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

Cluster 3
Subsidence and surface effects of seismicity
Can we understand and model how the processes at depth are translated through the subsurface to an effect at the Earth’s surface?
Research projects: 3
Researchers: 8 (co-)project leaders, 7 PhDs and 2 postdocs
Budget: € 2,635,253.-
Involved universities: TU Delft, Utrecht University

Cluster 2
Monitoring of conditions and forecasting
How can we monitor the subsurface conditions that could lead to earthquakes and forecast the occurrence of earthquakes?
Research projects: 5
Researchers: 15 (co-)project leaders, 12 PhDs and 1 postdoc
Budget: € 3,718,736.-
Involved universities: TU Delft, University of Twente, Utrecht University

Cluster 1
Analysis of processes and conditions that lead to seismicity and subsidence
Can we understand and model the conditions and processes in the deep subsurface that can ultimately lead to earthquakes and subsidence?
Research projects: 10
Researchers: 18 (co-)project leaders, 14 PhDs and 7 postdocs
Budget: € 7,116,062.-
Involved universities: Eindhoven University of Technology, TU Delft, University of Groningen, University of Twente, Utrecht University
With the DeepNL programme just about halfway, in 2022 the time had come to take stock through a midterm evaluation. DeepNL projects, especially those granted within the first calls of the programme, are delivering valuable results; in this annual report you will find their progress reports. Now we need to integrate all the individual pieces we have found so far to complete – as much as possible – the puzzle that describes the influence of human interventions on the deep subsurface.

The midterm evaluation was carried out by the International Advisory Committee (IAC), and was based on the Self-Evaluation report prepared by the programme committee and NWO programme office. The IAC assessed DeepNL as a timely and forward-looking research programme to bring together and strengthen the Dutch geoscience community, and build knowledge and tools to understand the deep subsurface in order to help advise on and address questions associated with the energy transition, climate change, the extraction of natural resources, geological storage, and associated hazards. For the second half of the programme, the IAC advised the DeepNL community to focus on collaboration and integration within the programme, and on jointly delivering the key outcomes that are important for non-academic stakeholders.

Taking into account these recommendations, the programme committee prepared the text for Call 2b, to be published in 2023. While the first generation of DeepNL PhD and postdoc researchers are finalising their projects, and the projects from the second and third research calls are picking up steam, this last major call of the programme will play a key role in achieving the overall DeepNL goals. Besides adding some twenty more researchers to the community, new projects will aim at demonstrating the applicability of the main DeepNL results for wider problems of safe reservoir operations, beyond the questions related to Groningen gas extraction.

In addition to this strategy for the short term, for the longer term, the DeepNL programme committee and the expert panel of the KEM programme jointly developed an initiative for a national research strategy concerning activities in the subsurface of the Netherlands. After consultation of all parties involved, this initiative was submitted to the Ministry of Economic Affairs and Climate Policy, where it was well-received. Further decisions and steps concerning a possible implementation of the proposed strategy are expected in the context of the final report of the Parliamentary Inquiry into natural gas extraction in Groningen and the government’s response thereto.

Over the years, we have seen the DeepNL community grow steadily and gradually get more intertwined. As the International Advisory Committee stated, so far, DeepNL has already considerably strengthened the Dutch geoscience community and has started building models that could help manage future subsurface activities related to the energy transition and geological storage. Let us build further on these foundations to establish strong and dynamic fundamental knowledge and human capacity bases as key components of a knowledge ecosystem (as proposed to the above mentioned Ministry) that can help assess and manage the risks associated with a variety of subsurface activities.

Rinus Wortel
Chair programme committee DeepNL
Looking back on 2022

4th KEM-DeepNL colloquium
This colloquium focused on both reversible and non-reversible seismic site response effects. Floris Besseling (Witteveen+Bos) presented the study on site-amplification approaches for the SHRA. Piet Meijers (Deltares) presented the non-reversible aspects of soil behaviour during earthquakes.

Annual DeepNL Stakeholder Meeting
After a long period of virtual meetings, over a hundred participants met in person to network and learn about the progress made so far in DeepNL. The programme included three presentations on priorities and opportunities for knowledge application by Energie Beheer Nederland (EBN), TNO and State Supervision of Mines (SodM).

Appointment DeepNL International Advisory Committee
The NWO Domain Science Board appointed five international scientists to form the DeepNL International Advisory Committee (IAC). The IAC’s first task was to conduct a midterm evaluation of the DeepNL programme.

4th KEM-DeepNL colloquium
This colloquium on seismological data collection methods and the induced seismic earthquake catalogue Groningen included presentations by Daniela Kuhn (NORSAR) and Barnard Oost (KNMI) on the results of KEM-11a and KEM-11b. Participants discussed the collection and quality of seismological data in Groningen.

Second Workshop on Mmax for Seismic Hazard and Risk Analysis in the Groningen Gas Field
Several DeepNL researchers attended and presented at this scientific conference organised by NAM. Based on the new scientific insights gained here, the international expert panel lowered their assessment of the maximum magnitude earthquake considered to be possible in Groningen to a range of 4.0 until 6.5, with 4.6 as the most likely Mmax value.

DeepNL Summer School
35 young researchers and professionals attended the first DeepNL Summer School in Groningen. The summer school aimed to broaden the knowledge base of the young researchers on the DeepNL theme and strengthen mutual contacts. The participants immersed themselves in the DeepNL theme through lectures, workshops, site visits and an excursion to Germany.

6th KEM-DeepNL colloquium
The subject was ‘Post-abandonment fluid migration and ground motion risks’, which is an important part of the hazard and risk assessment. After a presentation by the TNO-Deltares project team of KEM-19, participants engaged in a lively discussion.

Netherlands Earth Sciences Conference (NAC)
The DeepNL community contributed with ten talks during various parallel sessions and eleven poster presentations. DeepNL researcher Ylona van Dinther gave a keynote lecture on combining physics-based models and observations to understand earthquakes.

Midterm evaluation report finalised
The IAC completed the midterm evaluation. Their report contains an assessment of the ongoing projects and the progress towards the overall DeepNL goals, and provides recommendations for the next phase of the programme.

Midterm evaluation report finalised
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Annual DeepNL Scientific Meeting
A central theme during the day was collaboration and integration. 80 DeepNL researchers shared their progress and results through presentations and posters. In the afternoon, three IAC members presented the recommendations from their midterm evaluation. This was followed by a strategic discussion with the senior researchers, while the young researchers worked on the interfaces between their projects.

2022

25 January
8 April
22 April
31 May
9 June
13-17 June
1 July
22-26 August
5-6 September
31 October
6 November
18 November

Young DeepNL visits Utrecht University
Young researchers from the various DeepNL projects visited the ToC Lab and High Pressure and Temperature facilities of the Earth Simulation Laboratory at Utrecht University.

Young DeepNL visits EBN
Young DeepNL organised its first stakeholder visit in collaboration with EBN. The main purpose was to introduce the young researchers to the activities of EBN, which is a potential user of their research results and possible future employer.

Young DeepNL visits Utrecht University
Young researchers from the various DeepNL projects visited the TecLab and High Pressure and Temperature facilities of the Earth Simulation Laboratory at Utrecht University.
The eight projects that received funding within the first DeepNL call form the basis under the DeepNL programme. In the following two Calls for proposals an additional ten projects were added to the programme. These eighteen DeepNL projects are grouped into three clusters, based on their research focus and the interfaces between projects.

**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. - p22
- InFocus: An Integrated Approach to Estimating Fault Slip Occurrence - Vossepoel et al. - p24
- μFAULT - scaling friction from micro-contacts to faults at the reservoir scale - Mishra et al. - p29
- Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field - Willingshofer et al. - p37

**RESERVOIR BEHAVIOUR**
- A multi-scale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction - Hangx et al. - p16
- Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields - Janssen et al. - p19
- The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs - Mocioi et al. - p27
- Making digital rocks a practical reality for energy storage within subsurface reservoirs - Rücker et al. - p31
- Quantitative constraints on pre-production reservoir stresses in Groningen - Govers et al. - p33
- Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoirs - Hangx et al. - p35

**Cluster 2**
Monitoring of conditions and forecasting

**DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity** - Barnhoorn et al. - p42
- Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations - Trampert et al. - p45
- PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling - van Dinther et al. - p48
- Deep, deeper, deepestNL: Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM) - Fadel et al. - p50
- LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data - Pires de Vasconcelos et al. - p52

**Cluster 3**
Subsidence and surface effects of seismicity

**Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension** - Hanssen et al. - p56
- SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential - Hicks et al. - p58
- 3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis - Ghose et al. - p60
Analysis of processes and conditions that lead to seismicity and subsidence

Can we understand and model the conditions and processes in the deep subsurface that can ultimately lead to earthquakes and subsidence?

The preparation of a heterogeneous sample for the rotary shear apparatus at Utrecht University, which is used to simulate fault mechanics (project Willingshofer et al.)
A multiscale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction

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.

Highlighted research results 2022
To understand the response of reservoir sandstones to pore pressure changes resulting from subsurface exploitation, this project combines rock deformation experiments with microstructural observations to determine which microstructural deformation mechanisms control the long-term subsurface response to fluid extraction. As a result of the COVID-pandemic, the labs in Utrecht have been closed for a couple of months, leading to delays in the experimental work. For this reason, Takahiro Shinohara was granted with a five-month extension of his contract.

Mark Jefferd joined the team as a postdoc researcher in May 2022, to further explore some of the interesting results he found as a postdoc researcher in the Science4Steer project and to connect these insights to results he found as a postdoc researcher in the Groningen gas field in the Netherlands, up to 50 percent of the compactive strain may be inelastic (permanent). What is currently unclear, is how inelastic strain will develop within a sandstone reservoir once production has stopped. To establish which time-dependent grain-scale mechanisms control inelastic strain, conventional triaxial deformation experiments were performed on Bleurswille and Slochteren sandstone, an analogue for the Slochteren sandstone, at pressure and temperature conditions representative of the Groningen reservoir. The experiments were performed at different deformation rates, spanning six orders of magnitude from 10^-1 to 10^-5 s^-1 (i.e. from 10 seconds to two weeks experiment duration). The slowest rate that was achieved in the laboratory experiments approaches the current reservoir strain rate but is still about four orders of magnitude too fast. However, even in the investigated range, the results show that slower deformation significantly weakens the rock, leading to more deformation at a given stress state. This suggests that conventional laboratory tests, at strain rates of ~10^-3 s^-1 (~1 hour experiment duration), can underestimate the in-situ amount of deformation by 30-50 percent. Therefore, understanding the grain-scale mechanisms controlling deformation ensures that predictions of in-situ compaction will be more accurate.

In collaboration with the Geomechanics Lab of Shell Global Solutions at the Energy Transition Campus Amsterdam, additional experiments were performed on Bleurswille and Slochteren sandstone under uniaxial compression conditions (i.e. zero lateral deformation, similar to the in-situ boundary conditions). These experiments will provide additional constraints on how boundary conditions impact the grain-scale deformation behaviour.

