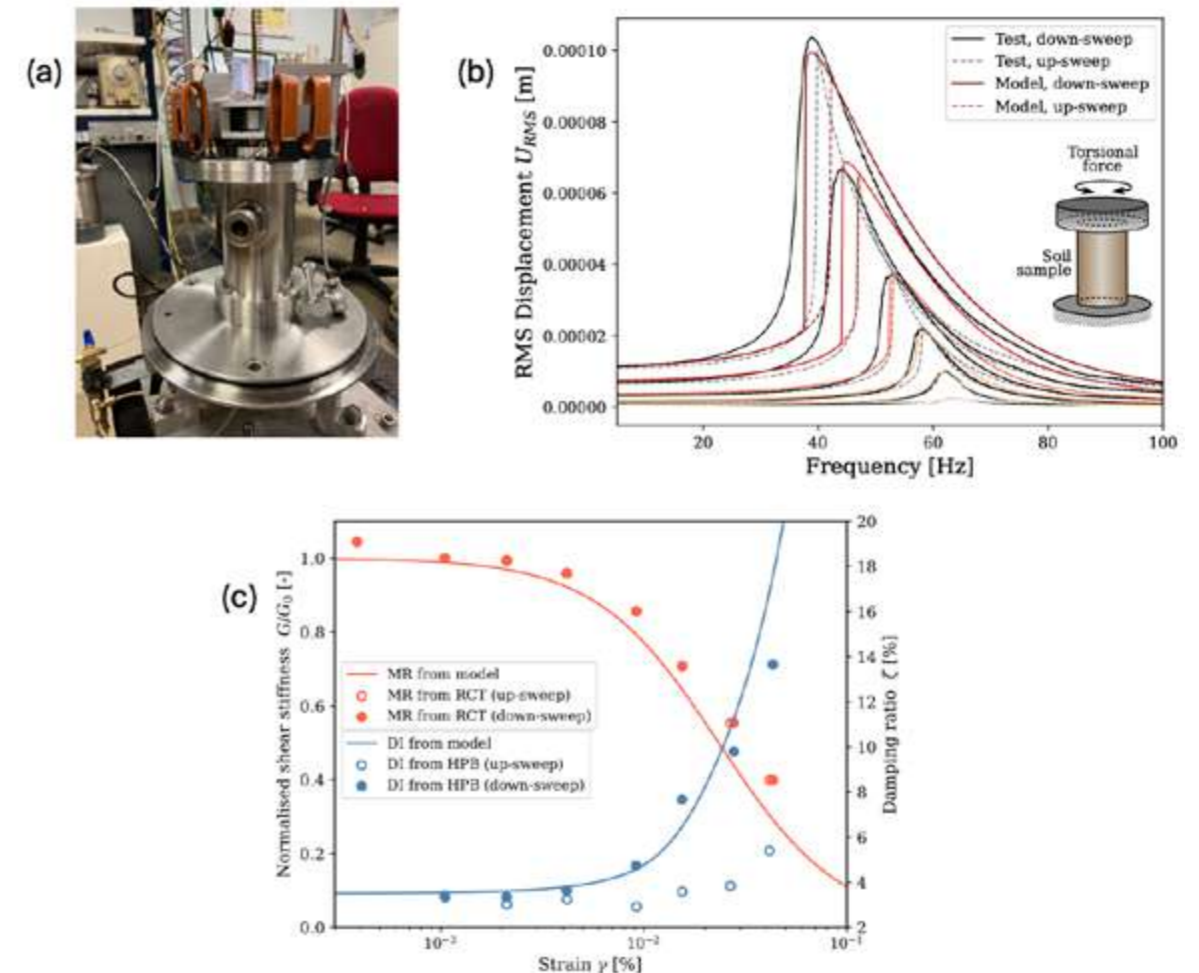
## Collaboration and integration within DeepNL

The PhD researchers in the DAMPINGSOIL project are maintaining a close contact with Eddy Revelo Obando from the 3DSOIL project, who is finishing his PhD thesis. In addition to the seismic dataset, also the CPT/SCPT dataset, the estimated stiffness variability, and the methodology from 3DSOIL will be useful in the nonlinear site response calculations in the DAMPINGSOIL project. These outcomes are directly relevant to the goal of the DeepNL programme, which is understanding the effect on the earth's surface of the anthropogenic activities in the subsurface, such as the extraction of natural gas, geothermal energy and salt, and underground storage of energy, CO<sub>2</sub>, and waste.

## Relevance for and knowledge exchange with stakeholders

Site response analyses so far mostly ignore the variability of the small-strain damping factor and the MRDI curves, because they are hard to estimate. This leads to large uncertainties in site response forecasting, and therefore, large risks. The outputs of the DAMPINGSOIL project will be directly useful to alleviate this problem. Preliminary research shows that the nonlinear damping coefficient is largely overestimated by conventional methods. Also, the stiffness is mostly overestimated, making soils appear less susceptible to amplification at lower frequencies than they are in reality. The anticipated improvements are relevant especially for Dutch soils, where very weak, soft peat and clay layers and their variability strongly determine the seismic ground motion and

structural damages at the surface. The developed approach and the obtained insights will be useful not only for earthquake site response analysis but also in other domains, for example for vibration due to moving trains, wind turbines, or large construction works. In 2025, there were significant collaborations with researchers at Turin University, Italy, resulting in extensive experiments at their laboratory. This collaboration benefits both sides, as the researchers in Turin are experienced in dynamic testing, while the research at TUD helps them improve the testing protocol. New field work and laboratory experiments will be performed in 2026 in discussion with colleagues at KNMI and TNO. These will provide vital datasets for the research of the two PhD researchers in the DAMPINGSOIL project.



(a) Resonant Column Test (RCT) experimental facility at Politecnico di Torino, used in this research. (b) Experimental data: measured frequency response curves from RCT during increasing forcing frequency (up-sweep) and decreasing forcing frequency (down-sweep), compared with the calibrated model predictions (coloured lines) for different torsional force amplitudes. (c) Continuous strain-dependent shear modulus reduction (MR) and damping ratio increase (DI) curves derived using the theoretical (modelling) framework developed in this research, compared with the equivalent-linear parameters (scatter points) obtained from RCT data and half-power bandwidth method. The experimental values are evaluated at the maximum shear strain corresponding to each applied torsional force amplitude, whereas the modelled curves represent the continuous, intrinsic strain dependency of the material response.

## Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region (SubsApp)

**Project leader:** Dr Rob Govers (UU)

**Associate project leaders:** Prof. Ramon Hanssen (TUD); Prof. Esther Stouthamer (UU); Prof. Femke Vossepoel (TUD)

**Postdoc:** t.b.d. (UU)

**PhDs:** Yuta Hiruma (UU); Lina Hagenah (TUD)

**Data analytics engineer:** t.b.d. (TUD)

**Budget:** € 1,065,252,- (Call 2b)

**Duration:** 2024 - 2028

**WP1:** Adaptation of a data-assimilation approach for spatially correlated geodetic data and develop-

ment of the InSAR Fractal Tree approach. (Hiruma)

**WP2:** Development of a surface deformation model for unsaturated soils, a mechanical model for sub-Holocene depths of the Groningen gas field, and a coupled mechanical model for subsidence driven in the Groningen gas field region. (Hagenah)

**WP3:** Data assimilation of geodetic time series and assimilation of Sentinel-1 InSAR, GPS, and levelling time series for the Groningen field. (t.b.d.)

**WP4:** Development of a computational implementation of the InSAR Fractal Tree approach. (t.b.d.)

### Research aim

To develop a data-constrained, physical model to hindcast and forecast horizontal and vertical surface deformation above the Groningen gas reservoir as a result of both deep and shallow driving mechanisms in the Groningen gas field region.

### Highlighted outcomes 2025

Yuta Hiruma collaborates with colleagues Tom de Gast and Benthe Lexmond from the NWO-LOSS project to complete a physical model called SoftSoil1D. In this model, soil compaction and swell is driven by precipitation and evaporation, and by changes in groundwater content and pore pressure. Model benchmarking and validation has been completed. The first publication is nearly completed. This describes how SoftSoil1D is used to connect observations in the Oostvaardersplassen to physical soil properties. Initial steps are underway with Ensemble Smoother Multiple Data Assimilation (ESMDA) to explore the resolvability of soil properties from twin experiments. In identical twin experiments, SoftSoil1D is used as the forward model in ESMDA, but also to generate synthetic time series for a given soil layering as the data. Lina Hagenah started working on ESMDA and on various InSAR related projects.

### Focus for 2026

After finalising the twin experiments, Yuta Hiruma will move to estimating soil parameters from time series at locations where extensometer data are available. This includes the Nieuwolda site in the Groningen gas field area. Lina Hagenah will collaborate closely with him on the next step, to use InSAR time series for the same locations in the ESMDA. Combining the ESMDA results for the extensometer with the InSAR time series will be pivotal, in the sense that the results will guide the understanding of the resolvability of soil properties from InSAR time series.

### Collaboration and integration within DeepNL

The clearest connection is with the Subsidence project lead by Ramon Hanssen, since SubsApp continues where the previous project ended. The project contributes directly to the objectives and intended outcomes of the DeepNL programme, where SubsApp specifically aims to achieve the following five-year and ten-year targets as mentioned in the call 2b description: Large-scale computational and data handling methods are in place; 3D modelling software for geomechanical behaviour; integration of programme components; integrated 'model-based feedback control approach',

based on continuous measurements and fundamental understanding of source mechanisms, to forecast subsidence; quantitative evaluation of uncertainties of all measurements, models, and control measures.

### Relevance for and knowledge exchange with stakeholders

Reservoir compaction is the principal driver of seismicity in Groningen. Consequently, mechanical model studies of dynamic rupture and observational studies of reservoir stress changes will benefit from the constraints from this study on the reservoir compaction history. In addition, identifying the value of diverse data types for accurate subsidence forecasting is anticipated to aid

in the development of datasets applicable to regions beyond Groningen. New techniques for assimilation of big data and of multiple data types developed in this project may serve as a prototype for future studies in the Netherlands where subsurface activities are, or will be, taking place. There are ongoing collaborations with the LOSS and NOBV projects that study various shallow compaction processes. A partnership is foreseen with TNO for GEOTOP model properties and Deltares for data from scientific monitoring sites. Furthermore, collaborations exist with Niko Wanders (UU), leveraging his hydrology expertise, and with Tom de Gast from Deltares. Other potential collaborations will be developed when there are pertinent results.



Photo: Lina Hagenah, TUD

Visiting the Nieuwolda extensometer sites in September 2025 for the purpose of instrument maintenance and installation of a camera to capture daily images of crop growth and farming activities. Groundwater and extensometer time series are used to model deformation. The radar transponder supports local InSAR surface displacement estimates. From left to right: Dita Lumbar Gaol, Lina Hagenah, Nicholas Hartono, Yuta Hiruma.

## SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential

**Project leader:** Prof. Michael Hicks (TUD)

**Associate project leaders:** Prof. Cristina Jommi (TUD/ Politecnico di Milano); Dr Mandy Korff (TUD/Deltares)

**Postdocs:** Dr Jose Leon Gonzalez Acosta (TUD);

Dr Divya Varkey (TUD)

**PhDs:** Hilmi Bayraktaroglu (TUD); Ching-Yu Chao (TUD)

**Budget:** € 1,042,454,- (Call 1a)

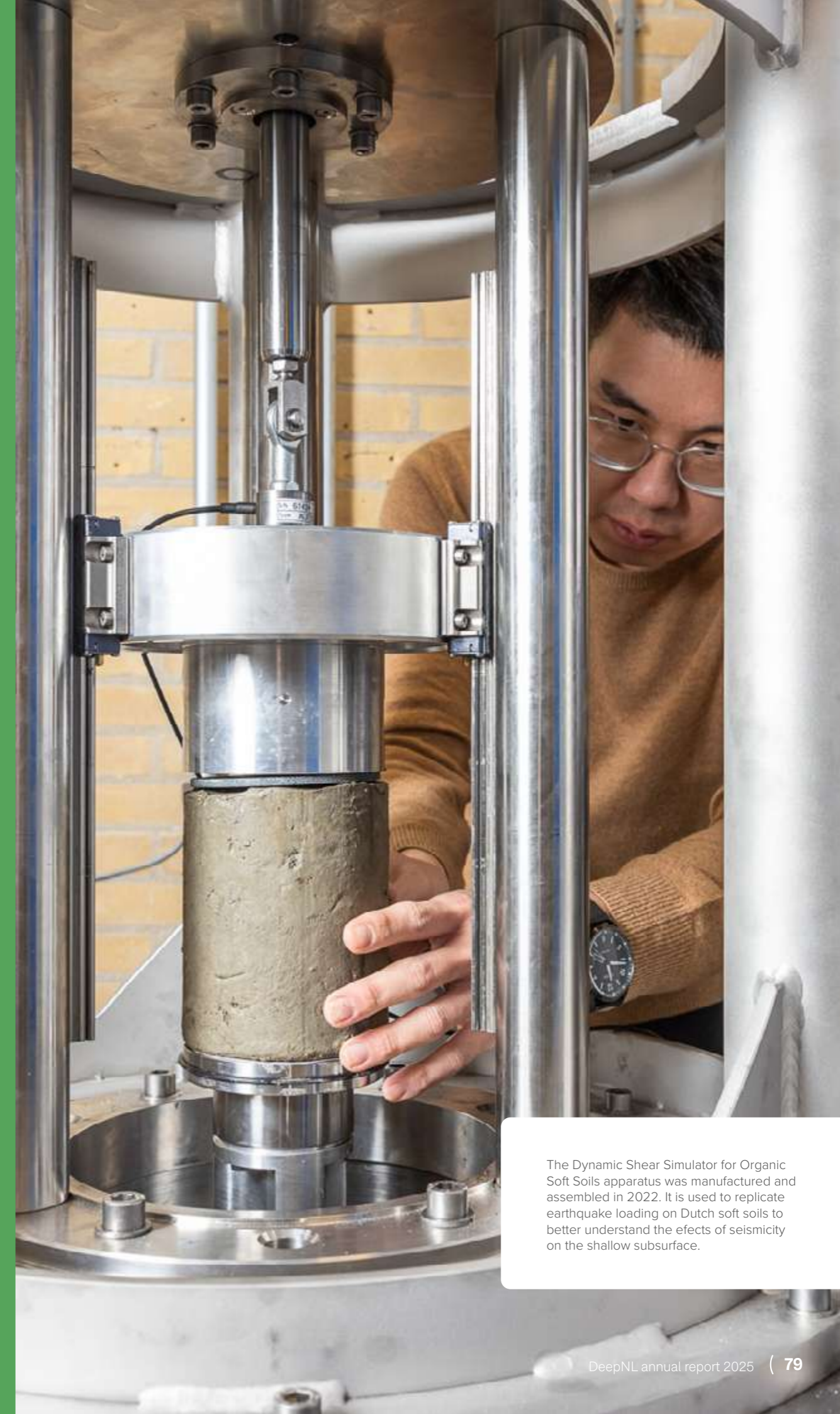
**Duration:** 2019 - 2024

### Research aim

To accurately predict ground surface motion and deformation resulting from induced seismic load at depth. The SOFTTOP project explicitly takes into account spatial variations of material characteristics in the shallow subsurface, specific characteristics of sand

and clay layers, and characteristics of induced earthquakes such as short duration repetitive loading.