In order to obtain as much information as possible from rock microstructures regarding the grain-scale mechanisms controlling deformation, high-resolution 3D models will be developed and performed to understand the role pressure solution may play in controlling the long term (tens to hundreds of years) deformation of the reservoir. Mathematical equations, so-called constitutive relations, will be derived to describe the mechanical data. In the imaging-focused part of the project, machine learning plays an important role and deep generative adversarial networks will be used to generate robust and statistically representative novel rock volumes. These volumes can be used for a number of investigation purposes on material behaviours and physical processes. A new algorithm will be developed to create a model which takes thin sections (imaged in the three principal directions) and combines these to generate a 3D volume to be used for fluid flow analysis and other inherently volumetric processes. These 3D models can also be used as input for the previously developed grain-scale Finite...
Science4Steer – a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields

Relevance for stakeholders

The project results to date already provide new insights into stress localisation at grain contacts, both verified through modelling efforts and imaging techniques, as well as insights into the detailed workings of grain-scale deformation mechanisms, such as mass transfer and microcracking. Since the amount of compaction of the heavily faulted reservoir at depth is directly linked to induced seismicity, this research is relevant for all stakeholders involved in DeepNL and for future subsurface activities, such as CO₂ sequestration and H₂ storage. The machine learning technique to automate the analysis of thin slice images can be used for a broad area of studies.

Plots showing the mechanical data obtained in combined hydrostatic plus deviatoric loading experiments performed in the triaxial vessel on water-saturated (a,b) Bleurwiller sandstone and (c,d) Bentheimer sandstone at temperature of 100°C. (a,c) Mean effective stress (P) versus total porosity reduction data, and (b,d) differential stress versus total axial strain data.

Element model to investigate distributions and magnitudes of the grain contact and grain body stresses. The experimental and microstructural work on selected porous sandstones (two analogues and the Stiechener sandstone) will be continued to investigate the effect of deformation rate on the grain-scale processes. In addition, a microphysical model will be developed to describe the rate effect based on the identified deformation mechanisms.

Collaboration and integration within DeepNL

There is a tight collaboration with the Science4Steer project, which is reflected in the recent exchange of personnel between both projects: Mark Jefford smoothly transitioned from the Science4Steer project to this project, and Hadi Mehranpour in an equally smooth process transferred from this project to Science4Steer. Both project teams meet on a weekly basis, exchanging ideas and results.

In addition, interesting links exist with other DeepNL projects, such as the SOFTTOP project and the projects led by tenure track researchers Maja Rucker and Johannes Miocic. One of the PhD researchers from the project led by Johannes Miocic will come to Utrecht to perform experiments.

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.

Highlighted research results 2022

Geopolitical developments greatly influenced the personal lives of two of the PhD researchers. As a result, in the numerical modelling part of the project not as much progress was made as was originally planned. In this numerical part, two numerical modelling techniques are central: one approach focuses on complex phenomena at the scale from centimetres to metres, the other technique is focused on the heterogeneous multi-faulted systems from metre to kilometre scales. Analytical solutions to theoretical, physics-based models show that injection results in Coulomb stress peaks at the external reservoir/fault corners and that depletion produces stress peaks at the internal corners. Induced slip may be either aseismic or seismic depending on the nucleation mechanism/model, being, e.g., slip-weakening, rate-and-state-dependent or CSN-type friction. All of these phenomena depend on the physical characteristics of the rock. The analytical results proved very useful to systematically improve various numerical and modelling aspects of

New team member

Hannah Vogel

Hannah Vogel joined the team in November 2022 as a non-academic team member to support the machine learning based image analysis part of the project. Since Hannah carried out her master’s end project as part of this DeepNL project, she hit the ground running.

Project leader: Prof. Jan Dirk Jansen (TUD)
Associate project leaders: Dr. Auke Barnhoorn (TUD); Dr. Hadi Hajibeygi (TUD); Dr. Suzanne Hangx (UU); Prof. Chris Spiers (UU); Dr. Denis Voskov (TUD)
PDs: Dr. Pavan Cornelissen (TUD); Dr. Mark Jefford (UU); Dr. Mohammad Hadi Mehranpour (UU)
PhDs: Milad Naderloo (TUD); Alekssei Novikov (TUD); Sara Shokrollahzadeh Behbahani (TUD)
Budget: €1,451,531 – through Cal1a

WP1: Compaction and decompaction behaviour of Rotliegendes reservoirs. (Jefford – completed)
WP2: Physical experiments to determine the frictional response of faults. (Mehranpour – completed)
WP3: Physical experiments to determine mechanical and acoustic properties. (Naderloo)
WP4: Model development and upscaling. (Novikov)
WP5: Model development and numerical experiments to assess temporal and spatial changes. (Shokrollahzadeh Behbahani)
WP6: Numerical experiments to investigate system-theoretical aspects and develop control strategies. (Cornelissen)
the in-house finite-element simulator. Microseismicity during experimental cyclic loading shows that the majority of the seismicity occurs in the first cycle, with diminishing number and magnitude during subsequent cycles. Loading pattern and loading rate also influence the seismicity pattern, indicating possibility to ‘steer’ seismicity during cyclic storage.

To mimic fault reactivation in the reservoir, a large-scale displaced fault experiment was designed and built. In preparation for the experiments, the effect of pore pressures, differential stresses and stress magnitude on the internal pressure, Coulomb stress, shear stress, and normal stress was simulated. From these simulations it was concluded that to activate the fault, increasing differential stress is the preferred way, rather than injecting a fluid.

**Research focus for 2023**

So far, most of the work has focussed on what happens after depletion. In 2023, the goal is to study reverse effects numerically, analytically and experimentally. As a part of this effort, the numerical framework will be used for modelling fault slip in 2D field-wide slices of the Groningen field to model pressure equilibration and reversal effects in the field after shut in. Lab experiments will be conducted with 30 x 30 x 30 cm blocks containing a fault plane in a triaxial loading cell to mimic reservoir conditions.

**Collaboration and integration within DeepNL**

There are clear links with the DeepImage project that studies how to trace back earthquakes to their source. Furthermore, for the compaction and decompaction studies, there are contacts with the experimental work in the project of Suzanne Hangx and André Nemeijer. For the numerical part of the work there are frequent discussions about the models with Femke Vossepoel from the InFocus project.

**Relevance for stakeholders**

The results of this project are relevant to mitigate induced seismicity of past and future human activities in the subsurface, such as natural gas extraction, or (seasonal) storage of hydrogen, carbon dioxide or methane. A notable result is that cyclic loading (i.e. repeated depletion and subsequent repressurisation) of Rotliegendes reservoir rock does not seem to significantly increase the amount of plasticity that was earlier shown to develop during initial depletion. A similar trend is shown for seismicity; repeated cycles lead to a lower seismicity rate.
Probing the micromechanics of small magnitude earthquake slip

Research aim
To determine how hot and weak faults get during small magnitude earthquake slip.

Highlighted research results 2022
One part of the project aims to resolve whether magnetic measurements to reconstruct temperatures known to work well for earthquakes magnitude five or higher, can also be used for earthquakes that are a thousand times weaker, as is the case in Groningen. Due to personal circumstances, the postdoc who initially worked on this WPI resigned. A new postdoc started on this part in March 2022. This researcher spent most of their time constructing, testing, and calibrating the quantum diamond magnetometer (QDM), the first of its kind in Europe. The QDM will be able to probe local magnetisation in three dimensions (i.e., the full magnetic vector) with a resolution down to 1-2 microns and will be sensitive enough to detect the weak magnetisation effects in the Groningen sandstone that may be associated with elevated temperature and/or fluid motion tied to seismic activity. The QDM will be used to perform magnetic measurements both on experimental and natural samples. In the meantime, another magnetic technique was used to better understand the magnetic signature of the samples. High- and low-temperature magnetic measurements were performed on all samples to determine the exact magnetic mineralogy of the material. In addition, thermal fluctuation tomography was used to measure the bulk changes in the magnetic grain size distribution properties of powdered samples of Slochteren sandstone. These were compared with similar powders that had been sheared experimentally under both dry and wet conditions. Since such experiments require specialist instrumentation, these were carried out during a research visit at the Institute for Rock Magnetism, a dedicated facility for magnetic research in Minneapolis (Minnesota, USA). These results show a change in the magnetic signature related to the shearing. Likely, tiny grains (< 100 nm) of magnetite form during the experiments, and this reaction might be the result of the heat generated through sliding in the experiments. The same samples are now being analysed with the QDM. If the changes in the magnetic signature are due to shear, the expectation is that spatial changes can be observed as a function of distance to the moving shear zone boundary.

The second part of the project aims to provide constraints on the dynamic strength of gouge-filled faults under conditions relevant for Groningen induced seismicity by identifying the main weakening mechanisms and understanding how these relate to temperature rise. In 2022, a series of systematic experiments was performed at seismic velocities, both in the HPT laboratory in Utrecht as well as at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome. Experiments performed under comparable conditions in Utrecht and Rome at a velocity of 5 cm/s show good consistency. Fault gouges derived from Slochteren sandstone show moderate weakening under these conditions. An increase in velocity to about 1 m/s causes additional weakening, with a dynamic friction of 0.3-0.35. Different slip velocity functions (i.e., acceleration and deceleration) have negligible effect on weakening. Detailed microstructural investigations of the dominant deformation mechanisms are currently underway. In addition, experiments were performed to monitor the spatial distribution of temperature. The results still need further processing, but initial analysis suggests peak temperatures up to ~250 °C were reached in less than 3 milliseconds. The results will provide constraints that can be used in the development of constitutive equations for dynamic weakening in fluid-saturated fault gouges.

Research focus for 2023
For the magnetic part of the project, the focus will be on obtaining and analysing results of the spatial distribution of magnetic properties in experimental and natural samples of sheared fault gouges. The results obtained with experimental samples should allow for calibration of a thermometer based on the magnetic signatures which can then be applied to infer spatial distributions of temperature in the sheared samples obtained from cores which were active millions of years ago. In the other part of the project, the focus is on aggregating all the information obtained in the previous three years in terms of where sliding occurs, how this affects the local temperature, and how this in turn affects dynamic strength in the presence of different fluids and for variable porosity or permeability fault rocks. Ultimately, the aim is to derive a set of constitutive equations that can be used in large scale models of fault reactivation.

Collaboration and integration within DeepNL
Together with the project of Willingshofer et al. samples were obtained of suspected faults within cores from the NAM repository. Samples have been collected, macroscopically analysed using CT imaging and selected sub-samples have been thin-sectioned for further higher resolution analyses. The produced thin sections will be shared and in the context of this project will be investigated with the QDM. A further collaboration is ongoing with the projects of Vossepoel and Van Dinther, specifically regarding the physics of fault weakening and how this can or should be best incorporated into the different fault models. The aim is to collaboratively come up with a description of fault strength which honours the physics and known complexities of fault structure and composition, while still being simple enough to be included in existing models of fault rupture in single fault and multiple fault systems.

Relevance for stakeholders
Faults might weaken more in fault patches where thermal dissipation is diminished. Conversely, weakening will be suppressed where heat can dissipate rapidly. Similarly, brine saturation will have a large effect on dynamic weakening. Variable fluid properties (thermal expansion and compressibility) will affect the amount of weakening that can occur due to frictional heating. Both phenomena have huge effects on the earthquake rupture extent and need to be included in future physics-based models of fault reactivation due to stress changes in the subsurface.
InFocus:
An Integrated Approach to Estimating Fault Slip Occurrence

Project leader: Dr Femke Vossepoel (TUD)
Associate project leaders: Dr Ylona van Dinther (UU); Dr André Niemeijer (UU)
PhD: Hamed Ali Diab-Montero (TUD); Meng Li (UU)
Budget: € 818,831.- through Call 1a

Research aim
To assess the potential of ensemble data assimilation methods for estimating fault stresses and forecasting laboratory earthquakes using 2D-3D coupled simulations of geomechanics, dynamic earthquake rupture and two-phase flow.