**For a summary and output see:**



The Dynamic Shear Simulator for Organic Soft Soils apparatus was manufactured and assembled in 2022. It is used to replicate earthquake loading on Dutch soft soils to better understand the effects of seismicity on the shallow subsurface.

# How does the soft, top part of the subsurface impact surface motion and deformation resulting from induced earthquakes?

## OBJECTIVES

### Understand soil behaviour

To provide new insights into the physical response of typical Dutch soils under repeated short duration loading from earthquakes.

### Model the impact

To develop a numerical framework to model the impact of soil behaviour and shallow subsurface heterogeneity on the propagation of seismic waves through the soil and the resulting ground motions.

## APPROACH

### Experiments

Laboratory experiments to study and describe the behaviour of organic clays.

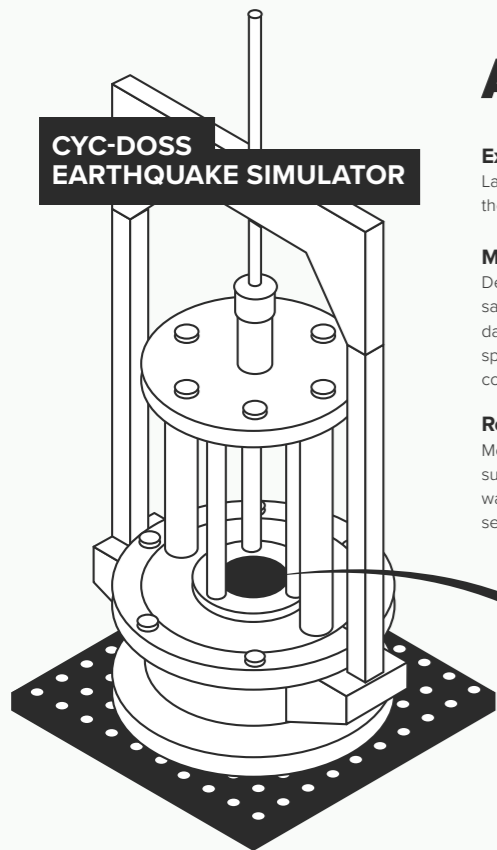
### Modelling

Developing numerical models for laminated sandy soils and organic clays from laboratory data, and developing a model that describes the spatial variability of the shallow subsurface composition.

### Response analysis

Modelling the response of the shallow subsurface to induced seismicity in terms of wave propagation, ground motion, soil settlement and liquefaction potential.

### CYC-DOSS EARTHQUAKE SIMULATOR

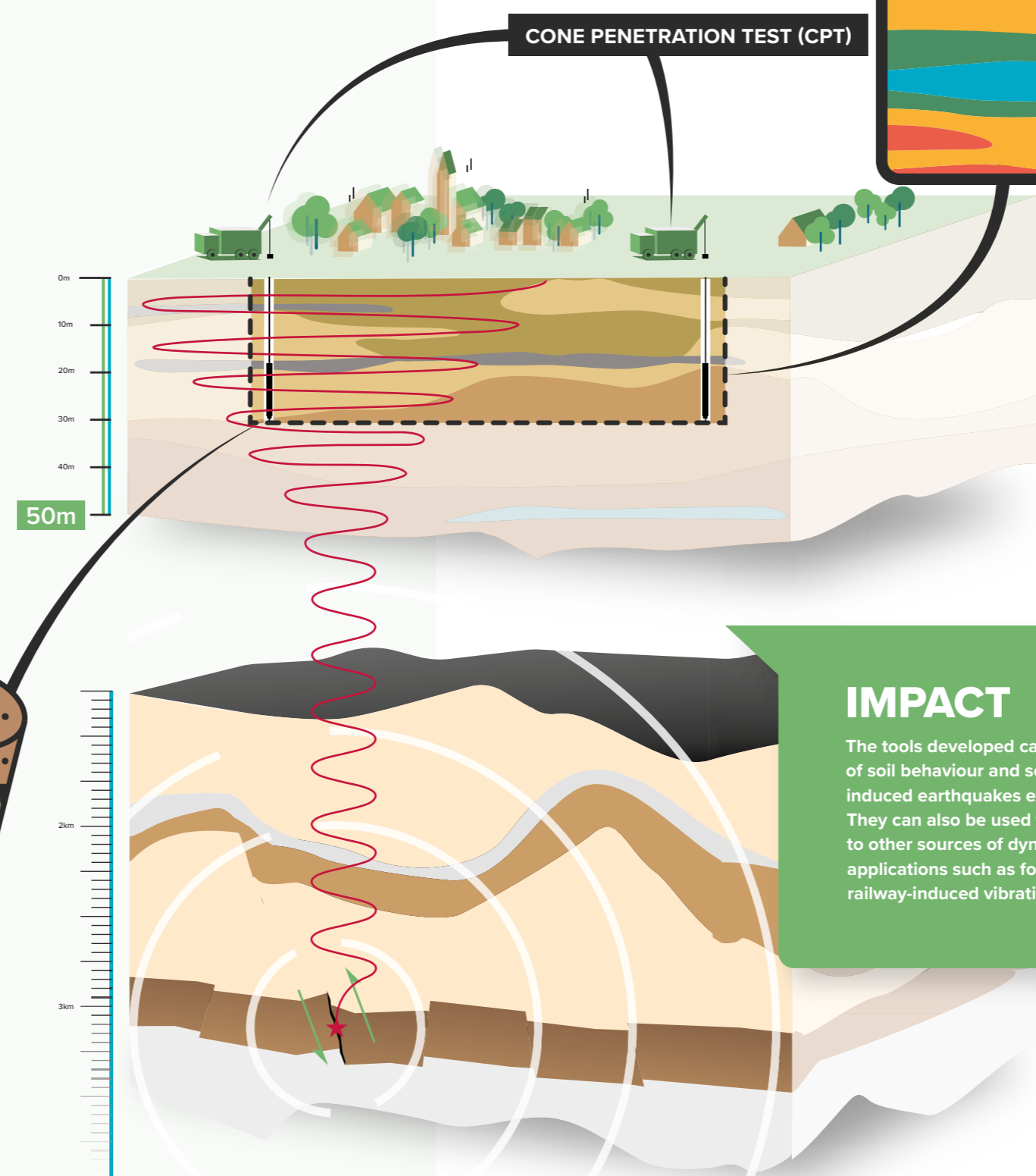


### ORGANIC CLAY SAMPLE

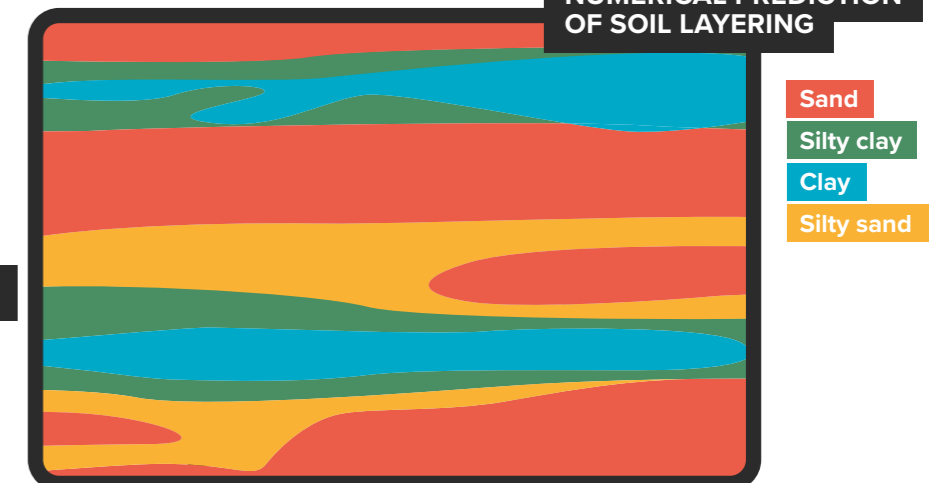


## KEY OUTCOMES

1. The constitutive model framework for laminated (anisotropic) sands is successful in capturing the wide range of direction-dependent responses under drained and undrained loading conditions.
2. Initial fabric anisotropy in the sands may cause significant variation in soil response. The relative orientation of the anisotropy with respect to the loading direction controls the behaviour.
3. New insights into the effects of loading frequency, soil composition, initial stress state, and cyclic stress amplitude on the mechanical properties and behaviour of Dutch organic clays.
4. In soft organic clays, creep behaviour plays a significant role during consolidation. This is contrary to the expected purely elastoplastic response.
5. Results of coupled numerical analyses demonstrate that 2D or 3D analyses are needed for realistic assessments of surface motion and deformation.



### NUMERICAL PREDICTION OF SOIL LAYERING



## DEVELOPED TOOLS

1. Improved constitutive soil models for laminated sands and organic clays, such as those found in Groningen.
2. A probabilistic method for characterising subsurface heterogeneity based on limited CPT-data, taking into account uncertainties and measurement errors.
3. A reliability-based numerical framework, that includes both soil heterogeneity and complex soil behaviour, to model the response of the shallow subsurface to induced seismicity.
4. The cyclic-dynamic multi-directional shear apparatus for organic soft soils (CYC-DoSS): a cutting-edge earthquake simulator for studying the response of Dutch soils to cyclic loads in various engineering applications.

## IMPACT

The tools developed can be used to investigate the effects of soil behaviour and soil heterogeneity on the impact of induced earthquakes experienced at the Earth's surface. They can also be used to assess the response of Dutch soils to other sources of dynamic loading in engineering applications such as foundations under cyclic loads and railway-induced vibrations.



More information about this project:

*SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential (Hicks et al.)*

An integrated research programme to understand subsurface dynamics caused by human activities.





## News from the DeepNL network

## Funding received by DeepNL researchers

### NWO Vidi grant for Anne Pluymakers

In her project 'The influence of fluid composition on limestone', Anne will investigate how fractures develop in rocks composed of limestone. She will experiment with different fluid compositions inside the pores of limestone samples. In addition, she will develop innovative monitoring techniques based on acoustic and electromagnetic signals and apply these to large rock samples (up to 40 centimetres). Monitoring fracture processes in large samples is challenging, as some signals tend to fade quickly. The fundamental insights gained from this research will benefit geothermal projects, among others.

### Hydrogen storage in Offshore Porous geological formations in the Netherlands (HOPE) funded by UU Faculty of Geosciences

In this project at UU, Wenzhuo Cao, Liviu Matenco and Suzanne Hangx focus on hydrogen flow and mixing dynamics, geochemical reactions, and geomechanical behaviour in fractured porous media, particularly those of potential Dutch storage reservoirs. Particular emphasis will be placed on how the coupled interactions among these processes, together with cyclic hydrogen injection and withdrawal, influence caprock integrity, fault re-activation, and fluid-rock interactions. The outcomes will support the identification of optimal storage sites and the development of safe and efficient operational strategies for hydrogen storage in porous geological formations.

### NWO Open Technology project about thermal impact on fault stability

The NWO domain Applied and Engineering Sciences has awarded Phil Vardon and his DeepNL colleagues Anne Pluymakers and Dennis Voskov a project within the Open Technology Programme. In their project 'From distress to de-stress: unravelling the thermal impact on fault stability', the researchers will look into seismic activity stemming from reservoir cooling in geothermal projects. The project will combine laboratory experiments, field monitoring and numerical modelling.

### COVRA project on containment capacity of a radioactive waste repository

The principal uncertainty regarding the containment capacity of a radioactive waste repository sited in rock salt formations lies in predicting the long term convergent creep and sealing behaviour of backfilled shafts, galleries and boreholes created in the construction of the facility. To model the closure evolution in the context of system performance, using finite element or other methods, constitutive equations describing the mechanical behaviour and evolving transport properties of crushed salt backfill are essential. This project funded by COVRA has a special focus on further improving our understanding of the microscale mechanisms of solution-precipitation transfer resulting in long-term healing and permeability reduction during late stage cavity closure and is led by Suzanne Hangx, together with Hans de Bresser and Chris Spiers.

### EU funding for quantitative strain monitoring

Auke Barnhoorn is participating in the recently funded Q-Fibre project Quantitative Strain Monitoring for Well and Seal Integrity through Wellbore Fibre Optics Cables, funded by the Clean Energy Transition Partnership. The main objective is to realise a quantitative characterisation and monitoring toolbox for CO<sub>2</sub> storage integrity by exploiting well-borne fibre optic cable data and enabling storage operators to have high confidence in managing the storage integrity.

### Project on fault-slip models funded by Ministry of Climate Policy and Green Growth

Femke Vossepoel and André Niemeijer initiated a EZK-funded project (MATURE) with TNO. The project will deliver a benchmark of existing fault-slip models and a web-based interface that allows operators and other stakeholders to access specific versions of fault-slip models developed within DeepNL and at TNO.

## NWO funding for related projects

### Two Veni grants for subsurface research

Two researchers have been awarded an NWO Veni grant for innovative studies on subsurface processes. Jing Sun (TUD) is developing a reliable, physics informed AI foundation model to better interpret geophysical data and more accurately reconstruct the structure of the subsurface. Thanushika Gunatilake (VU) will investigate how frictional heating releases trapped fluids through thermal dehydration and how this process influences the Earth's internal dynamics and improves predictions of natural and human induced seismic activity.

### Open Science NL funding for international re-use of Dutch geoscientific data (GeoFAIR)

Research on global challenges like climate adaptation or natural hazards relies on effective use of internationally available, Earth scientific data. However, data generated in the Netherlands remain difficult to find and re-use. Existing infrastructure for effective sharing and re-using data remains fragmented, and poorly known. Furthermore, several national data sources are not yet linked to international data portals of EPOS or Danubius-RI. With funding from NWO's Open Science NL, GeoFAIR will improve the impact of Dutch Earth scientific data on global research by integrating existing digital resources into a coherent Open Science infrastructure, to support Earth scientific research globally. The principle investigator is Ronald Pijenburg (UU and EPOS-NL).

## New funding opportunities

### DeepNL Top-Up Call: Opportunities for Integration and Impact

In order to increase the scientific and societal impact of DeepNL, a top-up call is published that enables DeepNL researchers to build on previous projects and take concrete steps towards integration, upscaling, application and/or outreach. This call for proposals aims to make results from DeepNL accessible and usable for professionals and other knowledge users. Researchers may apply for a small project with a maximum budget of € 50,000,- and duration of one year. With a budget of € 500,000,- NWO can fund at least ten of these small projects. Researchers are eligible to apply if they are or have been involved in an ongoing or completed DeepNL project as a (co-)project leader, postdoctoral researcher, or PhD researcher. Proposals can be submitted continuously until 22 September 2026 and will be awarded on a first-come-first served base. NWO plans to publish a similar call with a similar budget for 2027.