Highlighted research results 2022
Ensemble data assimilation is applied to both 2D and 3D rate-and-state friction models. Various ensemble generation approaches have been evaluated for the representation of the uncertainties in the physical models, specifically in the shear stresses at the fault. Perfect model experiments were used to study the impact of the non-linear physics and the non-Gaussian behaviour during the transition of the interseismic phase to the co-seismic phase of the earthquake sequences. From an evaluation of the ensemble distributions in the data assimilation methods, it was concluded that the Adaptive Gaussian Mixture filter and the Particle Flow Filter can adequately represent the non-linear and non-Gaussian behaviour of the co-seismic phase. A first start was made with the implementation of these methods on the perfect model experiments to evaluate their benefits on the estimation of fault-slip occurrence. The performance of the ensemble Kalman filter was further tested on non-periodic earthquake cycles. Data assimilation significantly improves the estimates of temporal occurrence of slow slip events and to a large extent also of earthquakes. These results confirm that data assimilation is a promising approach for the combination of uncertain physics and indirect, noisy observations for the estimation and forecasting of both slow-slip events and earthquakes.

A paper was published on the characteristics of earthquake sequences. The paper describes a systematic study of the advantages and limitations of simplifications that eliminate spatial dimensions in quasi-dynamic earthquake sequence models, from 3D models with a 2D fault plane down to 1D models with a 0D fault point. When 2D or 3D models produce quasi-periodic characteristic earthquakes, their behavior turns out to be qualitatively similar to lower-dimension models. Certain co-seismic characteristics like stress drop and fracture energy are largely comparable. Other observations like recurrence interval and amount of slip are affected by dimension reduction, but a correction to the stressing rate is proposed that fully corrects for dimension reduction. All in all, the paper provides qualitative and quantitative guidance on economic model design and interpretation of modelling studies. In addition, 2D-3D models are developed that feature more physics, including dynamic earthquake ruptures and simplified reservoir mechanics and fluid flow through faults. Some of these are benchmarked against other earthquake sequence and aseismic slip models in two peer-reviewed and one submitted papers. Another paper that will soon be published features the first application of novel phase field methods to earthquake sequences. Two papers are in preparation on how earthquake nucleation arises under velocity-strengthening friction and how much aseismic slip can be expected. This has important implications for induced seismicity world-wide, but is particularly relevant for Groningen, where the possibility for this previously unthinkable option first came to light. In Groningen earthquake nucleation remains enigmatic as the reservoir rocks in which nucleation is thought to occur are measured in the laboratory to increase in strength when slip rates increase (i.e., be velocity-strengthening, VS), thereby inhibiting a seismic response. This study suggests healing, a process increasing interface strength during the millions of years inactivity, makes one earthquake possible. It quantifies the healing time required for an earthquake to occur under velocity-strengthening rate-and-state friction parameters and suggests that once the energy available for fracture is released a next earthquake at that specific location becomes highly unlikely.

The project team will conduct further experiments with the inverse Gas Chromatograph to fully explore its potential. They use different type of samples (glass beads and graphite) to develop a new model for multiphase flow, geochemical reactions and potential structural alterations.

WP1: Development forward model for seismicity and fluid flow in poro-viscoelasto-plastic media (Goudarzi) – completed
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)

The figures show:
(a) Shear stress estimation of earthquakes with prior distributions (b) during the seismic and (c) just after the co-seismic phase.

DeepNL research projects
The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs

Research aim
To provide a petrographic model of the Groningen gas field and its surrounding aquifers in order to predict reservoir compaction and surface subsidence.

Highlighted research results 2022
Different visits have been made to the NAM core store to select cores from the right depths of about 16 different wells, some of which are located in the aquifers surrounding the Groningen gas field. Some 300 blue-dyed epoxy impregnated thin sections have been made out of these cores. The first start was made with scanning electron microscopy analyses of these samples at the EPOS-NL facilities in Utrecht. In this first phase, an inventory is made of which clay minerals are present where and in which quantities.

A machine learning algorithm is under development to automatically determine grain and pore sizes and grain size distributions from the microscopic images of the thin sections. The researchers on the project have been heavily involved in the first DeepNL Summer School. They both gave lectures and organised a field trip.

Research focus for 2023
The core samples will be further analysed with optical microscopy and electron microscopy to determine the rock properties, including detrital and authigenic mineralogy, depositional environment, grain properties and model order reduction techniques that might help speed up the data assimilation of laboratory data with 3D rate-and-state friction models, and the project of André Niemeijer, concerning rate-and-state friction properties in Groningen lithologies.

Relevance for stakeholders
Data-driven physics-based tools such as the ones developed within this project are fundamental to establish operational frameworks that can estimate and potentially forecast the occurrence of induced seismicity. The use of assimilation of stress and velocity observations allows for better estimates by constraining fault slip occurrence to the observations. It is expected to contribute to better informed decision-making and more accurate hazard assessment, while considering the uncertainties of both the physical models and the available observations.

Research focus for 2023
The aim for 2023 is to complete the papers on model developments, quantification and understanding of velocity-strengthening friction for understanding and forecasting induced seismicity world-wide and in Groningen, as well as the implementation and performance of a Particle Flow Filter. The ensemble data assimilation methods will be applied in an experiment that represents a laboratory experiment conducted in the National Research Institute for Earth Science and Disaster Prevention, Ibaraki, Japan. The observations along the meter-scale fault in this experiment will be assimilated and the state of stress and velocities will be estimated to evaluate the forecastability of slip on this laboratory fault.

The same numerical forward model will be used to understand fascinating new processes observed in this laboratory experiment relating to the role of fault heterogeneity. The influence of heterogeneous stress and frictional properties on the nucleation and rupture behaviour as well as fault slip characteristics will be studied. Both PhD researchers will prepare their dissertations.

Collaboration and integration within DeepNL
The data assimilation work is carried out in close collaboration with Samantha Kim from the project of Ramon Hanssen. Mutual interactions exist with the DeepNL projects from Jeanot Trampert, particularly for the use of

Project leader: Dr Johannes Miocic (RUG)
PhDs: Dmitry Bublik (RUG); Sebastian Mulder (RUG)
Budget: € 749,754.- through Call 1b
μFAULT - scaling friction from micro-contacts to faults at the reservoir scale

Research aim
To develop physics-based friction models for fault contacts following a bottom-up approach and use these models to compute fault slip resulting in induced seismicity due to subsurface activities.

Highlighted research results 2022
In 2022, the research related activities included the design and testing of a new experimental setup for single-grain sliding experiments, learning and understanding of numerical methods to simulate friction in fault-gouge assembly, and selection and recruitment of a PhD candidate for the project.

A robust and novel technique was developed for scaling friction in single-grain contacts to model maximum fault slip events in granular gouge assembly. In an attempt to simulate the macroscopic behaviour, for the first time ever, the rate-and-state frictional (RSF) properties on single-grain contacts were measured. Using these values in a numerical model for seismic slip (so-called ‘seismic cycle simulator’), a seismic cycle was obtained.

Research focus for 2023
Work will be done on modelling frictional ageing in single-grain and rough contacts in faults, while taking into consideration the effects of capillary kinetics, chemical ageing and deformation creep on static friction in silica contacts. A high precision experimental setup will be used to validate the model. The model will compute static friction as a function of hold (dwell) time.

Collaboration and integration within DeepNL
The geomechanical experiments for this project will be conducted in the lab in Utrecht. To this end, extensive contacts with Suzanne Hangx exist. This year, a joint paper was published together with Suzanne Hangx, though not about this DeepNL project. The microscopy work at Utrecht University is supported by EPOS-NL. Once finished, the machine learning algorithm for analysing sandstone images will be made openly available. This can be of broader use for people who want to determine the capacity of a certain sandstone for gas storage (e.g. hydrogen or CO2).

Relevance for stakeholders
The reservoir’s behaviour depends on rock properties. Hard geological data is thus of crucial importance to understand compaction, subsidence and seismology as a result of fluid extraction from the underground. This is not only relevant for gas production, but also for future applications such as subsurface hydrogen storage.

DeepNL research projects
**Making digital rocks a practical reality for energy storage within subsurface reservoirs**

**Research aim**
To develop a digital rock model containing data about the internal surface of the rock at the smallest scales, that can serve as input for models on multiphase flows and reactor transport.

**Highlighted research results 2022**
A novel workflow was developed to investigate 3D fluid films in porous rocks at the nano- and micrometre scale. This method, consisting of AFM measurements combined with computational modelling, was used to study static, frictional behaviour of quartz microcontacts with relevance to friction in sandstone faults. Pins made from monocrystalline quartz with tip sizes of 50-500 μm will be slid on quartz sheets under varying operating conditions. The potential will be studied of the discrete particle solver YADE-DEM to model friction in granular fault gouge systems using contact and friction laws derived from the micro-scale experiments.

**Relevance for stakeholders**
Understanding and modelling of frictional ageing will be of help in the feasibility studies of subsurface (depleted) reservoirs for storage applications.

**Collaboration and integration within DeepNL**
There is an obvious link with the project of Suzanne Hangx, which also uses single-grain contact models to study reservoir compaction. It would be good to exchange contact and friction models. Also, there are interesting links with the project of André Niemeijer. Both projects are looking at fault friction under different conditions: Niemeijer’s project looks at frictional heating in dynamic slip, while this project focuses on friction in quasi-static slip instead. Nevertheless, the developed microscale models and numerical models will be mutually beneficial. In developing the models for frictional aging and including effects of capillary kinetics, knowledge will be shared with the project of Maja Rücker on capillary driven multiphase flow in rough contacts.

**Relevance for stakeholders**
This project will help constrain friction in the reservoir faults. As a result, more accurate predictions of the expected magnitudes of earthquakes related to the Groningen gas reservoir will become feasible.

**New team member**

**Malek Jaran**
Malek Jaran joined the DeepNL programme as the PhD researcher for the μFault project starting 15 September 2022. He has completed his Masters in Advanced design of ships and offshore structures from University of Liege, Belgium and Ecole Centrale de Nantes, France. Prior to this, he completed his Bachelors in Mechanical engineering from the University of Jordan. Malek is keen on being among the first contributors to the upcoming field of Geotribology in the Netherlands. He is motivated to contribute to improving human lives affected with induced seismicity and to improving the role of the Dutch subsurface in the ongoing energy transition.
DeepNL research projects

Quantitative constraints on pre-production reservoir stresses in Groningen

Project leader: Dr Rob Govers (UU)
PhD: Renato Gutierrez Escobar (UU)
Budget: € 291,328.- through Call 2a

Research aim
To gain understanding about why 1991 was a tipping point in inducing seismicity, by reconstructing natural stresses in Groningen before gas production started.

Highlighted research results 2022
Forces in the plate arise where lateral differences in the gravitational potential energy occur. Thus, to quantify the likely ranges of magnitudes and directions of forces in the plate, a model is needed that can account for the effects of these lateral differences.

Gravitational potential energy (GPE) for one of the most accurate complete lithospheric models.
that may explain present-day natural stresses within the Eurasian plate, the first focus within this project was on quantifying the gravitational potential energy. A new method was developed to determine the gravitational potential energy from recently published models of the density layering of the lithosphere. Differences exist in the methods and observations that were used in these studies, with significant variability in the resulting models and particularly in lithospheric thickness. The aim was to determine how much this variability affected the plate tectonic forces that are associated with them. The resulting differences in the directions and magnitudes of stresses were computed with finite element models that also incorporate other plate driving forces. The computed stresses were compared to observed directions of the natural stress field. This comparison led to the development of different objective functions to quantify the misfit of the modelled and observed stresses, fault slip directions and magnitudes, the deviation of the net torque on the plate from zero, and the model representation error.