### New NWO programme on salt research under development

NWO will develop a Dutch Research Agenda Call in 2026 for research on safe and sustainable salt activities in the Dutch subsurface. The programme will have a budget of about 9 million euros and is initiated and co-funded by the Ministry of Climate Policy and Green Growth together with State Supervision of Mines, two provinces and four municipalities. The aim is to strengthen the knowledge base on the behaviour of rock salt and salt caverns in order to improve and validate the modelling of long-term effects in the context of mining, abandonment of caverns, underground storage of gasses and their societal embedding.

## Other news and achievements

**Sebastian Geiger** has been named new Department Chair Geoscience and Engineering at TUD, taking over from Timo Heimovaara.

**Karel van Dalen** has been elected Teacher of the Year for the TUD MSc Structural Engineering track by students. What makes Karel stand out is his ability to keep students engaged and inspired by always asking questions and sparking conversations.

**Gerdien de Vries** has been appointed full professor at TUD. Gerdien studies how human behaviour can speed up or slow down the interaction between societal and technological transitions. She also examines how policy, communication and technology can be better aligned with that behaviour.

Energi Simulation, a Calgary-based not-for-profit organisation, committed to support the Energi Simulation Centre for Geo-energy for another five years. This interdisciplinary research centre at TUD is jointly led by **Sebastian Geiger** and **Hadi Hajibeygi** and focuses on integrating geoscience and reservoir engineering research activities to accelerate the transition to a just and fair low-carbon energy future. Sebastian Geiger was also interviewed for Energi Simulation's documentary 'War on Carbon: the Battle for the Future of Our Planet'.

**Giovanni Bertotti** retired in 2025 as Professor of Applied Geology at TUD. He continues to serve as chairperson of the DeepNL programme committee.

**Martyn Drury** retired in 2025 as Professor in Structural Geology and Electron Microscopy at UU. He will phase out his activities in the DeepNL programme committee during 2026.



### Utrecht Centre for Sustainable Use of the Subsurface (UCSUS)

The Utrecht Centre for Sustainable Use of the Subsurface (UCSUS) was established in 2025 at Utrecht University to contribute to safe, responsible, and sustainable use of the subsurface, supporting the global energy transition. The centre integrates fundamental understanding of the Earth System with modelling and monitoring of subsurface processes to make evidence-based and accurate assessments of beneficial use of the subsurface, as well as potential hazards associated with these activities. Key to this is multidisciplinary collaboration among researchers and stakeholders with complementary expertise, enabling inclusive solutions to complex subsurface challenges. The centre brings together expertise from a range of Earth Sciences disciplines to conduct problem-driven fundamental research on subsurface processes including:

- The impact of subsurface activities on (bio)geochemical reactions in altering subsurface characteristics
- Quantifying risks (e.g. subsidence, earthquakes, and leakage) due to subsurface activities
- Modelling and monitoring changes due to subsurface activities

Anyone interested in collaborating can contact the coordinators (**Eldert Advokaat, Amir Raouf, Suzanne Hangx, and Ylona van Dinther**).

## News from EPOS-NL

The Delft Subsurface Urban Energy Laboratory (DSUEL) is a unique open research infrastructure for geothermal heating and monitoring that is currently being installed on TUD campus. It includes: (i) a deep geothermal doublet, (ii) a local seismic monitoring system based on three boreholes between 200 and 500 metres deep, (iii) a high temperature aquifer thermal energy storage (HT-ATES) system (to be installed in 2026) at a depth of 120-180 metres to store excess thermal energy, and (iv) a multi-use monitoring and exploration borehole (to be drilled in 2028). The research infrastructure in DSUEL is funded by three projects: EPOS-NL and EPOS-eNLarge funded by the Dutch Science Foundation (NWO), and the Horizon Europe-funded PUSH-IT project. Over the last three years several activities have been carried out around the Delft Subsurface Urban Energy Laboratory, including:

- The setup of a seismic monitoring network consisting of three permanent stations deployed in 50, 200 and 500 metres depth boreholes that have been operational since 2022, and a temporary monitoring array of 20 sensors installed in October 2025 for complementary time-lapse measurements on the surface. Seismic data from these stations is accessible via the KNMI website.
- The geothermal doublet was drilled in the second half of 2023, comprising two wells to approximately 2.1 kilometres vertical depth. It is operated by Geothermie Delft, a consortium of Gaia Energy, EBN and TUD, while Shell Geothermal left the consortium in 2025.
- A coring programme provided 15 metres of 4 inch core from the immediate caprock of the producer reservoir section in the lower Rodenrijs Claystone Member, 71 metres of 4 inch core from the uppermost of the reservoir section of the producer in the Delft Sandstone Member, and 78 sidewall cores from the injector reservoir section.
- A mud logging programme provided 2400 cuttings samples.
- A logging programme provided 3000 metres of open-hole and cased-hole logging data during drilling in 2023. Open-hole data was collected in the reservoir sections of both the producer and the injector and included three runs: gamma ray, spectral gamma ray, acoustics and resistivity, ultrasonic and resistivity images as well as neutron porosity, density and nuclear magnetic resonance. A cased hole logging programme was carried out to measure the baseline before cooling. Additional logs are available from the seismic monitoring station DAP-GEO-02.



Core description on the drill site. Core barrels were cut in 1 m segments and transported to the core storage on TUD campus.



EPOS-NL (European Plate Observing System - Netherlands) is a national project, improving the means for research into our subsurface.

- Monitoring with fibre optic cables for distributed temperature and acoustic sensing (DTS, DAS). Fibre optic cables were installed in the injector and producer well of the geothermal doublet and around the soon to be installed HT-ATES system.

In the next years, the DSUEL will be completed with the HT-ATES system and the multi-use borehole. The system will be used to store excess heat produced from the geothermal well in summer, and used in winter to meet peak demand. As for the geothermal doublet, the HT-ATES system is accompanied by an extensive monitoring system to understand the changes in the subsurface and improve models. The multi-use monitoring and exploration borehole is scheduled to be drilled around 2028. The borehole will be up to 4500 metres deep and located between the producer and injector of the geothermal doublet. The drilling will include an extensive sampling and logging programme. The focus of the borehole is to allow surface-to-borehole electromagnetic and fibre optic monitoring by installing electromagnetic sensors and a fibre optic cable on a composite casing in the geothermal reservoir and up to 3000 metres depth. These monitoring capabilities will allow for assessing how the subsurface responds to long-term cooled water injection and to understand how the cold front and reservoir pressures propagate away from the injection well.



### Sample and data access from the DSUEL

All project data from the DSUEL is compiled in the Geothermal Project on TU Delft Campus Collection. Here, the work on the initial borehole dataset from a monitoring borehole (DAP-GEO-02) and the campus geothermal wells are made publicly available. In addition, access is provided to physical samples from the geothermal project and associated monitoring stations through the TUD website.

### EPOS, EPOS-NL and EPOS-eNLarge

The European Plate Observing System (EPOS) is a multidisciplinary, distributed research infrastructure that facilitates the integrated use of data, products, and facilities from the solid Earth science community in Europe. EPOS-NL is a cluster of large-scale facilities within TUD, KNMI and UU, and was funded in 2018 through the NWO Roadmap for large-scale research infrastructure. EPOS-eNLarge builds on and expands this infrastructure and combines facilities within TUD, KNMI, UU and TNO. It was funded in 2023 and focuses on bridging scales for sustainable use of our subsurface. Anyone who wants to use EPOS-eNLarge labs free-of-charge can apply to the Facility Access Programme through [www.EPOS-NL.nl](http://www.EPOS-NL.nl).

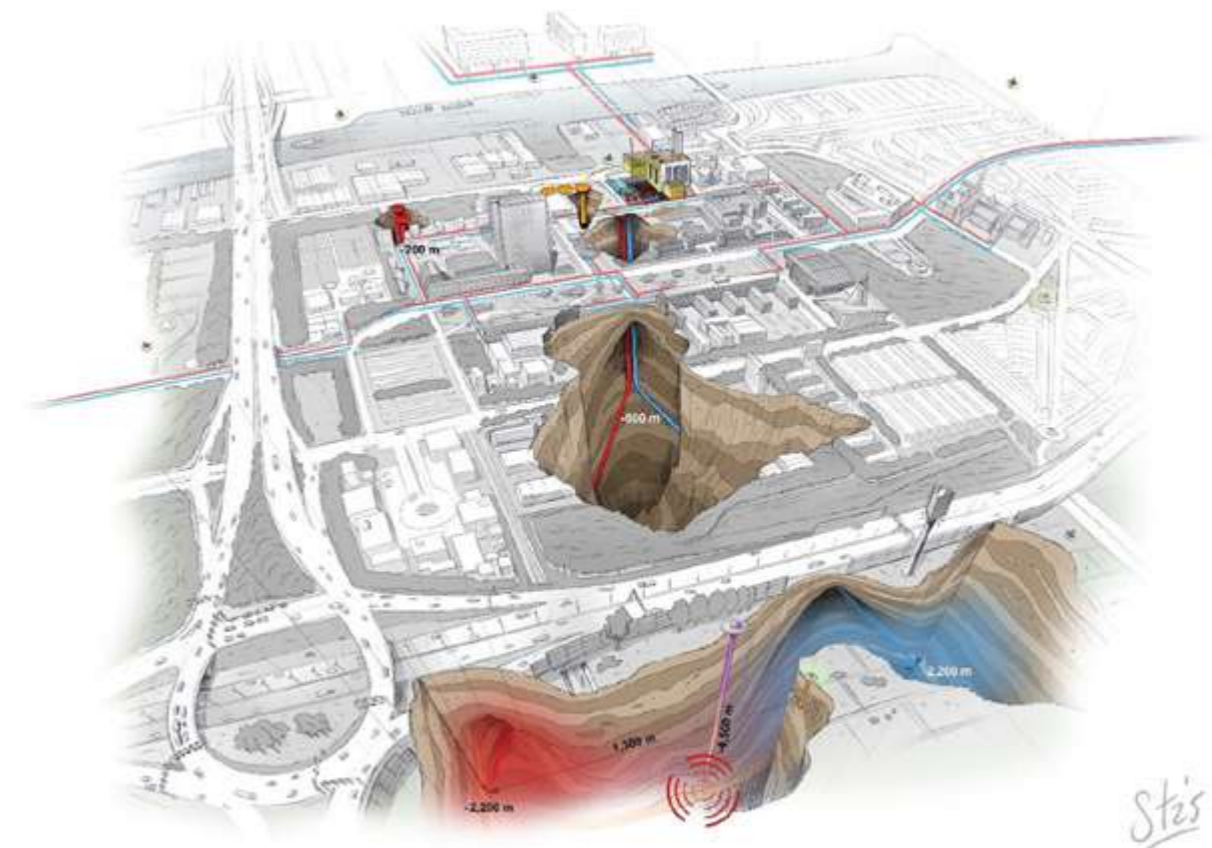
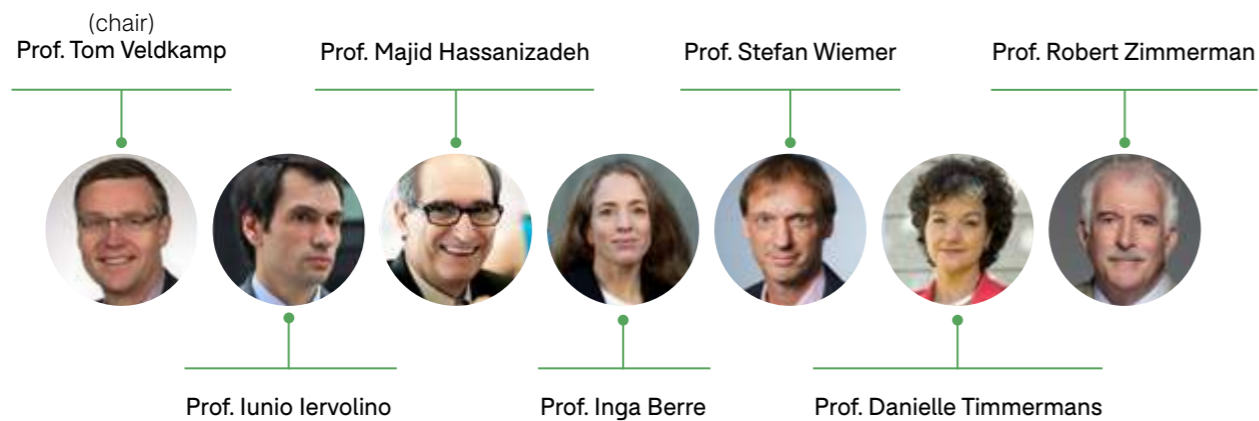


Illustration (credit: Studio Stephan Timmers) of the Delft Subsurface Urban Energy Laboratory facilities, including the gas-fired power plant, the geothermal wells, the heating grid, the subsurface energy storage (HT-ATES) system, and, in the front, the multi-use borehole between the producer and injector of the geothermal doublet. The schematic overview depicts roughly 1.5 by 1.5 km.

# News from KEM



The Knowledge Program on the Effects of Mining (KEM), initiated by The Minister of Economic Affairs (EZK) and jointly guided by the State Supervision of Mines, has been running since 2017. Its scope includes all mining activities falling under the Mining Law and focuses on induced seismicity, subsidence, fluid leakage, and abandonment effects potentially impacting people or the environment. KEM addresses specific research questions raised by public authorities or the public at large, which can be answered within one to three years by (inter)nationally leading experts or research groups. The results of the applied research projects contribute to enhancing the capabilities and instrumentation of mining hazard and risk assessment in the Netherlands.



## KEM activities in 2025

As in previous years, the KEM scientific expert panel, chaired by Prof. Tom Veldkamp, has assured the quality of the KEM research by aligning research questions and coaching and evaluating KEM research projects (see status of KEM projects). The scientific expert panel for questions and projects on societal effects of mining, the SEM-panel, has started in 2025. The SEM-panel consists of KEM-panel member Prof. Danielle Timmermans (chair), Dirk Postma and Michel Duckkers. The SEM-panel produced a SEM strategy document as a framework for future SEM research. The KEM scientific expert subpanel for advising the Ministry and State Supervision of Mines on the development and consolidation the public SHRA Groningen at TNO, has given an advice in February 2025.

## KEM priorities and synergy with DeepNL

KEM uses a dashboard for strategic steering, in 2024 based on a combination of knowledge gaps identified by scientists, and priorities formulated by various governmental authorities and bodies based on their urgency and societal relevance. It is has been reassessed in 2025, leading to research priorities for coming years.

The priorities are shifting from effects of Groningen gas and small gas fields production towards salt cavern abandonment and hydrogen storage in salt caverns. Also effects of geothermal energy systems and CO<sub>2</sub> storage have priority. Improving mining risk management protocols, hazard and risk assessment instruments and traffic light systems remain a priority.