Research focus for 2023
Validation of the new method, for instance by comparison with theoretical models, will be an initial focus. The upcoming period will be used to develop and optimise a workflow aimed at finding ranges of finite element model parameters that yield a good fit to available observations.

The aim is to map the magnitudes and directions of lithosphere-averaged stresses for the entire Eurasian plate by the end of the year. This model will then stepwise be improved upon to eventually be able to zoom in to the natural stresses occurring in the Netherlands and more specifically in Groningen.

Collaboration and integration within DeepNL
First interactions with other DeepNL projects and DeepNL researchers have been established, primarily focussed on knowledge exchange. Quantitative constraints on the natural stress field are critical for currently running DeepNL studies like InFocus and the project led by Jeannot Trampert. 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 project led by André Niemeijer and the Science4Steer project.

Relevance for 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 CO₂, 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.

Research aim
To provide the experimental rock mechanics data and quantitative understanding of the Groningen under- and overburden formations needed to further constrain the timescale upon which seismic activity and subsidence will slow down or halt after changes in production strategy.

Highlighted research results 2022
The method for the mechanical experiments has been developed. This included setting up the triaxial machine, calibrating it, developing a workflow, and testing it on Opalinus claystone, which can be considered a good analogue for the Groningen clay-rich rocks. The workflow is developed in such a way that the experiments can vary a set of parameters (temperature, stress, pore pressure, pore fluid chemistry) and monitor the mechanical response. Systematic variation in the parameters will provide information on the mechanism dominating sample deformation. This ultimately allows for determining the dominant deformation mechanism operating at the in-situ conditions.
Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field

Research aim
To constrain the structure, geometry and rheology of faults and fault zones in the Groningen reservoir at multiple spatial scales.

Highlighted research results 2022
Deformation experiments have been performed in a rotary shear configuration to understand how material mixing and clay-smearing affect the mechanical strength and stability of faults that juxtapose reservoir rocks (Slochteren sandstone) against contrasting lithologies such as the clay-rich Ten Boer claystone and Carboniferous shales. Results have shown that along-fault heterogeneity produces a complex evolution in sliding friction, depending on the shear-displacement and juxtaposition of mechanically contrasting lithologies. Light and electron microscopy analysis of the sheared gouges provides evidence for the development of clay-smears and strain-localisation within localised shear bands, and for lithology mixing at large shear-displacements, explaining the evolution in sliding friction and frictional stability. The results have important implications for modelling earthquake nucleation, propagation, and arrest and apply to faults in geological settings that exhibit induced seismicity, like the Groningen gas field.

Research focus for 2023
With the triaxial machine, the mechanical behaviour of the Opalinus claystone which serves as an analogue for the Groningen shales will be investigated first. An analogue shale is used to confirm the best approach, before testing the valuable samples obtained from the Groningen gas field, of which the Carboniferous shales are the first to be investigated.

Mechanical data friction experiments: a) Sliding friction as function versus displacement of endmember gouges (TB = Ten Boer claystone, SL = Slochteren sandstone) and spatially segregated gouge thereof. b) Corresponding rate sensitivity parameter (a-b) versus displacement where (a-b)>0 indicates velocity strengthening and (a-b)<0 indicates velocity weakening (prone to earthquake nucleation).
Collaboration and integration within DeepNL

Experimental results as well as quantitative petrological data and relations between fault architecture, lithologies and mechanical behaviour can be used to constrain input for numerical geomechanical models, reservoir models and dynamic rupture models. There is great potential for the application of scaling relations resulting from this project to the InFocus, Science4Steer, and the DeepImage projects. Close collaboration with the DeepNL project ‘Probing the micromechanics of small magnitude earthquake slip’ is anticipated on comparative studies of fault gouge micro structure in natural and experimental faults. Furthermore, knowledge exchange is already conducted with the PhysMmax, LabQuakeAI and ‘Probing the micromechanics of small magnitude earthquake slip’ projects.

Relevance for stakeholders

The relations between fault architecture, along-fault lithology distribution and mechanical behaviour are directly relevant to improving the forecasting capabilities of advanced geomechanical and seismic wave field modelling approaches, and hence to improving risk assessment associated with reservoir depletion.

Research focus for 2023

The research focus will shift to the field-micro-scale analysis of natural fault rock material and fault structure for comparison with the already obtained results from rock physics experiments. In particular, results from the quantitative petrographic analysis and established fault paragenesis will form the basis of a detailed microstructural analysis of grain-scale deformation. High resolution SEM will be used to quantify the observed variations in microstructural state variables of the faulted rocks including the porosity, grain size distribution and presence of cements, which is key to understand the microphysics behind the fault frictional behaviour. These results will be integrated with data on simulated fault gouges from the friction experiments and natural gouges from outcrop analogues to be able to extrapolate mechanical behaviour in the lab to larger scale deformation of Groningen type faults.

In addition, structural scaling relationships will be further developed by setting up a first series of analogue models of fault zone development and re-activation.

on the presence of faults, fractures and other deformation features. Core depth intervals were successfully selected based on the NAM PetRel Geological model of the Groningen gas field and the NAM core photographs dataset. Quantitative petrographic analysis has demonstrated the presence of different generations of cements (anhydrite, dolomite, siderite and quartz) related to the fault activity. These results are correlated with stratigraphic well-logs to obtain a fault material paragenesis (chronological order of diagenetic processes/phases in relation to the faults). Reconnaissance fieldwork in the Central and Northern UK served to select suitable sites for the study of exposed faults and fault systems that cut through sand and shale sequences analogues to the subsurface of the Groningen gas field. Promising outcrop analogues were found to study the multi-scale relationship between deformation structures and lithologies for intra-Rotliegend fault systems (e.g. the Clashach fault and small scale faults in the Vale of Eden), intra-Carboniferous fault systems (e.g. Hopwick fault) and large displacement fault systems where the Rotliegend is juxtaposed against Carboniferous (90-Fathom fault). The most promising sites will be selected for subsequent detailed structural studies.
Monitoring of conditions and forecasting

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

An 30x30x30 cm reservoir analogue including a displaced fault, which is used in large-scale fault reactivation experiments (project Jansen et al.)
DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity

Project leader: Dr. Auke Barnhoorn (TUD)
Associate project leaders: Prof. Kees Wapenaar (TUD), Dr. Deyan Draganov (TUD), Dr. Ranajit Ghose (TUD), Dr. Kees Weemstra (TUD/KNMI)
PhD: La Ode Marzuibar Masfara (TUD); Jingming Ruan (TUD); Faezeh Shirmohammadi (TUD); Auke Veltmeijer (TUD)
Budget: € 1,053,152. through Call 1a

WP1a: Development of seismic imaging and monitoring methodology. (Shirmohammadi)
WP1b: Development of seismic imaging and monitoring methodology. (Masfara)
WP2: Laboratory experiments: early detection of stress changes, failure and seismicity in rocks using acoustic techniques. (Veltmeijer)
WP3: Numerical seismic modelling. (Ruan)

Research aim
To develop an integrated methodology for seismic imaging and monitoring of the Groningen subsurface and its induced seismicity, based on innovative scaled rock-mechanics experiments, advanced geomechanical and seismic modelling, and advanced seismic-data imaging and inversion techniques.

Highlighted research results 2022
After Kees Wapenaar retired, the formal project lead was taken over by Auke Barnhoorn (Kees stays on as Co-PI). Together with DeepNL project 3DSoIL, extensive fieldwork was conducted in the Groningen region to acquire active-source seismic data focusing on body-wave reflections, for WP1a, and on complete wavefield, for 3DSoIL. In a 2D set-up containing 600 receivers and 150 sources, vibrational stimuli were applied to the surface, and seismic reflections from different layers in depth were recorded. Also, using 26 x 26 3-component receivers, 3D seismic data were acquired in two square patches of different sizes at the same site. Different shear-wave velocity models derived from the observed data as well as the velocity model of NAM were used to test their applicability for monitoring purposes. In the numerical modelling work, the focus was on determining the effects of source-model parameters on the dynamic rupture and the resulting seismic wavefield. To come to a realistic source-region structure as input for the simulation of the ground motion due to an induced earthquake, different intersecting fault models and their geomechanics were studied. Through numerical modelling, an earthquake was simulated with a magnitude of 3 on the Richter scale at uniform depletion conditions, using the Zeerijp reservoir structure from NAM. A sharper fault-intersection angle turned out to increase the required depletion value for triggering a seismic event. The fault reactivation in the Zeerijp model elucidated a combined nucleation pattern due to the intersecting faults, where an upper seismic slip patch at the juxtaposition expands and merges with a lower aseismic slip patch, followed by expansion of the total patch in the strike direction and an acceleration of the slip inside the slip patch.

A 3D seismic moment-tensor inversion method was applied both to the simulated seismic data and to a real induced seismic event (M 3.4) that struck the Westerwijtwerd village in 2019. The developed workflow estimates different earthquake parameters: the hypocenter, the moment tensor, and the time of origin. The results not only turned out to be in good agreement with the previous findings, but, most importantly, also with the geological features of the area. According to these results, the earthquake occurred near a major fault located a couple of hundred metres above the reservoir. In the lab, active acoustic measurements were done at millimetre and centimetre scales on Groningen equivalent sandstone samples at different fluid pressures, both under stepwise and cyclic loading conditions. The acoustic signals showed small but clear changes directly prior to the fault reactivation. To upscale the measurements and determine if the detected changes can be used for monitoring purposes at field scales, a 30 x 30 x 30 cm experimental set-up was subsequently constructed and tested.

There is a lively exchange of information between the four PhD researchers in the project. They use each other’s results to verify or improve their own models and/or methodologies. Data from the experiments is fed into the models/methodologies and vice versa: insights from the models are also used to improve the experiments.

Research focus for 2023
In 2023, larger-scale lab experiments will be conducted with the 30 x 30 x 30 cm set-up to observe when and where the slip occurs along a fault, and if the seismic event is preceded by an observable change in the acoustic signals. The fault rupture model will be extended to include multiple intersecting faults that interact with each other. The geomechanical simulation will be combined with seismic moment-tensor inversion, applying constraints from field-seismic observations. Reservoir pressure history will be used for geomechanical modelling for simulation of the 2018 Zeerijp M 3.4 event.

To improve the accuracy of the velocity model and to proceed toward the envisioned layer-specific imaging and monitoring methodology, Marchenko redatuming and non-physical-reflection techniques will be used to project surface seismic data to specific locations in the subsurface. The 3D source-modelling methods will be applied to larger datasets.
Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations

**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 will be used to forecast seismic hazards of production scenarios based on advanced statistics.

**Highlighted research results 2022**
In the aftermath of the COVID pandemic, two members of staff decided to return to their home country to be closer to family. As a consequence, the project has been reconstructed somewhat while honouring its research aim. WP1 has been dropped from the project and is now reconstructed somewhat while honouring its research aim. WP1 has been dropped from the project and is now being redeployed by the DICTUM researchers. WP3: Generation of Green’s functions for varying seismic sources and changes in geometry, stress, and elastic structure (de Jong)
WP4a: Development of neural network tools for monitoring time dependent properties using the Green’s functions as training data (Fokker)
WP4b: Development of neural network tools for monitoring time dependent properties using the Green’s functions as training data (Hawkins – replacement t.b.d.)
WP5: Application of the monitoring data to stochastic decision tools for future production scenarios (Baki)
• The Python wrappers around the open-source wave propagation code SPECFEM3D that have been developed within this project have been used in DeepImage to develop a workflow to infer seismic sources for induced events. This resulted in a joined publication.