Many DeepNL and KEM projects are jointly addressing knowledge gaps in various fields in the dashboard. KEM, together with DeepNL, is actively contributing to a national research agenda along the lines of the dashboard with the aim to provide society with a solid knowledge base for a responsible use of the subsurface. The GeokennisNL initiative and ambitions are expected to be instrumental in funding research and strengthening collaboration in academic research into mining effects at universities (such as DeepNL) and public applied research (such as KEM or at TNO, KNMI or Deltares).

**Prof. Tom Veldkamp**  
Chair of the Scientific Expert Panel of KEM

Mining activity versus H&R type		Seismic hazards and risks	Subsidence hazards and risks	Environmental hazards and risks
Oil and gas reservoir production	Groningen	3,00	3,10	2,10
	Small gas fields	3,00	3,30	2,60
	Oil fields	1,10	1,00	1,70
Underground storage in porous reservoirs	Methane cyclic storage	2,60	2,60	2,80
	Hydrogen cyclic storage	3,00	2,70	2,70
	Production water injection	1,20	1,10	2,50
	CO <sub>2</sub> storage	2,60	1,10	2,90
Geothermal reservoir energy production	Conventional doublet systems	3,10	1,60	2,90
	Enhanced Geoth. Systems (EGS)	2,60	1,10	2,20
Salt cavern development and production	Shallow caverns (<750m)	1,50	2,80	2,60
	Deep Caverns (>750m)	2,50	3,70	3,40
Underground storage in caverns	Methane cyclic storage	1,50	1,90	1,60
	Oil strategic storage	1,00	1,10	1,50
	Hydrogen cyclic storage	3,10	3,30	3,00
	Nitrogen cyclic storage	2,00	2,10	1,60
	Compressed Air	1,50	1,70	1,00
Mining infrastructures	Wells	1,50	1,00	3,60
	Installations	1,00	1,60	2,70
	Pipelines	1,00	1,10	2,29
Coal mining domains and infrastructure	Limburg	2,80	2,90	2,60

H&R measures vs H&R type	Seismic risks	Subsidence risks	Environmental risks
Public HRA instruments	3,5	3,4	3
Public monitoring systems	3,6	3,6	2,7
Public norms, TL systems and mitigating actions	3,6	3,6	3,2
Legend	3 = high	2 = medium	1 = low

## Status of KEM projects

### Finished in 2025/early 2026

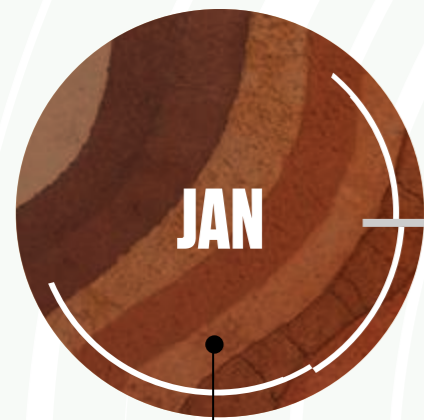
- Groningen post-abandonment effects, southwestern aquifer (KEM-19b)
- H<sub>2</sub> subsurface storage in conglomerates of salt caverns (KEM-28)
- Modelling impact of subsurface heterogeneities on subsidence variability above a gas fields (KEM-47)
- Cumulative effects of mining in the Grijpskerk area (KEM-48)

### Ongoing in 2026

- Cavern collapse and possible sinkhole development (KEM-26)
- Localised subsidence: a potential source for building damage (KEM-44)
- Salt cavern controlled bleed-off behaviour and risks (KEM-45)
- Subsidence in the Twente area measured by satellites and coupling with salt caverns (KEM-49)
- Hazards of use of multiple reservoirs in geothermal operations (KEM-52)
- Constraining-the-maximum-magnitude-for small-gas fields (KEM-56)

Results of all KEM projects (and KEM strategy 2023-2027) are or will be published on [www.kemprogramma.nl](http://www.kemprogramma.nl).

# Looking ahead to 2026



JAN

## 6 January

**Publication DeepNL Top-Up Call**  
DeepNL researchers can submit applications for small projects that build on previous DeepNL projects. Proposals should take concrete steps towards integration, upscaling, application and/or outreach, to increase the scientific and societal impact of the programme. Applications are processed on a first-come-first-served basis and can be submitted until 22 September 2026.



MARCH

## 4 - 5 March

**Structures of Strength (SoS) Days on Sustainability, Utrecht**



APRIL

## 9 - 10 April

**NWO NAC in Noordwijkerhout**  
The annual conference for researchers across the Earth and Environmental Sciences in the Netherlands.

## 16 April

**DeepNL Stakeholder Meeting in Utrecht**  
This annual meeting is aimed at researchers and professionals from the public and private sector who are interested in subsurface dynamics caused by human activities. The aim is to provide a networking occasion and a platform for knowledge dissemination and discussions.



MAY

## 3 - 8 May

**EGU General Assembly in Vienna, Austria**  
Jesse Steinvooort will co-organise a session on 'Geo-modelling for the future: Unlocking the subsurface for the energy transition' and Rob Govers will co-organise a session on 'Observing and Understanding Continental Deformation and Seismic Strain Accumulation'.

## 18 - 23 May

**InterPore in Nantes, France**

## 24 - 28 May

**International Conference on Advanced Geographic Information Systems, Applications, and Services (GEOProcessing), Venice, Italy**



JUNE

## 8 - 11 June

**EAGE Annual Conference and Exhibition, Aberdeen, United Kingdom**

## 23 - 25 June

**SPE Europe Energy Conference and Exhibition in Istanbul, Türkiye**



**AUG**

**24 - 26 August**  
International Conference on Advances and Innovations in Soft Soil Engineering (ISSMGE) at TUD



**SEP**

**6 - 11 September**  
General Assembly of the European Seismological Commission (ESC) in Istanbul, Türkiye

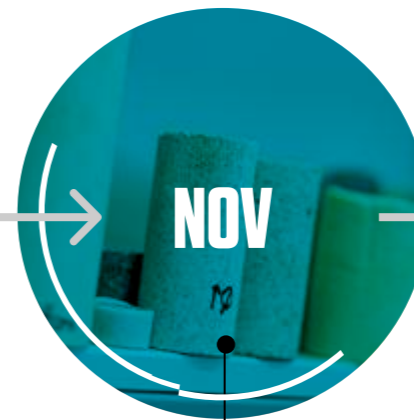
**8 - 11 September**  
European Conference on the Mathematics of Geological Reservoirs (ECMOR) in Porto, Portugal

**27 September - 1 October**  
International Conference on Structural Dynamics (EURODYN) in Hannover, Germany



**OCT**

**30 October - 6 November**  
XV International Association for Engineering Geology and the Environment (IAEG) at TUD



**NOV**

**2 - 6 November**  
EAGE Global Energy Transition Conference and Exhibition in Hannover, Germany

**November**  
DeepNL Scientific Meeting  
This meeting brings together all DeepNL research projects and provides an opportunity for researchers to discuss progress and results and strengthen the coherence of the programme.

**30 November - 2 December**  
17th International Symposium on Wettability and Porous Media and 7th InterPore BeNeLux Meeting, Amsterdam



**DEC**

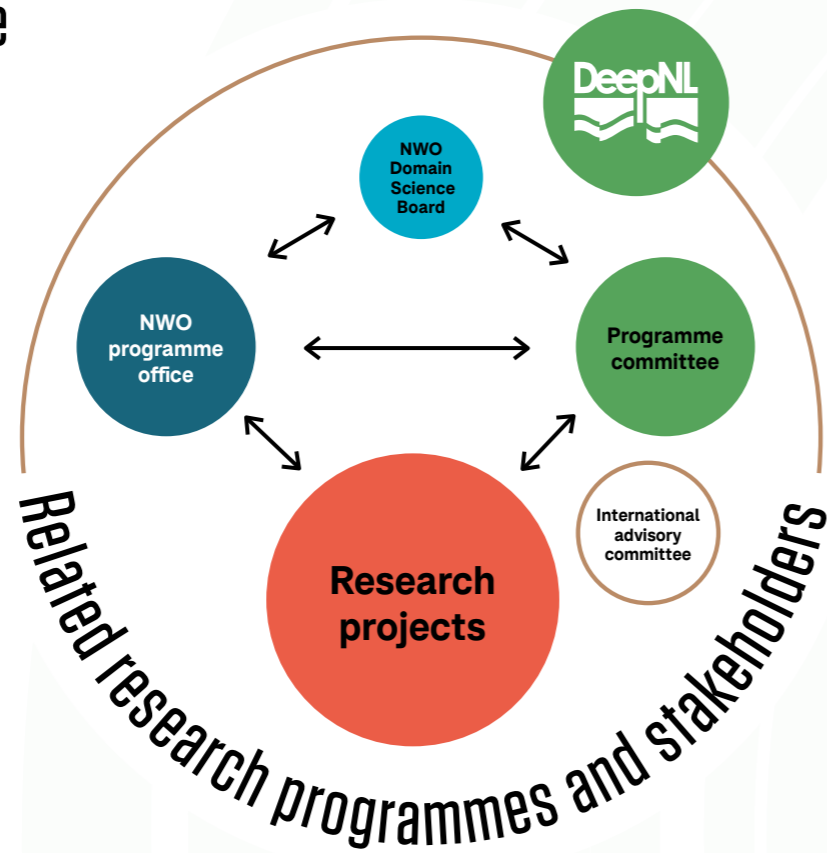
**7 - 11 December**  
American Geophysical Union (AGU) in San Francisco, United States



## Organisation of the DeepNL programme

# Organisation structure

Within the Dutch Research Council (NWO) the DeepNL programme falls under the responsibility of the Domain Science. The NWO Domain Science Board decides on the procedure and publication of funding rounds, the granting of research proposals, and the appointment of committee members. DeepNL research projects have been funded through consecutive calls for proposals. The research itself takes place at Dutch knowledge institutions. Interaction with related research programmes and stakeholders takes place at various levels.








## DeepNL programme committee

The programme committee is the driving force in realising the overarching objectives of DeepNL and advises NWO on the implementation of the programme. It monitors the coherency and progress of the research, initiates activities that facilitate this coherency, and encourages the sharing of knowledge with stakeholders and the public. The programme committee advises on the design and scope of the different calls for proposals and the implementation of the reserved funds for opportunities and programme activities.

In 2025, the programme committee convened in three dedicated meetings. They discussed topics such as the progress of the research projects, implementation of recommendations of the International Advisory Committee (IAC), contours of the Top-up Call for Opportunities, planning of events and the position of DeepNL in a broader national subsurface research landscape.

-  em. Prof. Giovanni Bertotti (chair)  
TU Delft
-  Prof. Arwen Deuss  
Utrecht University
-  em. Prof. Martyn Drury  
Utrecht University
-  Prof. David Smeulders  
Eindhoven University of Technology
-  Dr Hanneke Verweij  
Formerly TNO

## Young DeepNL Committee





-  Mike Sep  
Utrecht University
-  Jesse Steinvoot  
TU Delft
-  Ailsa Tucker  
University of Groningen
-  Mhina de Vos  
Utrecht University
-  Fan Wang  
TU Delft

## International Advisory Committee

The IAC has the overall task to monitor and evaluate the progress and impact of the DeepNL programme from an independent and international state-of-the-art perspective. They provide recommendations to the research projects, programme committee and board of the NWO Science Domain for the duration of the DeepNL programme.

- Prof. Torsten Dahm**  
GFZ German Research Centre for Geosciences  
Potsdam
- Prof. Saskia Goes (chair)**  
Imperial College London
- Prof. Francesca Verga**  
Politecnico di Torino
- Prof. Robert Zimmerman**  
Imperial College London

## NWO programme office

-  Dr Niels van den Berg  
Coordinator
-  Dr Linda Jongbloed  
Programme officer
-  Ajita Ramautar  
Programme officer
-  Maxime de Jong  
Communication advisor

## Young DeepNL

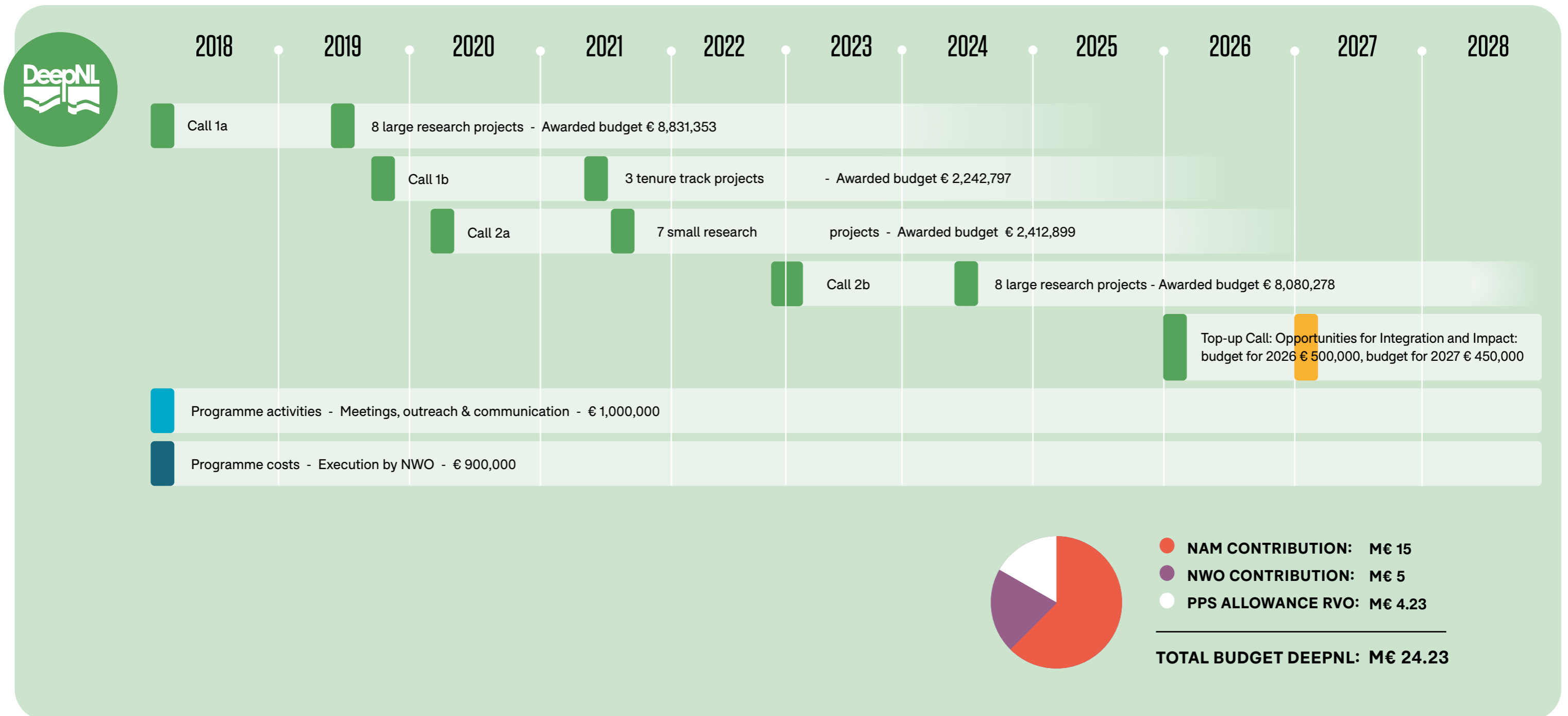
The Young DeepNL Committee is composed by several early-career researchers. Together with the NWO programme office they initiate and organise social and scientific activities. The aim of the activities is to strengthen the bond between the early-career researchers to create a long-lasting network, stimulate collaborations, deepen knowledge and broaden perspectives. The Young DeepNL Committee is renewed in 2025 and has organised the speed date session during the DeepNL Scientific Meeting, and a visit to the Rijswijk Centre for Sustainable Geo-energy. Currently, the committee is organising an excursion to visit outcrops in the UK that are analogues for lithologies in the Dutch subsurface.