For the other work packages, work has continued as planned. Significant progress has been made on model order reduction. A scheme was proposed similar to the techniques developed in normal mode seismology. It significantly reduces computational time and allowed for performing a fully non-linear inversion for a stress perturbation in the Groningen reservoir using full waveform modelling. In addition, a reduced model is being built from solutions of the seismic wave equation in the frequency domain. This approach has the main advantage that it has an excellent accuracy with much smaller reduced models than existing approaches, reducing the computational time dramatically.

Collaboration and integration within DeepNL
There are collaborations with the project of Jeannot Trampert with regard to the seismic velocity models and with the Science4Steer project regarding lab experiments. Joint field experiments were conducted in collaboration with the 3D5Oil project led by Ranajit Ghose and Michael Hicks.

Relevance for stakeholders
The geomechanical modelling workflow can be used to explain field observations and to predict the consequence of future fluid extraction or injection. The developed methodology for retrieval of non-physical reflections can be very interesting for monitoring of the reservoir layer for temporal and cyclic storage of H2 and reflections can be very interesting for monitoring of the reservoir layer for temporal and cyclic storage of H2 and for CO2 sequestration. In fact, several of the methods developed within DeepImage are also used in the SUCCEED project on injection of CO2 in geothermal systems (project led by the Imperial College London) and the SHARP project on CO2 storage and seismicity (project led by NGI, Norway). Both projects are funded by ACT.

The tools and knowledge on failure forecasting can be used for the understanding and monitoring of induced seismicity in gas reservoirs, and of geothermal or H2 storage or other subsurface operations. The new workflow for 3D source modelling is more accurate and less time consuming than other existing methods. This workflow, and individual parts thereof, are also relevant to assess the effects of fluid injection in geothermal energy exploration and in hydrogen storage projects.

Map showing the difference in the epicenter estimates when using different strategies. Assuming the earthquake was due to a major subsurface fault movement, data from three seismometer components give a better constraint on the earthquake’s location.
In seismology, receiver functions are used to image seismic discontinuities due to compositional or phase changes. Using SPECFEM3D, the receiver function technique has been adapted in the context of full waveform inversion to image interfaces and discontinuities in a fully 3D Earth. The theoretical framework has been published and a paper has been submitted on global scale applications. Proof of concept examples have been made for monitoring changes in discontinuities in the Groningen setting.

For the shallow subsurface, a technique was devised where seismic noise, which often is discarded, is used to infer small temporal and spatial variations in seismic wave speeds. These seismic wave speed changes can then be inverted for pore pressure changes in the first few hundred meters of the subsurface. This is the first time that seismic noise has been used to directly monitor induced stress changes in the subsurface.

An investigation into the effect of gas production volumes on the number of annual earthquakes has been published and a paper has been submitted on global scale applications. Proof of concept examples have been made for monitoring changes in discontinuities in the Groningen setting.

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Photograph of the TWI team: Dr. Thijssen, Dr. Gritti, Dr. Vars, and Dr. van Lieshout.

**Research focus for 2023**

While the normal mode approach to model order reduction produces considerable speed-ups of SPECFEM3D, approaches based on judiciously chosen combination of specific solutions to the seismic wave equation in the frequency domain are more efficient. As a next step the latter will be developed into so-called localised model order reduction approaches, where the computational domain is decomposed and localised reduced models are built on the subdomains (small parts of the original computational domain). This will allow for applying (localised) model reduction to truly large-scale 3D simulations, reducing the computational time of one forward simulation tremendously.

Having finalised the proof of concept of monitoring discontinuities with sensitivity kernels for receiver functions, it will be investigated how the technique can be adapted to the Groningen subsurface to image compaction directly.

The pore pressure modelling will be extended by including temperature effects in the stress-strain relations. This might be important, especially in geothermal applications.

**Collaboration and integration within DeepNL**

When the project was restructured, the NARS equipment, which was installed over the Groningen gas field, was offered to the DICTUM-project. The seismometers are now being installed together with other equipment over a larger area in the Netherlands with the aim to produce high-resolution information on the Dutch crust and uppermost mantle. The Python wrappers to the SPECFEM3D community code was offered to the DeepImage project, allowing it to develop a workflow to infer seismic source information of induced events using full waveform modelling.

**Relevance for stakeholders**

The developed Python wrappers allow stakeholders to run SPECFEM3D to model wave propagation in the Groningen gas field. The code is freely available and can be found in the output overview of this project at the end of the annual report. The NARS broadband data recorded across the Groningen gas field are openly available via the KNMI. The method to monitor induced stress using seismic interferometry will be valuable in many settings outside the Groningen gas field. Code for non-parametric hazard map estimation (bw.CvL, adaptive) has been made available in the open source R-package spatstat. An informed decision-making tool will be relevant for stakeholders.

**Research in WP5 is now devoted to a modified rate-and-state model, which takes into account changes in gas production volumes, latent random effects and uncertainty in the pore pressure field. The model will be used to monitor seismic hazard and guide policy makers by quantifying the effects of various production policies.**
PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling

Research aim
To generate the best possible, physics-based, probabilistic constraints on the maximum earthquake magnitude for induced seismicity in Groningen through novel coupling in 3D physics-based modeling, theoretical developments and their combination with geological and geophysical data.

Highlighted research results 2022
The project explores two different routes to simulate earthquake rupture behaviour and fault stresses. First, 3D dynamic earthquake rupture modelling was performed on complex faults using the high-performance computational seismology software SeisSol. Phenomena under study were fault dip, dynamic friction, fault offset, and fault roughness using material parameters and geometrical configurations typical for Groningen. These largely confirm findings of previous studies in 2D, although reflecting waves transform ruptures into pulses and increase slip somewhat. The first 3D dynamic rupture simulations of the 2022 ML3.1 Wirdum earthquake showed spontaneous nucleation in vicinity of the observed hypocentre, propagation in two directions and spontaneous arrest near fault bends that affected stress build up. This is the basis for a proof of concept supporting our understanding and modelling chain of stress build up under gas depletion and earthquake rupture propagation. Finally, a re-interpretation of the fault geometry beneath Wirdum revealed significantly shallower dipping faults than currently used in the available fault model; both within the reservoir (average of 63 instead of 79 degrees) and beneath it due to a more lystric extension. This is more consistent with observations from focal mechanisms and our geomechanical understanding.

Second, Linear Elastic Fracture Mechanics models were used to determine rupture potential along Groningen fault structures. 2D fracture mechanics and rupture tip equation of motion were used to estimate along-dip rupture width, along-strike rupture length, and the amount of slip for single planar faults. Work was initiated to determine a critical step-over jump distance for dip-slip rupture.

Research focus for 2023
Finalise simulations of the 2022 ML3.1 Wirdum earthquake and compare them to reproduce seismological observations to understand this earthquake’s nucleation, propagation and arrest, the role of large-scale fault roughness and geometry, and validate our understanding of fault loading in Groningen.

Second, simulate stress loading and earthquake ruptures near fault intersections to better understand the frequent occurrence of earthquakes near intersections and rupture jumping. This will be combined with the determination of a critical step-over jump distance for dip-slip rupture, such that rupture tip equation of motion can be extended for fault branching and step-over jumps, and ultimately Mmax can be re-evaluated using LEFM methods for a complete fault network.

Collaboration and integration within DeepNL
Through bridging from observations and fundamental understanding to important applications on Probabilistic Seismic Hazard Analysis in Groningen, PhysMmax will increase the cohesion between and strengthen the impact of the eight current DeepNL Call 1a projects for Groningen.

Relevance for stakeholders
The maximum magnitude is the most important parameter influencing probabilistic seismic hazard assessment (PSHA) and thereby decision-making. However, it is ill-constrained as observations on which estimates are based are inevitably too limited in time. Adding physics will not only provide the critical information needed to better decide on Groningen, but can afterwards also be extended to significantly improve PSHA and decision making when utilising subsurface resources more sustainably. The new theory on rupture propagation and arrest and to be developed understanding of the role of fault roughness and rupture across complex faults may also revolutionise our hazard assessment for natural earthquakes.
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.- through Call 2a

Research aim
To develop new high-resolution, multi-physics, seismic velocities, density, and thermal models of the Dutch crust and upper mantle down to 200 kilometres depth using data from a proposed densified broadband seismological network of inland and sea bottom seismometers integrated with the freely available high-resolution Bouguer gravity data and upper crust thermal models.

Highlighted research results 2022
A comprehensive literature review was carried out on the crust and upper mantle structure of the Netherlands. Moreover, the preliminary work to update the available crustal thickness map of the Netherlands using standard seismological techniques has been started.

One of the main project activities in 2022 was the densification of the broadband seismological network in the Netherlands. Currently, 20 broadband seismological stations are in operation for the DICTUM project, and 14 of them are new sites that will provide new seismological coverage in the Netherlands for the first time.

Another interesting milestone was the first North Sea Bottom Seismometer experiment at Texel Island to test the possibility of observing earthquakes and long-period seismic noise in the Dutch North Sea. The experiment had a twofold aim: to better understand the effect of the environment on the seismological measurements (especially sand dynamics), and to test the instrument’s protection against living organisms and rust. Colleagues from NIOZ and AWI worked on a new design for the sea bottom seismometer (SBS) to improve the equipment’s protection, stabilise the instrument’s frame, and increase the coupling of the sensor to the ground. Because the conditions near the shore are more aggressive than in deeper water, the new design was deployed in shallow waters near NIOZ harbour at Texel for two months. To evaluate the SBS performance, in addition a land station was deployed at a 700 meter distance. Considering the extreme deployment conditions, promising data was obtained from the SBS. The conclusion was that the new design would potentially be able to detect teleseismic earthquakes and long-period noise with the possibility of getting cleaner signals at deeper water depths.

Research focus for 2023
The 3D shear-wave velocity model and the 1D layered models underneath the seismic stations in the Netherlands will be updated using standard seismological techniques. Moreover, the land-based network will be fully deployed and running. Finally, there is an ongoing effort to develop a new sea-bottom seismometer that can be instrumental for both 3D subsurface imaging and monitoring applications.

Relevance for stakeholders
Given the future ambition of utilising the Dutch subsurface for ultra-deep geothermal energy from the deep Dinantian rock formations below five kilometres depth, there is an urgent need to understand and image the crust and upper mantle structure of the Netherlands in great detail. Also, for locating and characterising seismicity, a refined velocity model of the deeper structure is indispensable.

Collaboration and integration within DeepNL
The NARS equipment, which was installed over the Groningen gas field within the scope of the project led by Jeannot Trampert, was offered to the DICTUM project. In a broader sense, the fundamental and quantitative understanding of the distributions of the Earth’s resources and the risk of seismic hazard requires high-resolution regional seismic velocity, density, and thermal models. For example, to understand earthquake impact over distances beyond a ten kilometre radius, accurate regional velocity and density models and their uncertainties are essential for seismic risk assessment and hazard mitigation. Moreover, the derived regional seismic velocity, thermal and density models can be used for regional perspective mapping of the thermal resources in the subsurface.

Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), University of Münster, KNMI, and Utrecht University. The experiment had a twofold aim: to better understand the effect of the environment on the seismological measurements (especially sand dynamics), and to test the instrument’s protection against living organisms and rust. Colleagues from NIOZ and AWI worked on a new design for the sea bottom seismometer (SBS) to improve the equipment’s protection, stabilise the instrument’s frame, and increase the coupling of the sensor to the ground. Because the conditions near the shore are more aggressive than in deeper water, the new design was deployed in shallow waters near NIOZ harbour at Texel for two months. To evaluate the SBS performance, in addition a land station was deployed at a 700 meter distance. Considering the extreme deployment conditions, promising data was obtained from the SBS. The conclusion was that the new design would potentially be able to detect teleseismic earthquakes and long-period noise with the possibility of getting cleaner signals at deeper water depths.

Research aim
To develop new high-resolution, multi-physics, seismic velocities, density, and thermal models of the Dutch crust and upper mantle down to 200 kilometres depth using data from a proposed densified broadband seismological network of inland and sea bottom seismometers integrated with the freely available high-resolution Bouguer gravity data and upper crust thermal models.

Highlighted research results 2022
A comprehensive literature review was carried out on the crust and upper mantle structure of the Netherlands. Moreover, the preliminary work to update the available crustal thickness map of the Netherlands using standard seismological techniques has been started.

One of the main project activities in 2022 was the densification of the broadband seismological network in the Netherlands. Currently, 20 broadband seismological stations are in operation for the DICTUM project, and 14 of them are new sites that will provide new seismological coverage in the Netherlands for the first time.

Another interesting milestone was the first North Sea Bottom Seismometer experiment at Texel Island to test the possibility of observing earthquakes and long-period seismic noise in the Dutch North Sea. The experiment had a twofold aim: to better understand the effect of the environment on the seismological measurements (especially sand dynamics), and to test the instrument’s protection against living organisms and rust. Colleagues from NIOZ and AWI worked on a new design for the sea bottom seismometer (SBS) to improve the equipment’s protection, stabilise the instrument’s frame, and increase the coupling of the sensor to the ground. Because the conditions near the shore are more aggressive than in deeper water, the new design was deployed in shallow waters near NIOZ harbour at Texel for two months. To evaluate the SBS performance, in addition a land station was deployed at a 700 meter distance. Considering the extreme deployment conditions, promising data was obtained from the SBS. The conclusion was that the new design would potentially be able to detect teleseismic earthquakes and long-period noise with the possibility of getting cleaner signals at deeper water depths.

Research focus for 2023
The 3D shear-wave velocity model and the 1D layered models underneath the seismic stations in the Netherlands will be updated using standard seismological techniques. Moreover, the land-based network will be fully deployed and running. Finally, there is an ongoing effort to develop a new sea-bottom seismometer that can be instrumental for both 3D subsurface imaging and monitoring applications.

Relevance for stakeholders
Given the future ambition of utilising the Dutch subsurface for ultra-deep geothermal energy from the deep Dinantian rock formations below five kilometres depth, there is an urgent need to understand and image the crust and upper mantle structure of the Netherlands in great detail. Also, for locating and characterising seismicity, a refined velocity model of the deeper structure is indispensable.

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The NARS equipment, which was installed over the Groningen gas field within the scope of the project led by Jeannot Trampert, was offered to the DICTUM project. In a broader sense, the fundamental and quantitative understanding of the distributions of the Earth’s resources and the risk of seismic hazard requires high-resolution regional seismic velocity, density, and thermal models. For example, to understand earthquake impact over distances beyond a ten kilometre radius, accurate regional velocity and density models and their uncertainties are essential for seismic risk assessment and hazard mitigation. Moreover, the derived regional seismic velocity, thermal and density models can be used for regional perspective mapping of the thermal resources in the subsurface.
LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data

Research aim
To use machine learning techniques on acoustic measurements of complex analog fault experiments to uncover information about the state of the fault and to inform predictions of the time to failure.

Highlighted research results 2022
After initially reproducing previous AI-based time-to-failure predictions on existing data, additional failure experiments were performed to learn experimental techniques and to grow the existing database of laboratory earthquakes with continuous acoustic emission monitoring. This new set of experiments was chosen according to the initial AI predictions, thus taking the first step toward the greater goals of the project. In previous research, a supervised machine learning technique was developed and used to successfully predict the timing of laboratory earthquakes. Those results have been reproduced on the Utrecht data sets, while also gaining new insights into the AI-based prediction itself. In the older approach, the data are treated independently in different windows which means that any temporal evolution in the signal – i.e., information across the time scales of individual time windows – is neither considered nor inferred. Novel dimension reduction techniques have been used to visualise the full temporal evolution of features of the data. Visual inspection of the embedded features showed that different shear stress measurements map to distinct patterns, meaning that it is not only the snapshot in time of the feature holding information but the temporal evolution as well, and that the patterns repeat for multiple laboratory earthquake cycles. Feeding the embedded features into a ML model in addition to the traditional time-windowed information results in improved predictions. Besides improving the predictions, the embedded features also provide a quantitative data-driven framework to study the temporal evolution of features. In the greater context of the project, together with the new data, having access to data features and their patterns across temporal scales – from short time windows to several failure cycles – may prove key in studying acoustic precursors and their relation to failure in more complex, heterogeneous fault analogue experiments.

Research focus for 2023
In 2023, the project will focus on the design, construction, calibrations and testing of the direct shear stress (DSS) apparatus, together with combining it with the laser-acoustics setup – now operational and capable of automated waveform data collection. During the design and construction phase, additional experiments will be performed using a rotary shear apparatus in the context of an MSc thesis project to establish which materials are suitable for creating laboratory earthquakes and to obtain a baseline for the variation in time-to-failure for the different materials under otherwise similar boundary conditions.

In addition, a digital twin will be developed of the direct shear stress apparatus – in terms of geometry, mechanical properties and wave propagation fidelity – to optimise the design and placement of sensors and to be able to fully model wave field propagation in the future.

Collaboration and integration within DeepNL
The PhD researcher on this project is a founding member of a group of Utrecht-based researchers who meet bi-weekly to discuss scientific papers relevant to the problems associated with subsurface activities such as induced seismicity and subsidence. In 2023, on the topic of modelling wave propagation on a digital twin of the DSS apparatus, a potential collaboration is envisioned on numerical wave modelling with the 3DSOIL project.

Relevance for stakeholders
Although no conclusive results are available yet on the study of precursor signals, the novel, improved data science/AI toolkit could be of interest for stakeholders interested in revealing hidden patterns in time-series analysis. This could be applicable to the analysis of passive acoustics or field seismic data, although the interpretation and meaning of the patterns arising from other types of time-series data would be subject of further research, possibly beyond the scope of this project.

Research projects

<table>
<thead>
<tr>
<th>Project leader</th>
<th>Dr Ivan Pires de Vasconcelos (UU)</th>
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<tbody>
<tr>
<td>Associate project leader</td>
<td>Dr André Niemeijer (UU)</td>
</tr>
<tr>
<td>PhD</td>
<td>Rens Elbertsen</td>
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<tr>
<td>Budget</td>
<td>€ 358,358 - through Call 2a</td>
</tr>
</tbody>
</table>

The application of data-science-based dimensionality reduction to the variance of acoustic emission data from many cycles of slip experiments display clear organized patterns of variance in connection to stress-state of analogue fault gouges (blue is low stress, yellow is high). This is of great value, e.g., to expose information hidden in the data over very long time scales (many cycles), as well as to choose training (left) and validation (right) data sets in ensuring their underlying long-time-scale patterns remain consistent.

PhD researcher Rens Elbertsen with a small model prototype of the direct shear stress apparatus that is being built at Utrecht University.
Subsidence and surface effects of seismicity

Can we understand and model how the processes at depth are translated through the subsurface to an effect at the Earth’s surface?

The Dynamic Shear Simulator for Organic Soft Soils apparatus was manufactured and assembled at TU Delft in 2022. It is used to replicate earthquake loading on Dutch soft soils in order to better understand the effects of seismicity on the shallow subsurface (project Hicks et al.).
Monitoring and Modelling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension

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 research results 2022
A method was developed based on a new, radar amplitude based approach to derive an a priori quality estimation of the estimated subsidence from InSAR observations. Such an error description is required to correctly use the data for the data assimilation. The method has been tested and is currently being implemented. Also, a method has been developed that enables the observation of short-term dynamics of the upper soil layers resulting from changes in temperature and precipitation on grass-covered areas. It is less suited for areas with intensive agricultural use. Simple synthetic models of fault slip have shown that co-seismic slip and potential creeping faults at reservoir depth do not result in a surface response that is detectable in geodetic observations (InSAR). Therefore, this fault slip can be excluded from the geophysical model design. Sensitivity studies of the geophysical models show that the level of model detail can be simplified significantly without a significant impact on the simulated surface response. For example, the reservoir geometry complexity can be simplified by more than two orders of magnitude. The first two sites for measuring shallow (sub)surface processes in the Groningen gas field area were installed in Nieuwolda, Groningen. These monitoring sites involve extensometers with measuring anchors at several depths, wells for measuring phreatic groundwater, hydraulic heads, and ditch water level, and meteorological station devices such as soil moisture monitors, thermometers, precipitation and radiation monitors. Preliminary results show a clear correlation between vertical layer movement as measured by the extensometers and groundwater level fluctuations. A regional shallow subsidence model was developed; Atlantis. When finished, this model will give subsidence as a result of compression and oxidation as output. A hydrological model of all the layers in the Groningen subsurface (from top to several hundreds of meters depth) was developed in iMOD, based on all groundwater extraction data from the province of Groningen from 1960 until present. The well data and lithological data from REGIS were used as input to generate hydraulic head changes in the Pleistocene aquifers as a result of groundwater extraction. The applicability of data assimilation method in the case of the Groningen gas field was studied. It was evaluated how to implement spatially correlated observations in the particle filter and how to increase the number of observations to represent the entire Groningen area. Results show that the particle filter with adapted implementation remains efficient for subsidence estimation in the example of Groningen with both levelling and InSAR data.

Research focus for 2023
The a priori quality estimation of the estimated subsidence from InSAR observation will be applied on an area in Groningen, and the results will be validated with the observations of the extensometer test side in Nieuwolda. A radar transponder will be installed at the test side to validate the InSAR-derived estimates. A 15 year long time series of data will be obtained from the shallow measuring sites to gain a better understanding of the boundary conditions that govern the shallow subsurface processes leading to deformation of the (sub)surface. The Atlantis model will provide the contribution of oxidation and compression to subsidence in the Groningen gas field area on a regional scale over the course of the last 20 years. These results will be validated with actual data. The hydrological model (iMOD) will be coupled to a compression model (SubCReep) to generate subsidence per year as a result of hydraulic head changes caused by extraction of groundwater. The sensitivity study of the geophysical models will be finalised and the models will be integrated with the data assimilation procedure. The particle filter methodology will be used with models of higher complexity. Additional knowledge of stochastic models in the InSAR data used for assimilation will help reduce the uncertainty in the estimation of the origin of subsidence.

Collaboration and integration within DeepNL
Within the project, there are close connections between the different work packages. Results from the geophysical and shallow subsurface modelling work and InSAR observation data are fed into the data assimilation procedure that is under development. The data assimilation part of the project is conducted in close cooperation with the InFocus project. Topic-wise, common ground exists with SOFTTOP and 3DSOIL.

Relevance for stakeholders
The overall project goal of disentangling and forecasting subsidence originating from either deep or shallow parts of the subsurface can be of relevance for both inhabitants and policy makers in Groningen, for example regarding the connection between management of groundwater levels and soil deformation. Furthermore, the project provides insights into the precision and reliability of satellite-derived surface motion estimates. This helps in accurately detecting effects of the cessation of gas production.
DeepNL research projects

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 Koff (TUD/Deltares)
PDs: Dr José León González Acosta (TUD); Dr Divya Varkey (TUD)
PhDs: Hilmi Bayraktaroglu (TUD); Ching-Yu Chao (TUD)
Budget: € 1,042,454 - through Call 1a

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.