## NWO programme office

The NWO programme office executes the practical realisation of DeepNL activities and funding rounds. It acts as a point of contact for DeepNL researchers, committees and stakeholders. The programme office supports the activities initiated within the network and facilitates the overall communication and outreach.

# Financial framework

The DeepNL budget is divided over four sequential calls for proposals through which the majority of the budget has been committed to research projects. In addition there is an earmarked budget of ~950 k€ for opportunities (small projects for integration and application) and a dedicated budget for programme activities and communication. The overall financial framework for DeepNL was originally based on a budget of 20 M€, of which the NAM contributed 15 M€ and NWO 5 M€. In addition, the programme received a budget of 4.23 M€ from the Netherlands Enterprise Agency (RVO) through an allowance scheme for public private partnerships ('PPS-toeslag'). This results in a total DeepNL budget of 24.23 M€.



# DeepNL research community



## Dr Hemmo Abels

TU Delft

Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.



## Dr Atiyeh Adelinia

University of Twente

Postdoc:  $\mu$ FAULT - scaling friction from micro-contacts to faults at the reservoir scale.



## Dr Juan Carlos Afonso

University of Tasmania (formerly University of Twente)

Associate project leader: INTEGRATION: Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions.



## Syukri Ainun Alfath

Twente University

PhD: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity.



## Dr Stephen Akinremi

University of Twente

PhD: Deep, deeper, deepestNL; Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM).

Postdoc: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach



## Job Arts

Utrecht University

PhD: Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field.



## Mahsa Ashraf Navir

Twente University

PhD: INTEGRATION: Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions.



## Dr Auke Barnhoorn

TU Delft

Project leader: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Associate project leader: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.



## Naud de Boeij

Eindhoven University of Technology

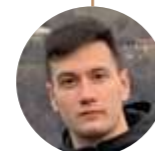
PhD: A digital twin for modelling and forecasting induced seismicity.



## Wietske Brouwer

TU Delft

PhD: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.



## Dmitry Bublik

University of Groningen

PhD: The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs.



## Dr Loes Buijze

(TNO / UU)

Associate project leader: PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling.



## Dr Hongyang Cheng

University of Twente

Associate project leader: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity.



## Dr Aad Correljé

TU Delft

Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.



## Dr Karel van Dalen

TU Delft

Associate project leader: DAMPINGSOIL: Providing the missing information of elastic damping ratio and strain-dependent modulus and damping curves for reliable, local site response analysis.



## Dr Alexandros Daniilidis

TU Delft

Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.



## Dr Ylona van Dinther

Utrecht University

Project leader: PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling.

Associate project leader: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence.

Associate project leader: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient natUre of iNdUced Seismicity.



## Prof. Martyn Drury

Utrecht University

Associate project leader: Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field.

Associate project leader: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.



## Lada Dvornik

TU Delft

PhD: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient natUre of iNdUced Seismicity.



## Jordan van Ekelburg

University of Groningen / TU Delft

PhD: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient natUre of iNdUced Seismicity.



## Rens Elbertsen

Utrecht University

PhD: LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data.



## Dr Islam Fadel

University of Twente

Project leader: Deep, deeper, deepestNL; Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM).

Associate project leader: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.

Associate project leader: INTEGRATION: Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions.



### Dr Ranajit Ghose

TU Delft

Project leader: 3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis.

Project leader: DAMPINGSOIL: Providing the missing information of elastic damping ratio and strain-dependent modulus and damping curves for reliable, local site response analysis.

Associate project leader: DeepImage: Multiscale geophysical imaging, monitoring and forecasting of induced seismicity.



### Dr Rob Govers

Utrecht University

Project leader: Quantitative constraints on pre-production reservoir stresses in Groningen.

Project leader: Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region.

Associate project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.



### Renato Gutierrez Escobar

Utrecht University

PhD: Quantitative constraints on pre-production reservoir stresses in Groningen.



### Dr Suzanne Hangx

Utrecht University

Project leader: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.

Project leader: Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoirs.

Associate project leader: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Associate project leader: INTEGRATION: Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions.



### Prof. Ramon Hanssen

TU Delft

Project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Associate project leader: Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region.



### Vincent van der Heiden

Utrecht University

PhD: PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling.



### Prof. Michael Hicks

TU Delft

Project leader: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.

Associate project leader: 3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis.



### Dr Chien-Cheng Hung

Utrecht University

PhD: Probing the micromechanics of small magnitude earthquake slip.

Postdoc: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity.



### em. Prof. Jan Dirk Jansen

TU Delft

Project leader: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Associate project leader: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient nature of induced Seismicity.



### Malek Jaran

University of Twente

PhD:  $\mu$ FAULT - scaling friction from micro-contacts to faults at the reservoir scale.



### Dr Mark Jefferd

Utrecht University

Postdoc: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Postdoc: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.

Postdoc: INTEGRATION: Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions.



### Lina Hagenah

TU Delft

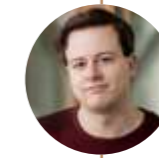
PhD: Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region.



### Yuta Hiruma

Utrecht University

PhD: Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region.



### Maarten Hodzelmans

Eindhoven University of Technology

PhD: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.



### Mohammad Hossein Khoeini

Eindhoven University of Technology

PhD: Making digital rocks a practical reality for energy storage within subsurface reservoirs.



### Lukas Huber

TU Delft

PhD: DAMPINGSOIL: Providing the missing information of elastic damping ratio and strain-dependent modulus and damping curves for reliable, local site response analysis.



### Tarlan Khoveiledy

Twente University

PhD: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.



### Janneke de Laat

University of Twente

Postdoc: INTEGRATION: Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions.



**Dr Meng Li**

Utrecht University  
(Moved to Stanford University)

PhD & Postdoc: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence.



**Dr Chong Liu**

Utrecht University

Postdoc: LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data



**Zach McBrearty**

Utrecht University

PhD: A digital twin for modelling and forecasting induced seismicity.



**Prof. Mark van der Meijde**

University of Twente

Project leader: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.

Associate project leader: Deep, deeper, deepestNL; Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM).

Associate project leader: INTEGRATION: Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions.



**Dr Johannes Miodic**

University of Groningen

Project leader: The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs.

Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.



**Dr Tanmaya Mishra**

University of Twente

Project leader:  $\mu$ FAULT - scaling friction from micro-contacts to faults at the reservoir scale.

Associate project leader: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity.



**Sebastian Mulder**

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PhD: The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs.



**Dr Rafael Nazareth Lopez**

University of Twente

Postdoc: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity.



**Dr André Niemeijer**

Utrecht University

Project leader: Probing the micromechanics of small magnitude earthquake slip.

Project leader: LabQuakeAI- AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data.

Project leader: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity.

Associate project leader: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence.



**Dr Ivan Pires de Vasconcelos**

Utrecht University/ Shearwater

Associate project leader: LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data.



**Dr Anne Pluymakers**

TU Delft

Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.



**Dr Joris Remmers**

Eindhoven University of Technology

Associate project leader: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.



**Eddy Revelo Obando**

TU Delft

PhD: 3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis.



**Dr David Rieder**

Eindhoven University of Technology

Postdoc: Making digital rocks a practical reality for energy storage within subsurface reservoirs.



**Dr Bart Root**

TU Delft

Associate project leader: INTEGRATION: Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions.



**Dr Maja Rücker**

Eindhoven University of Technology

Project leader: Making digital rocks a practical reality for energy storage within subsurface reservoirs.



**Dr Helena Schmidt**

TU Delft

Postdoc: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications



**Mike Sep**

Utrecht University

PhD: Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoirs.



**Dr Chengshun Shang**

Utrecht University

Postdoc: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity



**Prof. David Smeulders**

Eindhoven University of Technology

Associate project leader: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.



**Jesse Steinvooort**

TU Delft

PhD: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.



**Prof. Esther Stouthamer**

Utrecht University

Associate project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Associate project leader: Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region.



**Prof. Federico Toschi**

Eindhoven University of Technology

Associate project leader: A digital twin for modelling and forecasting induced seismicity.



**Prof. Jeannot Trampert**  
Utrecht University

Project leader: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Project leader: A digital twin for modelling and forecasting induced seismicity.



**Ailsa Tucker**  
University of Groningen

PhD: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenergy applications.



**Dr Clemens Verhoosel**  
Eindhoven University of Technology

Associate project leader: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.



**Mhina de Vos**  
Utrecht University

PhD: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient natUre of iNdUced Seismicity



**Prof. Femke Vossepoel**  
TU Delft

Project leader: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence.

Project leader: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient natUre of iNdUced Seismicity.

Associate project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.



**Prof. Gerdien de Vries**  
TU Delft

Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenergy applications.



**Dr Henk van Waarde**  
University of Groningen

Associate project leader: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient natUre of iNdUced Seismicity.



**Fan Wang**  
TU Delft

PhD: DAMPINGSOIL: Providing the missing information of elastic damping ratio and strain-dependent modulus and damping curves for reliable, local site response analysis.



**Dr Kees Weemstra**  
KNMI (formerly TU Delft)

Associate project leader: DeepImage: Multiscale geophysical imaging, monitoring and forecasting of induced seismicity.

Associate project leader: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.



**Prof. Jan-Diederik van Wees**  
Utrecht University/TNO

Associate project leader: PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, datadriven modeling.

Associate project leader: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient natUre of iNdUced Seismicity.



**Gijs Wensink**  
Eindhoven University of Technology

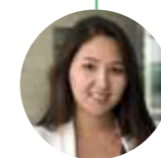
PhD: Making digital rocks a practical reality for energy storage within subsurface reservoirs.



**Dr Ernst Willingshofer**  
Utrecht University

Project leader: Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field.

## Former DeepNL researchers



**Dr Zhuldyzay Baki**  
University of Twente  
(Moved to Halyk Bank, Kazakhstan)

PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**Hilmi Bayraktaroglu**  
TU Delft (Moved to PLAXIS Geotechnical Analysis, Netherlands)

PhD: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.



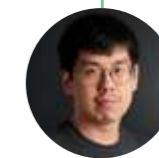
**Marc Bruna**  
TU Delft (Moved to Sweco, Netherlands)

Other staff: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.



**Dr Adam Candy**  
Utrecht University

Postdoc: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations



**Dr Ching-Yu Chao**  
TU Delft

PhD: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.



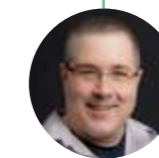
**Dr Jianye Chen**  
Utrecht University / TU Delft  
(Moved to CEA, China)

Postdoc: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.



**Dr Pavan Cornelissen**  
TU Delft  
(Moved to WUR, Netherlands)

Postdoc: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.



**Thomas Cullison**  
Utrecht University  
(Moved to MIT, United States)

PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**Dr Mark Dekkers**  
Utrecht University

Associate project leader: Probing the micromechanics of small magnitude earthquake slip.



**Dr Hamed Ali Diab-Montero**

TU Delft  
(Moved to TNO, Netherlands)

PhD: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence



**Dr Deyan Draganov**

TU Delft

Associate project leader: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.



**Dr Eldert Fokker**

Utrecht University  
(Moved to TNO, Netherlands)

PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**Dr Qiang Fu**

Utrecht University

Postdoc: Probing the micromechanics of small magnitude earthquake slip.



**Dr José León González Acosta**

TU Delft  
(Moved to TNO, Netherlands)

Postdoc: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.



**Dr Mohsen Goudarzi**

Utrecht University  
(Moved to DIANA FEA, Netherlands)

Postdoc: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence.



**Dr Annika Greve**

Utrecht University  
(Moved to Beca, New Zealand)

Postdoc: Probing the micromechanics of small magnitude earthquake slip.



**Prof. Hadi Hajibeygi**

TU Delft

Associate project leader: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.



**Dr Rhys Hawkins**

Utrecht University  
(Moved to ANU, Australia)

Postdoc: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**Chayenne van Woerden - Janssen**

Utrecht University  
(Hoogheemraadschap De Stichtse Rijnlanden, Netherlands)

Postdoc: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**Prof. Cristina Jommi**

TU Delft/Politecnico di Milano

Associate project leader: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.



**Dr Janneke de Jong**

Utrecht University  
(Moved to Ministry of Economic Affairs, Netherlands)

PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**Muhammad Hamza Khalid**

University of Twente

PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**Dr Samantha Kim**

TU Delft  
(Moved to TNO, Netherlands)

PhD: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.



**Dr Helen King**

Utrecht University  
(Moved to Universität Bremen, Germany)

Associate project leader: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.



**Dr Mandy Korff**

TU Delft/Deltares

Associate project leader: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.



**Prof. Marie-Colette van Lieshout**

University of Twente/CWI

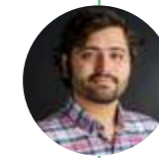
Associate project leader: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**Dr La Ode Marzujriban Masfara**

TU Delft  
(Moved to Viridien, France)

PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.



**Dr Mohammad Hadi Mehranpour**

Utrecht University  
(Moved to Baker and Hughes, Netherlands)

Postdoc: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.

Postdoc: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.



**Dr Marcel Mizera**

Utrecht University  
(Moved to Victoria University of Wellington, New Zealand)

Postdoc: Probing the micromechanics of small magnitude earthquake slip.



**Dr Milad Naderloo**

TU Delft

PhD: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.



**Dr Aleksei Novikov**

TU Delft

PhD: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.



**Dr Hanneke Paulssen**

Utrecht University

Associate project leader: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**Dr Oliver Plümper**

Utrecht University  
(Moved to Universität Bremen, Germany)

Associate project leader: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.



**Dr Jingming Ruan**

TU Delft  
(Moved to DIANA FEA, Netherlands)

PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.



**Dr Takahiro Shinohara**

Utrecht University  
(Moved to TU Delft, Netherlands)

PhD: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.



**Dr Faezeh Shirmohammadi**

TU Delft

PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.



**Dr Sara Shokrollahzadeh Behbahani**

TU Delft  
(Moved to Shell, Netherlands)

PhD: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.



**Dr Kathrin Smetana**

Stevens Institute of Technology  
(formerly UT)

Associate project leader: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.



**em. Prof. Chris Spiers**

Utrecht University

Associate project leader: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.



**Floris Teuling**

Utrecht University  
(Moved to WUR, Netherlands)

PhD: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.



**Dr Cedric Thieulot**

Utrecht University

Associate project leader: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.



**Dr Divya Varkey**

TU Delft  
(Moved to Royal HaskoningDHV, Netherlands)

Postdoc: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.



**Dr Aukje Veltmeijer**

TU Delft  
(Moved to SLB, Netherlands)

PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.



**Hannah Vogel**

Utrecht University

Other staff: A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction.



**Dr Michael Volk**

Utrecht University  
(Moved to ZEISS, Germany)

Postdoc: Probing the micromechanics of small magnitude earthquake slip.



**Dr Denis Voskov**

TU Delft

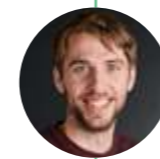
Associate project leader: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.



**em. Prof. Kees Wapenaar**

TU Delft

Associate project leader: DeepImage: Multiscale geophysical imaging, monitoring and forecasting of induced seismicity.



**Marius Wouters**

Utrecht University  
(Moved to SodM, Netherlands)

PhD: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

# Appendix 1: Research output 2025



## CLUSTER 1

### Analysis of processes and conditions that lead to seismicity and subsidence

#### Probing the micromechanics of small magnitude earthquake slip (Niemeijer et al.)

##### Scientific publications

- Hung, C.C., Niemeijer, A.R., Aretusini, S., Spagnuolo, E., Chen, J., and Hamers, M. (2025). Dynamic weakening in sandstone-derived fault gouges during simulated small-magnitude earthquakes under variable loading and environmental conditions. *Geophysical Journal International*, 241, <https://doi.org/10.1093/gji/ggaf077>
  - Hung, C.C., and Niemeijer, A.R. (2025). High-speed infrared thermography for measuring flash temperatures in sheared fault gouge analogues. *Geoscientific Instrumentation, Methods and Data Systems* 14, <https://doi.org/10.5194/gi-14-513-2025>
  - Hung, C.C., and Niemeijer, A.R. (in revision GRL), Effects of Pore Fluid Properties on Dynamic Slip in Sandstone-Derived Fault Gouges from the Groningen Gas Reservoir
  - Fu, Q., Dekkers, M.J., Spassov, S., Gurer, D., Volk, M., Hung, C.C., Arts, J., Niemeijer A.R. (draft for GRL). Fluid-induced magnetic enhancement in friction experiments: reconsidering coseismic fault temperature constraints
- ##### Presentations

- Hung, C.C., Niemeijer, A.R., Effects of Pore Fluid Properties on Fault Weakening and THM Processes in The Groningen Gas Reservoir. Poster presentation at GeoProc conference, Cyprus, October 2025

#### InFocus: An Integrated Approach to Estimating Fault Slip Occurrence (Vossepoel et al.)

##### Scientific publications

- Li, M., Niemeijer, A.R. & van Dinther, Y. (2025), Frictional healing and induced earthquakes on conventionally stable faults. *Nat Commun* 16, 9140 (2025). <https://doi.org/10.1038/s41467-025-63482-3>
- Li, M., Niemeijer, A., & van Dinther, Y. (2025). Earthquake nucleation and slip behavior altered by stochastic normal stress heterogeneity. *Journal of Geophysical Research: Solid Earth*, 130, e2024JB029857 <https://doi.org/10.1029/2024JB029857>

- Lambert, V. R., Erickson, B. A., Jiang, J., Dunham, E. M., Kim, T., Ampuero, J. P., ... & Yun, J. (2025). Community-driven code comparisons for simulations of fluid-induced aseismic slip. *Journal of Geophysical Research: Solid Earth*, 130(4), e2024JB030601 <https://doi.org/10.1029/2024JB030601>
- Li, M., Niemeijer, A.R., Vossepoel, F.C., van Dinther, Y., (To be submitted). Nucleation and rupture of induced earthquakes in Groningen confined to the gas reservoir

##### Presentations

- Lambert, V., Erickson, B., Jiang, J., Romanet, P., and Thakur, P. and the Sequences of Earthquakes and Aseismic Slip (SEAS) Community Code-Verification Initiative: Community Code Verification Exercises for Simulations of Earthquake Sequences and Aseismic Slip (SEAS): Effects from Fluids and Fault Friction Evolution (2025), EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-14426, <https://doi.org/10.5194/egusphere-egu25-14426>, 2025
- van Dinther, Y., Li, M., Niemeijer, A.N., Vossepoel, F.C. (2025). Nucleation and rupture of induced earthquakes in Groningen confined to the gas reservoir due to lithological variations, AGU General Assembly 2025, S44B-06, <https://agu.confex.com/agu/agu25/meetingapp.cgi/Paper/1928836>
- Li, M., van Dinther, Y., Niemeijer, A., Vossepoel, F. When stable faults shake: the role of frictional healing in induced earthquakes, Seismo Lab Seminar at California Institute of Technology, Pasadena, US, 2025
- van Dinther, Y., Li, M., van der Heiden, V., et al., (2025), What simulations of induced earthquakes in Groningen tell us. Friday Earth Sciences Talk
- van Dinther, Y., Li, M., van der Heiden, V., et al., (2025), What physics-based research and simulations of induced earthquakes in Groningen tell us. Keynote lecture at DeepNL Stakeholder meeting.
- van Dinther, Y., Li, M., van der Heiden, V., Mhina de Vos, Loes Buijze, Thomas Ulrich, André Niemeijer, Hui-hui Weng, Alice-Agnes Gabriel, Jean-Paul Ampuero, Femke Vossepoel, Jan-Diederik van Wees, Jesper Spetzler, Liviu Matenco (2025), What simulations of induced earthquakes in Groningen tell us. Schatzalp, Davos, Switzerland

##### Data and method products

- Li, M.. Data for "earthquake nucleation and slip behavior altered by stochastic normal stress heterogeneity" [dataset]. Zenodo. <https://doi.org/10.5281/zenodo.13991241>
- Li, M.. Software for "earthquake nucleation and slip behavior altered by stochastic normal stress heterogeneity" [software]. <https://bitbucket.org/cpranger/garnet/src/meng-eejit/experiments/lab3d/>
- Earthquake sequence models for Groningen. <https://bitbucket.org/lmuu/indnuc/src/master/>

#### μFAULT - scaling friction from micro-contacts to faults at the reservoir scale (Mishra et al.)

##### Presentations

- Mishra, T., (2025). Using an analytical model to compute the adhesive forces in pull-off force experiments with atomic force microscopy. EcoTrib 28-30th August 2025, ETH Zurich, Switzerland.

#### Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field (Willingshofer et al.)

##### Scientific publications

- Arts, J. P. B., Rodrigues, D., Nader, F. H., Drury, M. R., Matenco, L. C., Willingshofer, E., & Niemeijer, A. R. (2025). Interaction between diagenesis and faulting in sandstone reservoirs: Inferences from the Groningen gas field. *Journal of Structural Geology*, 105554 <https://doi.org/10.1016/j.jsg.2025.105554>
- Arts, J. P.B., Matenco, L. C., Niemeijer, A. R., Drury, M. R., Willingshofer, E., Rodrigues, D. & Nader, F. H. (in prep). Groningen fault zone architecture: inferences from multi-scale observations.
- Arts, J.P.B., Willingshofer, E., Rosenau, M. Niemeijer, A.R., Zhou, W. (in prep). The interaction between fault zone structural evolution and fault slip behaviour: An analogue modelling approach.
- Arts, J.P.B. (in prep). Geological Analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field [Doctoral dissertation, Utrecht University]

##### Presentations

- Arts, J. P., Rodrigues, D., Nader, F. H., Drury, M. R., Matenco, L. C., Willingshofer, E., & Niemeijer, A. R. (2025). Faults in the Groningen gas field: Microstructural constraints on reactivation and slip behavior. *Nederlands Aardwetenschappelijk Congres (NAC)*

##### Data and method products

- Arts, J. P., Rodrigues, D., Nader, F. H., Drury, M. R., Matenco, L. C., Willingshofer, E., & Niemeijer, A. R. (2025). Faulted samples from the Groningen gas field, the Netherlands. <https://doi.org/10.24416/UU01-9R3193>

#### FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity (Niemeijer et al.)

##### Presentations

- Rangel, R. L., Cheng, H., Barros, G., & Niemeijer, A. R. (2025). Grain-scale study of thermal effects during fault

gouge shearing. DeepNL Scientific Meeting 2025, Utrecht, Netherlands.

- Barros, G., Rangel, R. L., Thoeni, K., & Cheng, H. (2025). Coupling BEM-DEM for 1D heat conduction: A proof-of-concept towards 3D thermomechanics. Grain Days 2025.
- Rangel, R. L., & Cheng, H. (2025). A concurrent multiscale method for modeling dynamic friction in fault gauges. DeepNL Stakeholder Meeting 2025, Amersfoort, Netherlands.
- Rangel, R. L., Gimenez, J. M., Cheng, H., Oñate, E., & Franci, A. (2025). An efficient approach for continuum-discrete multiscale simulations of densely packed granular materials in the presence of thermal expansion. IX International Conference on Particle-Based Methods (PARTICLES 2025), Barcelona, Spain, 20–22 October 2025.

#### NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient nature of induced Seismicity (Vossepoel et al.)

##### Scientific publications

- Jansen, J. D., & Meulenbroek, B. J. (2025). The onset of depletion-induced seismicity in slip-weakening faults with interacting peaked shear stresses: Uenishi and Rice extended. *Journal of Geophysical Research: Solid Earth*, 130, e2025JB031577 <https://doi.org/10.1029/2025JB031577>

##### Presentations

- Jansen, J. D., & Meulenbroek, B. J. (2025). An extended Uenishi and Rice criterion for the onset of depletion-induced or cooling-induced seismicity in slip-weakening faults with interacting peaked shear stresses, AGU, New Orleans (December 2025)
- Dvornik, L., Muntendam-Bos, A., Buijze, L., Jansen, J.D., Causal processes of the temporal and spatial variations in the Gutenberg-Richter parameters, Schatzalp, Davos (March 2025) & DeepNL Stakeholder meeting (April 2025)
- Dvornik, L., Muntendam-Bos, A., Buijze, L., Jansen, J.D., Understanding the non-stationary nature of human-induced earthquakes and its impact on geothermal energy production, DeepNL Scientific Meeting, Utrecht (November 2025)
- de Vos, M., van Dinther, Y., Buijze, L. & van Wees, J.D., How do fluid injection-induced changes in temperature and pressure effect slip on a multiscale fracture network, 4th Induced seismicity workshop, Davos (March 2025)
- de Vos, M., van Dinther, Y., Buijze, L. & van Wees, J.D., How does Rate-and-State friction affects slip in geothermal reservoirs, AGU, New Orleans (December 2025)

## A multiscale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction (Hangx et al.)

### Scientific publications

- Shinohara, T., Thieulot, C., Spiers, C.J. & Hangx, S.J.T. (2025). Non-Hertzian stress fields in simulated porous sandstone grains and implications for compactive brittle failure - a high-resolution FEM approach. *Journal of Geophysical Research: Solid Earth*, 130(6), Article e2024JB030818. <https://doi.org/10.1029/2024JB030818>
- Shinohara, T., Verberne, B.A., Spiers, C.J., de Bresser, J.H.P. & Hangx, S.J.T. (2025). Time-dependent Inelastic Deformation of Slochteren Sandstone: Implication for Ongoing Reservoir Compaction in the Seismogenic GroninTime-dependent Inelastic Deformation of Slochteren Sandstone: Implication for Ongoing Reservoir Compaction in the Seismogenic Groningen Gas Field. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, 11(1), Article 83. <https://doi.org/10.1007/s40948-025-01014-5>
- Shinohara, T., Spiers, C.J., & Hangx, S.J.T. (2026). Microphysics of Time-Dependent Deformation of Clay-Bearing Sandstone: Grain Shape Matters. *Rock Mechanics and Rock Engineering*. <https://doi.org/10.1007/s00603-025-05192-2>
- Jefferd, M.A., Hangx, S.J.T. & Spiers, C.J. (In preparation). The impact of loading history on the mechanical behaviour of Slochteren sandstone.
- Mehranpour, M.H. & Hangx, S.J.T. (In preparation). Insight into the Mechanical Behavior of Groningen Sandstone Using Discrete Element Method: Grain Size Distribution and Mineralogy Effects.
- Mehranpour, M.H. & Hangx, S.J.T. (In preparation). How Uncertainty in 3D In-Situ Stress Affects Reservoir Compaction Behavior: A DEM Case Study of the Groningen Gas Field.

## Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields (Jansen et al.)

### Scientific publications

- Naderloo, M., Veltmeijer, A., Pluymakers, A., Jansen, J. D., & Barnhoorn, A. (2025). The Effect of Pressurization Rate and Pattern on Injection- Induced Seismicity in Highly Permeable Sandstone: An Experimental Study. *JGR Solid Earth*, 130(12), Article e2024JB029469. <https://doi.org/10.1029/2024JB029469>
- Novikov, A., Saifullin, I., Hajibeygi, H., & Voskov, D. (2025). A finite volume framework for the fully implicit thermal-hydro-mechanical-compositional modeling in subsurface applications. *Journal of Computational Physics*, 538, Article 114152. <https://doi.org/10.1016/j.jcp.2025.114152>

- Chen, J., Niemeijer, A. R., & Spiers, C. J. (2025). An Extended Microphysical Friction Model for Variable Normal Stress Conditions. *Journal of Geophysical Research: Solid Earth*, 130(7), Article e2025JB032033. <https://doi.org/10.1029/2025JB032033>

## The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs (Miocic et al.)

### Scientific publications

- Mulder, S. J., Felder, M., and Miocic, J. M.: The Diagenetic Fingerprint of Rotliegend Sandstones in the Groningen Gas Field, *EGUsphere* [preprint], <https://doi.org/10.5194/egusphere-2025-6504>, 2026. Under review in *Marine & Petroleum Geology*
- Mulder, S. J., Felder, M., and Miocic, J. M. Depositional and grain-scale controls on sandstone heterogeneity in arid continental settings: the Dutch Rotliegend (under review, *Sedimentary Geology*)
- Mulder, S. J., and Miocic, J. M. Structural and diagenetic controls on compaction of Rotliegend reservoir rocks in the Groningen gas field (in prep.)
- Bublik, D., Hangx, S.J.T., Mulder, S.J., and Miocic, J.M., Impact of sedimentary heterogeneity on compactional behaviour of Rotliegend Sandstones of the Groningen gas field (in prep.)

### Presentations

- Bublik, D., Mulder, S.J., & Miocic, J.M. (2025) Identifying thin mudstone beds using SWIR data. *Nederlands Aardwetenschappelijk Congres (NAC)*.
- Mulder, S.J., & Miocic, J.M. (2025). The Role of Dolomitization and Clay Rims in Shaping Sandstone Evolution: Insights from the Groningen Gas Field. <https://doi.org/10.5194/egusphere-egu25-12855>. *Copernicus Meetings*.