Highlighted research results 2022
A robust finite element (FE) code has been developed for the analysis of the shallow subsurface under cyclic loading. The method was used to investigate different traditional site response in a one dimensional column and in a coupled profile in 2D. While 2D schemes show a significant increase of liquefied area and less variability of results regarding released energy (in terms of peak ground acceleration and liquefied area and less variability of results regarding released energy (in terms of peak ground acceleration and liquefied area) 1D schemes exhibit difficulties in providing realistic results, showing minor liquefaction spreading and little variability of energy release regardless of using the same soil properties. Traditional 1D techniques are thus inappropriate to perform free-field ground response analysis when spatial variability is considered. Through utilising the random finite element method (RFEM) and two-dimensional schemes, more realistic estimations of a soil deposit’s dynamic response can be obtained.

WP1: RFEM analysis framework for heterogeneous soils
(González Acosta & Varkey)
WP2: Constitutive model for organic clay (Bayraktaroglu)
WP3: Constitutive model for laminated sand (Chao)

Computer simulation of liquefaction spreading due to earthquake loading at a spatially variable site.

The SOFTTOP project team: Ching-Yu Chao, José León González Acosta, Hilmi Bayraktaroglu, Christina Jommi, Divya Varkey and Michael Hicks

Research focus for 2023
The finite element code will be used to analyse the effects of cyclic loading on different types of soil layering in 2D for soil parameters relevant to Groningen.

The CYC-DoSS will undergo a series of validation tests to evaluate its performance and the accuracy of the in-house developed sensors. Once validated, the CYC-DoSS will be employed to carry out experiments on soft soils subjected to different cyclic loading scenarios, with the aim of simulating the acceleration time history from induced seismicity observed in Groningen. The experimental results will allow fine tuning of the bounding surface model under both low and high frequency loads. A user defined model routine will be made available for use in generic FE platforms, including the one developed in the parallel work-package.

Collaboration and integration within DeepNL
The SOFTTOP project is closely related to the 3DSOIL project, which will provide a clearer picture of the spatial distribution of soil variability in the top 30 metres of the subsoil. Furthermore, SOFTTOP provides the link between the multi-physics processes occurring in the deep geological units, investigated by Suzanne Hangx, to the time-space response at the surface, including its spatial variability. It underpins the interpretation of satellite observations on the effects on transportation infrastructure studied in the project of Ramon Hanssen.

Relevance for stakeholders
SOFTTOP will improve the capacity to predict earthquake loads at the ground surface, by providing new insights into the behaviour of laminated sands and organic soils under cyclic loading and new information on the impact of the shallow subsurface on the transfer of earthquake loads from deeper geological units to the ground surface. The earthquake testing machine can be used for any other application that involves soil behaviour under cyclic loading, for example when it comes to compaction associated with passing trains.

DeepNL annual report 2022
3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis

Research aim
To develop a new methodology for deriving subsoil spatial variability data (soil structure and shear-wave velocity \( V_s \)) from 3D seismic data constrained by Cone Penetration Test information at discrete locations, and to develop a machine-learning tool to predict CPT data from correlations with \( V_s \) at locations where CPT data are not available or feasible.

Highlighted research results 2022
A full waveform inversion (FWI) workflow was developed and tested on field seismic CPT data, successfully resolving the spatial variability and shear-wave velocity \( V_s \) structure in the top 30 metres of the subsoil. The inversion workflow now allows for extracting \( V_s \) information from surface seismic data with a resolution approaching that of downhole seismic measurements (SCPT). This very fine-scale seismic information will be crucial to the success of the next step, which will target extracting lateral variability of in-situ geotechnical (CPT) properties, which are key to reliable seismic site response analysis. In addition, an extensive seismic field campaign was completed in Groningen, acquiring high-quality 2D and 3D seismic datasets.

Research focus for 2023
A field campaign will be conducted to acquire CPT and SCPT data at the test site in Groningen where extensive 2D and 3D seismic data were acquired in 2022. Also, a new tool will be developed using machine learning, the DINO loket database, and data acquired in Groningen in this project. The aim of the tool is to translate high-resolution soil variability information extracted from surface seismic data through specially tuned FWI to lateral variability of CPT information and predict CPT at locations where CPT is absent or not feasible.

Collaboration and integration within DeepNL
There are tight relations with the SOFTTOP-project. For the machine learning part of the research, there will be a collaboration with the specialists both at TU Delft and Utrecht University. In 2022, initial discussions took place between DeepNL researchers at Utrecht (lead Suzanne Hang) investigating surface subsidence, the behaviour of the shallower (less consolidated) formations, and the grain-scale mechanisms that operate in deeper, consolidated rocks. The benefit of the research being carried out in this project to the DeepNL network is that it will drastically reduce the uncertainty in the in-situ ground conditions. This will enable the SOFTTOP research team to perform more realistic and focussed site response analyses. It will also enable the derivation of more reliable characteristic property values for representing the behaviour of the shallow subsurface which may be used for analyses in other DeepNL projects (e.g. Barnhoorn et al., Hanssen et al.).

Relevance for stakeholders
This project will lead to more realistic, local site response analyses than is now possible for Groningen. The results of the present research (i.e. potential for larger local datasets) will be fed directly into industry through the geo-engineering group’s on-going collaborations with Deltares and the flood defence, rail and offshore industries, and in particular, through the group’s work with industry in developing a reliability-based assessment framework for large geotechnical infrastructure.
News from the DeepNL network
Young DeepNL

Young DeepNL is a sub-community within the DeepNL programme, formed in 2021. This community aims to strengthen the bonds between PhD and post-doctoral researchers and create a long-lasting network. DeepNL believes this network will be beneficial for the careers of the researchers, and will have a positive effect on collaboration and knowledge exchange between the various researchers and their projects.

Organising networking activities

In 2022, Young DeepNL organised two activities, starting with a visit to the Earth Simulation Laboratory of Utrecht University, in particular the Tectonic Modelling Laboratory (TecLab) and HPT Lab. At the TecLab, the young researchers were shown an experiment with coloured sand to mimic plate tectonics and a new CT-scanner and sandbox experiment. It was interesting for other projects to see the CT-scanner and how it is used to understand the evolution of fault generation in the analogue models. The HPT Lab demonstrated the possibilities of triaxial experiments, petrographic analysis and DEM models, as well as 3D microtomography on cracks healing in salt. Overall, this visit was valuable to better understand what experiments are done within DeepNL projects how these labs differ from those of their own.

The second activity was a stakeholder visit in collaboration with EBN. The purpose of this visit was to learn more about the work of EBN, as a potential collaboration partner or future employer. The visit started with presentations from EBN experts on strategy and research activities, after which the DeepNL researchers pitched their projects. The afternoon was concluded with a tour around the EBN headquarters and an opportunity to network.

In 2023, Young DeepNL aims to organise at least two activities: a stakeholder visit to TNO and a visit to the University of Twente. The latter will be focussed on the numerical modelling and statistical aspects of the research within DeepNL.

The Young DeepNL organising committee currently consists of: Hamed Ali Diab Montero, Eldert Fokker, Muhammad Hamza Khalid, Samantha Kim and Aukje Veltmeijer.

DeepNL Summer School

The goal of the Summer School is to broaden the knowledge base of young researchers on the DeepNL theme and to strengthen mutual contacts. It was originally planned for the summer of 2020, but due to the pandemic it was transformed into a webinar series on induced seismicity. 2022 was the perfect year to finally organise a real in person summer school as the DeepNL programme had gained ten new PhD researchers from the projects funded in Calls 1b and 2a.

During the final week of August, 35 participants immersed themselves in the DeepNL theme through lectures on the geoscientific and societal aspects of the Groningen gas extraction. After two lecture days, there were three site visits in the Groningen area: the NAM core store with a unique collection of rock samples, the gas storage facility at Norg and the earthquake impacted region with explanations by experts of National Coordinator Groningen. For the second part of the week, the group travelled to Germany for a geological field excursion and visited several quarries and outcrops where rock formations similar to those in the subsurface of Groningen could be studied.

The Summer School was organised with the help of a programme committee that consisted of tenure track researchers Johannes Mooc, Tanmaya Mishra and Maja Rücker, and PhD researchers Samantha Kim and Sebastian Mulder.
Funding received by DeepNL researchers

**ACT grant for Suzanne Hangx and Martyn Drury**
Suzanne Hangx and Martyn Drury’s RETURN is one of the thirteen projects that received funding from the Accelerating CCS Technologies (ACT) initiative under the Horizon 2020 programme. RETURN, which stands for ‘Re-use of depleted oil and gas fields for CO2 sequestration’, aims to enable safe and cost-efficient long-term CO2 storage in depleted oil and gas reservoirs by understanding and handling cooling and CO2 phase change effects during injection.

**NWO GO funding for three DeepNL researchers**
Femke Vossepoel, Rob Govers and Oliver Plümper are amongst the fifteen researchers who have received funding through the NWO GO-programme. With GO funding the researchers will use space infrastructure for research on drought forecasting in the Rhone basin, earthquakes in Sulawesi and mantle flow near fault zones and melting ice sheets, respectively.

**NWA grant for Mandy Korff**
Mandy Korff received funding for the project ‘LiveQuay’ within the call ‘Quay Walls in Urban Areas’ of the NWO Dutch Research Agenda (NWA). The project provides an integrated assessment of the safety and condition of bridges and quay walls in an interactive decision support platform based on values from all stakeholders.

**EEU-TNO collaboration project on probabilistic subsidence predictions for building damage**
Ylona van Dinther will collaborate with researchers from TNO and the University of Padova for a PhD project funded through the TNO Early Research Program. The aim is to generate physics-informed predictions of human-induced subsidence at the spatial scale relevant for building damage. To reach this objective, models and observations will be combined throughout data assimilation schemes.

Awards received by DeepNL researchers

**NSF Career award for Kathrin Smetana**
Kathrin Smetana was granted an NSF Career award for her project ‘Randomized Multiscale Methods for Heterogeneous Nonlinear Partial Differential Equations’. With this five-year-award she will apply data science methods like randomisation to the design and analysis of new multiscale methods for real-life applications such as wind turbine efficiency.

**Outstanding Student Presentation Award for Eldert Fokker**
Eldert Fokker has been honoured with an Outstanding Student Presentation Award (OSPA) by AGU. This award is for the most exceptional presentations during the AGU 2022 Fall Meeting. His presentation was related to the paper ‘4D physics-based pore pressure monitoring using passive image interferometry’.

**Energi Simulation Chair for Hadi Hajibeygi**
Together with Sebastian Geiger, Hadi Hajibeygi has been awarded the Energi Simulation Chair in subsurface storage and multiscale modelling. Energi Simulation, a not-for-profit organisation, has committed an investment exceeding $1,000,000 Canadian Dollars over the next three years to support Hadi Hajibeygi and Sebastian Geiger to grow their geoscience and reservoir engineering research activities in the context of the energy transition.

**Marie Curie grant for Ylona van Dinther and André Niemeijer**
Ylona van Dinther and André Niemeijer are co-beneficiaries of a Marie Curie grant to form a doctoral network across Europe titled TREAD-daTa and pRocesses in eXismic HazARD. TREAD will start in January 2023 and run for four years, funding eleven PhD projects, including four supervised or co-supervised positions in Utrecht. The PhD researchers will use numerical models, laboratory experiments and geodetic observations to better understand and forecast the hazard in complex continental settings, such as the Central Apennines.