### Data and method products

- S. Mulder. (2026). Quantitative petrographic data for the paper: Diagenetic Evolution of Rotliegend Sandstones in the Groningen Gas Field. *DANS Data Station Physical and Technical Sciences*. <https://doi.org/10.17026/PT/DXA7VN>
- S. Mulder. (2026). Quantitative petrographic data for the publication: Depositional and grain-scale controls on sandstone heterogeneity in arid continental settings: the Dutch Rotliegend. *DANS Data Station Physical and Technical Sciences*. <https://doi.org/10.17026/PT/QEZHYF>
- SWIR scan raw data of Groningen cores (under development)
- Thin-section scans (under development)
- Python code for automated thin-section analysis (under development)

## Making digital rocks a practical reality for energy storage within subsurface reservoirs (Rücker et al.)

### Scientific publications

- M. H. Khoeini, G. Wensink, T. Vukovic, I. Krafft, A. van der Net, M. Rücker, and A. Luna-Triguero, "Nanoscale analysis of surface modifications on silanized glass: Wettability alteration and long-term stability," *Surfaces and Interfaces*, vol. 72, p. 107218, 2025. <https://doi.org/10.1016/j.surfin.2025.107218>
- M.H. Khoeini, A. Luna-Triguero, M. Rücker, "Detecting nucleation of water in super-hydrophobic PTFE powders using Inverse Gas Chromatography," *Colloid and Interface Science Communications*, vol. 67, p. 100849, 2025. <https://doi.org/10.1016/j.colcom.2025.100849>
- Mosalman, M. K. S., Rücker, M., Garfi, G., Krevor, S., Georgiadis, A., & Luckham, P. F. (2025). New insights on rock alteration by oil: An in-situ investigation at the nano-scale using atomic force microscopy. *Capillarity*, 17(1), 27-36. <https://doi.org/10.46690/capi.2025.10.03>
- Farber, E. M., Seraphim, N. M., Tamakuwala, K., Stein, A., Rücker, M., & Eisenberg, D. (2025). Porous materials: The next frontier in energy technologies. *Science*, 390(6772), eadn9391. <https://doi.org/10.1126/science.adn9391>
- Wensink, G., Rücker M. (2026). Evaporative precipitation of minerals in limestone rocks: a study of the microscale dynamics. *Geoenergy Science and Engineering* (Under review)
- Wensink, G., Cherukupally, P., Schröer, L., van Kempen, K., Cnudde, V., Williams, D.R., Rücker, M. Mechanism of dynamic oil absorption in surface engineered sponges for wastewater treatment. In draft
- Wensink, G. (2026). Sub-micron Scale Mechanisms of Multiphase Flow and Reactive Transport in Porous Media. [Doctoral dissertation, TU/e]. Eindhoven University of Technology.
- Rieder D.R., Khoeini M.H., Rücker M. Exploring the coupling of sample morphology and non-linear adsorption on the retention curves of inverse gas chromatographs with a pore network approach. Draft
- Berg, S., Armstrong, R. T., RÄžcker, M., Hansen, A., Kjelstrup, S., & Bedeaux, D. (2025). From Interface Dynamics to Darcy Scale Description of Multiphase Flow in Porous Media. *arXiv preprint arXiv:2510.19582*. (accepted to *Advances in Colloid and Interface Science*) <https://doi.org/10.48550/arXiv.2510.19582>

### Presentations

- Rieder D.R., Khoeini M.H., Rücker M. (2025) Enhancing Porous Material Characterization by combining inverse Gas Chromatography and Pore Network modeling. *Sustainable Energy & Process Technologies*, Netherlands

- Rieder D.R., Khoeini M.H., Kondor A., Luna Triguero A., Rücker M. Porensics - Unraveling Material Properties with iGC. *ME Innovation Day, TU/e, Netherlands*
- Rieder D.R., Heijkoop S., Moura M., Spurin C., Rücker M. (2025) How steady is steady-state multiphase flow in porous media? *Netherlands Process Technology Symposium 20, Netherlands*
- Khoeini, M.H., Ruecker, M, Luna-Triguero, A. (2025), Inverse gas chromatography, a new technique for correlating surface energy porous media to saturation. *15th fundamentals of adsorption (RIA15, Porto)*
- Wensink, G., Rücker, M. (2025). The microscale dynamics of water films during evaporative precipitation of minerals in porous media. *Interpore 2025, Albuquerque, USA*.
- Wensink, G., Rücker, M. Mosalman, M.K.S., Geurts, P., Gao, Y., Garfi, G., Krevor S., Georgiadis, A., Luckham, P., Schröer, L. Particia-Dell, H., Cnudde, V. (2025). *Microdynamics of Water films in porous media. Energizing Day 2025, Eindhoven, Netherlands*
- Rücker M., Khoeini M. H., Wensink G., Vukovic T., Luna-Triguero A., van der Net, A. Characterizing surfaces in porous materials with inverse gas chromatography. *16th International Symposium on Wettability and 4th Biennial Meeting of the Australian Chapter of Interpore, January, 2025, Sydney, Australia (oral presentation)*
- Rücker M., Fluid dynamics during spontaneous imbibition in multimodal porous media SPP2171, Mainz, Germany, February, 2025, Mainz, Germany

### Data and method products

- Wensink, G., Rücker, M., Schröer, L., Cnudde, V., Cherukupally, P. (2025). Reconstructed dynamic Micro-CT data of absorption of decane in wetted surface-engineered sponges and rocks. (Utrecht University - YODA), <https://doi.org/10.24416/uu01-h9gctp>
- Wensink, G., Rücker, M. Micro-computed Tomography scan of evaporative KI salt precipitation in limestone rock. (4TU research data). Under review.
- Wensink, G., Rücker, M. AFM force-mapping scans of drying of NaCl solution on the grain surface of limestone rock (4TU research data). Under review.

### Quantitative constraints on pre-production reservoir stresses in Groningen (Govers et al.)

#### Scientific publications

- Nijholt, N., Guitierrez Escobar, R., Wouters, M., Govers, R., (submitted to Geophysical Journal International, 2026) Lithospheric Driving Forces From Recent Global Density Models
- Gutierrez Escobar, R., Nijholt, N., Wouters, N., Govers, R., (in prep), Horizontal stress field in Eurasia, Journal of Geophysical Research - Solid Earth
- Gutierrez Escobar, R., Govers, R., (in prep), 3D natural stresses in the Groningen gas field area, Netherlands Journal of Geosciences
- Gutierrez Escobar, R., van de Wal, W. Govers, R., (in prep), Imprint of glacial isostatic rebound on the Groningen stress field, Netherlands Journal of Geosciences
- Gutierrez Escobar, R., [thesis in prep], Quantitative constraints on pre-production reservoir stresses in Groningen

#### Presentations

- Renato Gutierrez Escobar, Rob Govers, (2025) Numerical modelling of stresses and deformation in the Eurasian tectonic plate through Bayesian inversion, EGU annual meeting, Vienna, doi: 10.5194/egusphere-egu25-16972.
- Nicolai Nijholt, Renato Gutierrez Escobar, Rob Govers, (2025) Using Recent Data-constrained Models to Probe Global Gravitational Potential Energy and Lithospheric Forces, Asia Oceania Geosciences Society annual meeting, Singapore, SE16-A017.

#### Data and method products

- Gutierrez Escobar, R., Nijholt, N., Wouters, N., Govers, R., (2026, submitted to Geophysical Journal International). Public release of horizontal gravitational traction code [Software]
- Nicolai Nijholt, Renato Gutierrez Escobar, Marius Wouters, Rob Govers, (submitted to Geophysical Journal International, 2026) Lithospheric Driving Forces From Recent Global Density Models (global HGT data co-publication).

### Impact of fluid extraction on the creep behaviour of clayrich formations enveloping Rotliegend sandstone reservoir (Hangx et al.)

#### Presentations

- Sep, M.K., Hangx, S.J.T., De Bresser, J.H.P. (2025) Time-dependent deformation of clay-rich rocks enveloping reservoirs exploited for geo-energy purposes. EGU General Assembly.

### Constraining uncertainties across scales: From Groningen to future geoeenergy applications (CrossScale) (Geiger et al.)

#### Presentations

- Geiger, S, Abels, H.A., Barnhoorn, A., Correlje, A., Daniilidis, A., Pluymakers, A., Schmidt, H., Steinvooort, J.M., de Vries, G., Miocic, J., Tucker, A. (2025, November 21). Constraining uncertainties across scales: From Groningen to future geoeenergy applications., DeepNL Scientific Meeting, Utrecht, Netherlands.
- Steinvooort, J. M., Abels, H.A., Barnhoorn, A., Daniilidis, A., Pluymakers, A., Miocic, J., Tucker, A., and Geiger, S. (2025, March 20) Defining representative elementary volumes of geological heterogeneities using a sketch-based modelling software. NWO NAC, NH Noordwijk Conference Centre Leeuwenhorst, Netherlands. <https://doi.org/10.5281/zenodo.17434154>
- Steinvooort, J. M., & Tucker, A. H. (2025, oktober 24). Constraining uncertainties across scales: from Groningen to future geoeenergy applications. Annual Energi Simulation Review and Student Day, Delft University of Technology, Delft, Netherlands. <https://doi.org/10.5281/zenodo.17433939>
- Weert, A., Steinvooort, J.M., Martinius, A.W., Geiger, S. (2025, December 4) When heterogeneity becomes a hazard: the REV approach. De-Risking Geohazards in the Energy Transition (Challenges, Solutions and Future Research Directions): Energy Group. Geological Society of London, London, UK.
- Schmidt, H (2025, November 21). Digging Deep: Help me understand geoscientists' challenges in communicating research findings. DeepNL Scientific Meeting, Utrecht, Netherlands.
- Barnhoorn, A. (2025) Laboratory-derived active-acoustic monitoring strategies for forecasting stress changes and fault reactivation in subsurface reservoirs. Keynote presentation Seventh International Conference on Fault and Top Seals, Bucharest September 2025:
- Geiger, S. (2025), Reservoir Modelling for the Energy Transition. Invited presentation for Workshop 11 at the Annual Conference and Exhibition of the European Association of Geoscientists and Engineers, Toulouse, France

#### Data and method products

- Schmidt, H. (2025). The Dutch Subsurface: A Stakeholder Analysis. TU Delft (in prep.).



## CLUSTER 2

### Monitoring of physical conditions and forecasting

#### Deeplmage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity (Barnhoorn et al.)

##### Scientific publications

- Masfara, L. ODE. M. (2025). Estimating induced seismic source parameters using an efficient Hamiltonian Monte Carlo algorithm. [Dissertation (TU Delft), Delft University of Technology]. <https://doi.org/10.4233/uuid:a4b1c6b0-76df-4afb-b804-1425c087153f>
- Ruan, J. (2025). From Finite Fault Slip to Seismic Moment Tensor: Simulating Induced Earthquakes in Groningen. [Dissertation (TU Delft), Delft University of Technology]. <https://doi.org/10.4233/uuid:0bc78ed8-ce42-4bd6-a08f-17745b3bb2bb>
- Faezeh Shirmohammadi, Deyan Draganov, Ranajit Ghose, Eric Verschuur, Jan Thorbecke, Kees Wapenaar, Recursive interferometric surface-wave suppression for improved reflection imaging, Geophysical Journal International, Volume 243, Issue 3, December 2025, ggaf387, <https://doi.org/10.1093/gji/ggaf387>
- Faezeh Shirmohammadi, Deyan Draganov, Johno van IJsseldijk, Ranajit Ghose, Jan Thorbecke, Eric Verschuur, Kees Wapenaar, Application of Marchenko-Based Isolation to a Land S-Wave Seismic Dataset, Geophysical Prospecting, volume 73, Issue 6, July 2025, <https://doi.org/10.1111/1365-2478.70064> Digital Object Identifier (DOI)

#### Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations (Trampert et al.)

##### Scientific publications

- Baki, Z. (2025). Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large-scale field observations. [PhD Thesis - Research UT, graduation UT, University of Twente]. University of Twente. <https://doi.org/10.3990/1.9789036564908>
- Baki, Z., van Lieshout, M.N.M. A Cox Rate-and-State Model for Monitoring Seismic Hazard in the Groningen Gas Field. Math Geosci 58, 99–125 (2026). <https://doi.org/10.1007/s11004-025-10222-4>

- L Hoogerbrugge, M H Khalid, K W A van Dongen, D J Verschuur, Model-order reduced full-wavefield migration using proper orthogonal decomposition, Geophysical Journal International, Volume 243, Issue 2, November 2025, ggaf356, <https://doi.org/10.1093/gji/ggaf356>

#### PhysMmax: Constraining the maximum magnitude in Groningen through 3D multiphysics, data-driven modeling (van Dinther et al.)

##### Scientific publications

- van der Heiden, V., Buijze, L., Ulrich, T., van Wees, J.-D., van Isselt, M., Matenco, L., Spetzler, J., Gabriel, A.A. & van Dinther, Y. Hindcasting the 2018–2022 Wirdum induced earthquake sequence. Nearly submitted to Journal of Geophysical Research: Solid Earth.
- van der Heiden, V., Ulrich, T., Buijze, L., Gabriel, A.-A. & van Dinther, Y. Spontaneous nucleation, rupture, and arrest constrain geomechanical and earthquake parameters. Nearly submitted to Journal of Geophysical Research: Solid Earth.
- Weng, H., Buijze, L., Ampuero, J.-P. (near submission). Physics-based estimates of the maximum magnitude of induced earthquakes in the Groningen gas field – part I: theory.
- Buijze, L., Weng, H., Ampuero, J.-P. (near submission). Physics-based estimates of the maximum magnitude of induced earthquakes in the Groningen gas field – part II: application.
- van der Heiden, V., Weng, H.-H., Ampuero, J.-P., van Dinther et al., Y. (preparation), Rupture Jumping Across Fault Stepovers: an extension of Rupture-Tip Theory of elongated ruptures, in preparation for BSSA

##### Presentations

- van Dinther, Y., Li, M., van der Heiden, V., et al., (2025). What simulations of induced earthquakes in Groningen tell us. Friday Earth Sciences Talk
- van Dinther, Y., Li, M., van der Heiden, V., et al., (2025). What physics-based research and simulations of induced earthquakes in Groningen tell us. Keynote lecture at DeepNL StakeHolder meeting.
- van Dinther, Y., Li, M., van der Heiden, V., Mhina de Vos, Loes Buijze, Thomas Ulrich, André Niemeijer, Hui-hui Weng, Alice-Agnes Gabriel, Jean-Paul Ampuero, Femke Vossepoel, Jan-Diederik van Wees, Jesper Spetzler, Liviu Matenco (2025). What simulations of induced earthquakes in Groningen tell us. Schatzalp, Davos, Switzerland

- van der Heiden, V., Weng, H., Ampuero, J.P., van Dinther, Y. (presenting author) (2025). Rupture Jumping Across Fault Stepover: An Extension of Rupture-Tip Theory of Elongated Earthquakes. American Geophysical Union (AGU) Fall Meeting 2025
- van der Heiden, V., Ulrich, T., Buijze, L., van Isselt, M., van de Wiel, L., Gabriel, A.A., Matenco, L., van Wees, J.D., van Dinther, Y. (presenting author) (2025). Hindcasting the 2018 - 2022 Wadumburgh Induced Earthquake Sequence. American Geophysical Union (AGU) Fall Meeting 2025

#### Data and method products

- 3D Dynamic earthquake rupture model, <https://github.com/SeisSol>
- Semi-ANalytical Tool for Human-induced Earthquake Rupture approximating physics, <https://github.com/TNO/PANTHER/tree/main/examples>
- Repository with all code related to coupling PANTHER with SeisSol, [https://github.com/VvanderHeiden/PhysMmax\\_SeisSol](https://github.com/VvanderHeiden/PhysMmax_SeisSol)

#### Deep, deeper, deepestNL; Imaging the Dutch crust and upper mantle using multi-geobservables (DICTUM) (Fadel et al.)

##### Scientific publications

- Akinremi, S. (2025). Deep, Deeper, Deepest-NL: Imaging the crust and upper mantle of the Netherlands [PhD Thesis]. University of Twente. <https://doi.org/10.3990/1.9789036569781>
- Akinremi, S., Fadel, I., van der Meijde, M., Thomas, C., Afonso, J. C., & Elmer Ruigrok, E. (In preparation). Crustal structure of the Netherlands from waveform-fitting of receiver functions. *Journal of Geophysical Research: Solid Earth*.
- Akinremi, S., Fadel, I., Ruigrok, E., Afonso, J. C., Thomas, C., & van der Meijde, M. (In preparation). Crustal and Upper Mantle Shear Wave Velocity of The Netherlands. *Journal of Geophysical Research: Solid Earth*.

##### Data and method products

- Akinremi, S., Fadel, I., & van der Meijde, M. (2025). Data and crustal model of The Netherlands from receiver functions [Dataset]. DANS Data Station Physical and Technical Sciences
- Akinremi, S., Fadel, I., & van der Meijde, M. (2025). Shear wave velocity model of the crust and upper mantle of The Netherlands [Dataset]. DANS Data Station Physical and Technical Sciences

#### Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions (INTEGRATION) (Van der Meijde et al.)

##### Scientific publications

- Juan Carlos Afonso. A Multiscale MCMC Approach to Joint Geophysical Inversion: Tackling Dimensionality, Solver Integration, and Multiscale Data Fusion. Authorea. September 09, 2025. DOI:10.22541/au.175743557.79555552/v1
- Philip J. Ball, Graham Banks, Mikenna Montgomery, Juan Carlos Afonso, Chapter 12 - Global screening for superhot rock geothermal energy: Geodynamic settings, prospective heat endowment and extraction techniques, *Geothermal Energy Engineering*, 2025, 379-462, ISBN 9780443216626, <https://doi.org/10.1016/B978-0-443-21662-6.00009-8>.

##### Presentations

- Janneke I. de Laat, Piefan Jiang, Islam Fadel, Enhancing Teleseismic P-Wave Detection and Tomography in the Groningen Area: Comparing Traditional Methods and Machine Learning, IAGA/IASPEI Joint Scientific Meeting 2025 Lisbon

##### Data and method products

- The first dataset of the P- and S-wave arrival times from local and regional earthquakes using the freely available broadband seismological data (under development)
- A Multiscale MCMC Approach to Joint Geophysical Inversion (complete Matlab implementation published with the associated publication); the complete FORTRAN implementation is under development
- A preliminary subsurface model of the Netherlands (to be finished in June 2026)

#### SHAWave: Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach

##### Scientific publications

- Hodzelmans, M.M., Hiemstra, R.R., Remmers, J.J.C., Verhoosel, C.V. (2026). Isogeometric Analysis for Explicit Wave Propagation in Poro-Elastic Media. Article in preparation.

##### Presentations

- Hodzelmans, M.M., Remmers, J.J.C., Verhoosel, C.V. (2025, September 14). Isogeometric Analysis for Explicit Propagation of Seismic Waves in Poro-elastic Media [Conference presentation]. IGA 2025 Conference, Eindhoven, The Netherlands. <https://iga2025.cimne.com>

- Hodzelmans, M.M., Remmers, J.J.C., Verhoosel, C.V. (2025 October 30-31). Isogeometric Analysis for Poro-Elastic Wave Propagation [Poster presentation]. Engineering Mechanics symposium, Arnhem, The Netherlands. <https://engineeringmechanics.nl>
- Hodzelmans, M.M., Remmers, J.J.C., Verhoosel, C.V. (2025 November 21). Isogeometric Analysis for Poro-Elastic Wave Propagation [Poster presentation]. DeepNL Scientific Meeting, Utrecht, The Netherlands. <https://www.nwo.nl/en/researchprogrammes/deepnl>
- Khoveiledy, T., Fadel, I., Dahal, A., van der Meijde, M. (2025 April 15). Probabilistic Ground Motion Susceptibility Modelling [Poster presentation]. DeepNL Scientific Meeting, Utrecht, The Netherlands. <https://www.nwo.nl/en/researchprogrammes/deepnl>
- Khoveiledy, T., Fadel, I., Dahal, A., van der Meijde, M. (2025 November 21). Highlighting the complexity of the wavefield in the Groningen [Poster presentation]. DeepNL Scientific Meeting, Utrecht, The Netherlands. <https://www.nwo.nl/en/researchprogrammes/deepnl>

#### A digital twin for modelling and forecasting induced seismicity (Trampert et al.)

##### Presentations

- De Boeij, N. (2025, November). Numerical modeling of soft-glass systems as a digital twin for induced seismicity. Poster Presentation, DeepNL Scientific Meeting.
- Muuren, T. (2025, November). Avalanches in soft glasses at the yield stress transition. Poster Presentation, DeepNL Scientific Meeting.
- McBrearty, Z. (2025, November). Langevin Regression for a Softglass system. Poster Presentation, DeepNL Scientific Meeting.
- Trampert, J. (2025, November). A digital twin for modelling and forecasting induced seismicity. Presentation, DeepNL Scientific Meeting.



## CLUSTER 3

# Subsidence and the response of the Earth's surface to earthquakes

#### Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension (Hanssen et al.)

##### Scientific publications

- W. S. Brouwer and R. F. Hanssen, "On the Definition of an Independent Stochastic Model for InSAR Time Series," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 63, pp. 1-11, 2025, Art no. 4508311, doi: 10.1109/TGRS.2025.3600893.
- Marius C. Wouters, Rob Govers, Ramon Hanssen, Development of an efficient model to calculate subsidence above the Groningen gas field. *Netherlands Journal of Geosciences*, Volume 104, e12151. <https://doi.org/10.70712/NJG.v104.12151>
- Wietske Brouwer, Ramon Hanssen, 3D surface displacement estimation over the Groningen gas field, the Netherlands, *EarthArXiv*, 2025, doi: 10.31223/x5775w
- W.S. Brouwer, R.F Hanssen, Estimating three-dimensional displacements with InSAR: the strapdown approach. *J Geod* 98, 110 (2024). <https://doi.org/10.1007/s00190-024-01918-2>

##### Data and method products

- Input, output and scripting files for the geophysical modelling part of the study: <https://doi.org/10.24416/UU01-W3PCRY>.
- The data and methods for the geodetic part of the study: doi: 10.4121/34394aab-6139-4397-9235-f9f041ac9299 <https://github.com/TUdelftGeodesy/3D-Groningen> <https://surfdrive.surf.nl/index.php/s/mjERLrRs5a1jm5b>

#### SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential (Hicks et al.)

##### Scientific publications

- Gonzalez Acosta, J. L., van den Eijnden, A. P., & Hicks, M. A. (2025). Tied Free-Field boundaries to enhance numerical accuracy of earthquake simulations. *Frontiers in Built Environment*, 11, Article 1567604. <https://doi.org/10.3389/fbuil.2025.1567604>

- Bayraktaroglu, H., Korff, M., & Hicks, M. A. (2026). An anisotropic semi-micromechanical cyclic constitutive model for sands. *Computers and Geotechnics*, 191, Article 107772. <https://doi.org/10.1016/j.compgeo.2025.107772>
- Chao, C.-Y., Muraro, S., & Jommi, C. (2025). Improving Constitutive Modelling of Soft Organic Clays With New Experimental Insight. *International Journal for Numerical and Analytical Methods in Geomechanics*, 49(18), 4480-4501. <https://doi.org/10.1002/nag.70019>
- Chao, C.-Y., Muraro, S., & Jommi, C. (2025). Improving Constitutive Modelling of Soft Organic Clays With New Experimental Insight. *International Journal for Numerical and Analytical Methods in Geomechanics*, 49(18), 4480-4501. <https://doi.org/10.1002/nag.70019>

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**3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis (Ghose et al.)**

**Presentations**

- Ghose, R. & Revelo-Obando, E. D. (2026). Smooth, differentiable mapping in the multidimensional feature space providing more accurate subsurface property and variability estimates, *Proceedings of the European Association of Geoscientists and Engineers Annual Conference, 2026*.

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**DAMPINGSOIL: Providing the missing information of elastic damping ratio and strain-dependent modulus and damping curves for reliable, local site response analysis (Ghose et al.)**

**Presentations**

- Huber et al., 2025, Extracting nonlinear shear stiffness and damping ratio from resonant column tests based on nonlinear viscoelasticity, *Nonlinear Dynamics Conference (NODYCON)*.
- Wang, et al., 2026, Multimode damping inversion: do higher modes information matter?, *European Association of Geoscientists and Engineers Conference*.
- Huber et al., 2026, Extracting Nonlinear Shear Stiffness and Damping Ratio from Resonant Column Tests for Seismic Site Response Analysis, *International Conference on Structural Dynamics (EURODYN)*.
- Huber et al., 2026, Improving Experimental Determination of Modulus Reduction and Damping Curves using Nonlinear Resonant Column Modelling, *Journal paper draft*.

**Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region (Govers et al.)**

**Scientific publications**

- T. de Gast, B.R. Lexmond, Y. Hiruma, E. Stouthamer, R. Govers, K.G. Gavin, (in prep for *Géotechnique*) Predicting subsidence and emission driven by atmospheric pressure variations and external loading.

**Presentations**

- Yuta Hiruma, Tom de Gast, Esther Stouthamer, Ramon Hanssen, Femke Vossepoel, Rob Govers, (2025) Modeling (Sub)surface Deformation: Linking Groundwater Dynamics to Precipitation and Land Use, *Nederlands Aardwetenschappelijk Congres (NAC) Noordwijk*.
  - Yuta Hiruma, Esther Stouthamer, Tom de Gast, Rob Govers, November 13-14, 2025, Comparing new extensometer data from the Groningen gas field area with predictions of a new soil deformation model, *LaSII/ GSEU Workshop - Land Subsidence in Europe: from Science to Management, Belgium, Brussels*.
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## Appendix 2: List of abbreviations

<b>AFM:</b>	Atomic Force Microscopy
<b>ACT:</b>	Accelerating CCS (Carbon Capture and Storage) Technologies
<b>AFM:</b>	Atomic Force Microscopy
<b>AGU:</b>	American Geophysical Union
<b>BEM:</b>	Boundary Element Method
<b>COVRA:</b>	Central Organisation For Radioactive Waste
<b>CPT:</b>	Cone Penetration Test
<b>CWI:</b>	Dutch national research institute for mathematics and computer science
<b>DANS:</b>	Data Archiving and Networked Services
<b>DAS:</b>	Distributed Acoustic Sensing
<b>DEM:</b>	Discrete Element Model
<b>DSUEL:</b>	Delft Subsurface Urban Energy Laboratory
<b>DTS:</b>	Distributed Temperature Sensing
<b>EAGE:</b>	European Association of Geoscientists and Engineers
<b>EBN:</b>	Energie Beheer Nederland
<b>EGU:</b>	European Geosciences Union
<b>EPOS:</b>	European Plate Observing System
<b>ESMDA:</b>	Ensemble Smoother Multiple Data Assimilation
<b>EZK:</b>	Ministry of Economic Affairs and Climate
<b>FAIR:</b>	Findable, Accessible, Interoperable, and Reusable
<b>FEM:</b>	Finite Element Model
<b>HGT:</b>	Horizontal Gravitational Traction
<b>HPT:</b>	High Pressure and Temperature
<b>HT-ATES:</b>	High Temperature Aquifer Thermal Energy Storage
<b>IAC:</b>	International Advisory Committee
<b>IGA:</b>	IsoGeometric Analysis
<b>IGC:</b>	inverse Gas Chromatograph
<b>InSAR:</b>	Interferometric synthetic aperture radar
<b>KEM:</b>	Knowledge Programme Effects of Mining
<b>KNMI:</b>	Royal Netherlands Meteorological Institute
<b>LU:</b>	Leiden University
<b>MRDI:</b>	Modulus Reduction and Damping Increase
<b>NAC:</b>	Netherlands Earth Sciences Congress
<b>NAM:</b>	exploration and production company
<b>NIOZ:</b>	Royal Netherlands Institute for Sea Research
<b>NLOG:</b>	Dutch subsurface portal
<b>NOBV:</b>	Netherlands Research Programme on Greenhouse gas dynamics in Peatlands and organic soils
<b>NWA:</b>	Dutch Research Agenda
<b>NWO:</b>	Dutch Research Council
<b>PANTHER:</b>	Physics-based semi-ANalytical Tool for Human-induced Earthquake Rupture
<b>PGA:</b>	Peak Ground Acceleration
<b>PI:</b>	Principal Investigator
<b>RCT:</b>	Resonant Column Test
<b>REV:</b>	Representative Elementary Volume
<b>RU:</b>	Radboud University Nijmegen
<b>RUG:</b>	University of Groningen
<b>RUM:</b>	Region of Uniform Motion
<b>RVO:</b>	Netherlands Enterprise Agency
<b>SCPT:</b>	Seismic Cone Penetration Test

<b>SEM:</b>	Societal Effects of Mining
<b>SHRA:</b>	Seismic Hazard and Risk Analysis
<b>SodM:</b>	Dutch State Supervision on Mines
<b>SPE:</b>	Society of Petroleum Engineers
<b>SRIMA:</b>	Seal and Reservoir Integrity through Mechanical Analysis
<b>THM:</b>	Thermo-Hydro-Mechanical
<b>TNO:</b>	Netherlands Organisation for applied scientific research
<b>TUD:</b>	TU Delft
<b>TU/e:</b>	Eindhoven University of Technology
<b>UCSUS:</b>	Utrecht Centre for Sustainable Use of the Subsurface
<b>UT:</b>	University of Twente
<b>UU:</b>	Utrecht University
<b>XRD:</b>	X-Ray Diffraction
<b>VU:</b>	Vrije Universiteit Amsterdam

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The aim of the research programme DeepNL is to contribute to a better understanding of how the deep subsurface behaves under the influence of human interventions. In addition, the programme aims to strengthen and integrate the research community in the Netherlands around this theme.

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