**Funding from Merian Fund for Ramon Hanssen**
Ramon Hanssen received funding for the project ‘Geodetic resilience and adaptation to climate change: elevation, sea level rise and land subsidence for the Netherlands, Singapore, and Indonesia (Three Sisters)’ from the Southeast Asia-Europe Joint Funding Scheme of the NWO Merian Fund.

**NWO GO funding for three DeepNL researchers**
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EPOS-NL (European Plate Observing System – Netherlands) is the NWO funded Dutch research infrastructure for solid Earth sciences, and a partnership between Utrecht University, TU Delft and KNMI. EPOS-NL provides scientists from all over the world with access to Dutch research labs, notably: the Multi-scale Imaging and Tomography (MINT) facilities, the ESL High Pressure and Temperature (HPT) lab, the Delft Petrophysics Lab and the ESL Tectonic modelling lab. These labs enable researchers to for example use electron microscopy techniques such as SEM and TEM and X-ray tomography, explore rock deformation and fluid flow at high stress and temperature conditions, or investigate tectonic processes in scaled analogue models.

In 2022, EPOS-NL granted 14 research groups a total of 150 hours of time to be spent in these labs.

Besides providing access to specialised facilities, a second aim of EPOS-NL is to provide researchers with access to scientific data for frontier-breaking research on geo(thermal) energy, induced or natural geohazards, and geological storage of fluids and waste.

Data Portal launch
Currently, there are two major developments that are of importance for the DeepNL community. First, during this year’s EGU meeting on 23–28 April 2023, the EPOS Data Portal will be officially launched. This multi-disciplinary open data portal, to be found at www.ics-c.epos.eu.org, provides integrated access to European, solid Earth science datasets for example from volcanology, geology, geodesy, and seismology. This Data Portal also includes all data disseminated by the EPOS-Multi-Scale Labs data catalogue at https://epos-msl.uu.nl. This catalogue is meant for researchers who are looking for discipline-specific data from European Earth Scientific labs, i.e. rock physics, analogue modelling, microscopy, paleomagnetism, geochemistry and geo-energy test beds (field labs). It provides access to all data published openly at the Yoda (UU), CSIC and GFZ Potsdam repositories. Currently, the 4TU.Researchdata and British Geological Survey data repositories are being coupled to the catalogue, and via the catalogue also to the EPOS Data Portal.

Financial foundation strengthened
The second milestone to be mentioned here is that the EPOS-eNLarge proposal was granted by NWO. 18 million euros of funding will be available for a ten-year period to provide the missing link needed to apply our understanding of micro-processes in the subsurface at the kilometer-scale where subsurface operations and their effects take place. To this end, amongst others, a 4.5 kilometer-deep research well will be drilled adjacent to the geothermal injection and extraction wells that are part of the DAPwell project in Delft. EPOS-eNLarge further expands on the work done by the EPOS-NL crew to ensure that unique research data of the Dutch subsurface is made openly and centrally accessible for future re-use via the EPOS-Multi-Scale Labs data catalogue and the EPOS Data Portal. Last but not least through this new project the EPOS-NL consortium welcomes a new partner: TNO.

Sharing data in a findable and accessible way
For 2023, EPOS-NL’s focus will be on starting up the activities within the EPOS-eNLarge project, and coupling more data centers to the centralised EPOS Data Portal, notably within multi-scale labs, seismology and geology. To this end, DeepNL researchers are cordially invited to publish their research data at the Yoda or 4TU.Researchdata repositories, or for seismological data at the ORFEUS Data Centre. This will ensure that your data can be discovered along with other European data, all on a single website. Only by sharing our data in a findable, accessible way can we advance the Earth sciences and make an impact for the world.
News from KEM

The Knowledge Program on the Effects of Mining (KEM), initiated by The Minister of Economic Affairs (EZK) and jointly guided with State Supervision of Mines, is 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 on mining hazard and risk assessment in the Netherlands.

KEM activities in 2022
As in previous years, the KEM scientific expert panel has assured the quality of the KEM research by aligning research questions, and coaching and evaluating ongoing KEM research projects. In addition, KEM and DeepNL have organised a series of 3 joint colloquia to exchange and discuss results of KEM and related DeepNL projects and associated research priorities.

The KEM subpanel on seismic hazard and risk model (SHRA) development continued to advise the Ministry EZK and State Supervision of Mines on additional development and validation of the public SHRA model of TNO, as well as on the state-of-the-art model version to be used for the annual risk assessments. In 2022, TNO executed the second independent assessment of seismic risks related to the annual gas production plan for the Groningen reservoir, using the 2022 version of the public SHRA instrument.

Evaluation
In the second half of 2022, KEM has been externally evaluated. It was concluded that KEM was largely effective and efficient. The main recommendation was to continue executing the main task of KEM, which is the independent execution of applied research on the effects of mining. The Ministry EZK and the State Supervision of Mines subsequently decided to continue KEM for the period 2023-2027. In the evaluation report, suggestions for improvement were made, such as to slightly improve the focus of the mission; consider to include socio-economic research topics; improve strategic and operational reference documents; establish a more transparent process for gathering the research questions; and organise broader communication. How to follow-up on these suggestions is currently being worked out.

Status of KEM projects

Finished in 2022
- Groningen post-abandonment fluid migration and leakage effects and subsequent subsidence and seismicity effects (KEM-19)
- Effect of fluid injection on the Groningen seismicity risk profile (KEM-24)
- Infrasound related to mining operations and facilities (KEM-31)

Ongoing in 2023
- Thermo-mechanic seismicity risks of geothermal systems (KEM-15)
- CO₂ subsurface storage monitoring (KEM-27)
- H₂ subsurface storage in conglomerates of salt caverns (KEM-28)
- Safe operational bandwidths of H₂, N₂ and CO₂ storage in abandoned gas reservoirs (KEM-39)
- Subsidence hazard and risk modelling tools applied to 3 complex pilot areas (KEM-96)
- Salt cavern bleed-off behaviour and risks (KEM-45)

Results of all KEM projects are or will be published on kemprogramma.nl.

KEM and DeepNL chairs advocate a national research strategy on the responsible use of the Dutch subsurface

Motivated by the physical and social consequences of earthquake activity and subsidence in Groningen as a result of gas extraction in recent decades, in June 2022, DeepNL and KEM chairs have sent a proposal to the Ministry of Economic Affairs and Climate Policy outlining the development of a national research strategy regarding the effects of subsurface activities on the built environment, nature, environment, and safety. This proposal is supported by SodM and EBN and the key independent, public research organisations (universities, TNO, KNMI, Deltares) and aligns with recommendations previously made by the Dutch Safety Board and the Mining Council.

This initiative aims at securing continuity of independent long-term and pro-active research regarding the effects of mining and related subsurface activities. Building and maintaining top-level expertise and, very importantly, human capacity are essential elements in this endeavour. Continued funding for the currently temporary programmes DeepNL and KEM and a strong national knowledge ecosystem are prerequisites to achieve this. Realisation of this initiative would demonstrate that lessons have been learned from the Groningen situation. Although targeted at the situation in the Netherlands, the knowledge infrastructure cannot be built on a national basis only. Top-level scientific expertise requires close contacts with the international scientific community. Participation of Netherlands-based scientists in European and other international research programmes concerning the mining-induced dynamics of the subsurface are essential elements to achieve and maintain true frontier-type of expertise in the Netherlands.

The Ministry of Economic Affairs and Climate Policy has reacted positively to the proposal, asking to further elaborate on the initiative in 2023. Encouraging developments in this context are the recent decision to continue KEM for another five years and the explicit recommendation to further embed KEM in a national research ecosystem. The positive midterm evaluation of DeepNL includes recommendations in the same direction. Further decisions and steps are expected in 2023, taking into consideration the conclusions and recommendations of the Parliamentary Inquiry into gas production in Groningen. No matter the exact outcome, the DeepNL and KEM chairs feel that establishing the national research strategy should be an important element of the government’s response to this report.
Looking ahead at 2023

SOFTTOP workshop at TU Delft for knowledge exchange on the response of shallow subsurface to induced earthquakes

Publication DeepNL Call 2b
The fourth and last Call for proposals within the current DeepNL budget will be published in 2023 and has a budget of 7.9 million euros. Within a framework of three key goals this call aims to fund projects, that fill knowledge gaps and provide an added value with respect to ongoing projects and the overall targets of DeepNL.

European General Assembly (EGU) in Vienna, Austria

InterPore 2023 in Edinburgh, Scotland

EAGE Annual Conference & Exhibition in Vienna, Austria

2nd International Summer School on Underground Hydrogen Storage at TU Delft

15th Euroconference on Rock Physics and Rock Mechanics (EUROCONF23) organised by TU Delft in Woudschoten

KEM-DeepNL colloquia series
Together with KEM DeepNL will organise more online colloquia, aiming at knowledge sharing and debate, taking results of completed KEM projects as a starting point. In a colloquium, KEM researchers present their project results and discuss these with DeepNL teams with related expertise.

GeoScience & GeoEnergy Webinar Series
In 2023, Hadi Hajibeygi and Sebastian Geiger will continue to organise monthly webinars with an international range of speakers. All presentations are available on the YouTube channel GeoScience & GeoEnergy Webinars.

2023

23 january

26-3 february

1 march

23-24 march

23-28 april

12 may

22-25 may

5-8 may

19-22 may

3-7 july

23-26 october

11-15 december

>> on going

SIAM conference on computational science and engineering in Amsterdam

Netherlands Earth Sciences Conference (NAC) in Utrecht
This conference brings together the research fields within the Earth and Environmental Sciences and aims to provide an interdisciplinary forum for discussion. NAC is a place for young scientists to present their research results to a broad audience and get some really crucial feedback.

Annual DeepNL Stakeholder Meeting in The Hague
This 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.

Annual 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.

American Geophysical Union (AGU) in San Francisco, United States of America

GeoScience & GeoEnergy Webinar Series
In 2023, Hadi Hajibeygi and Sebastian Geiger will continue to organise monthly webinars with an international range of speakers. All presentations are available on the YouTube channel GeoScience & GeoEnergy Webinars.
News from the DeepNL programme
Financial framework and call overview

The DeepNL budget is divided between several sequential Calls for proposals, an earmarked budget for opportunities (small projects for integration, tuning, application etc.) 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€. The Calls for proposals are designed based on the DeepNL programme description. The programme committee advises NWO on the design of new funding rounds, the potential need for redirections and the use of reserved funds for opportunities and programme activities.

<table>
<thead>
<tr>
<th>Year</th>
<th>Call 1a</th>
<th>Call 1b</th>
<th>Call 2a</th>
<th>Call 2b</th>
<th>Final set of research projects</th>
<th>Opportunities</th>
</tr>
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<tbody>
<tr>
<td>2018</td>
<td>8 large research projects - Awarded € 8,831,353</td>
<td>3 tenure track projects - Awarded € 2,242,797</td>
<td>7 small research projects</td>
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<td>2028</td>
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</tbody>
</table>

Programme activities - Meetings, outreach & communication - € 1,000,000

Programme costs - Execution by NWO - € 900,000

TOTAL BUDGET DEEPNL: M€ 24.2

NAM CONTRIBUTION: M€ 15

NWO CONTRIBUTION: M€ 5

PPS ALLOWANCE RVO: M€ 4.23
Midterm evaluation

The original DeepNL programme description planned for a midterm evaluation, to be performed within five years after the start of DeepNL. In line with this, the board of the NWO Science Domain solicited an evaluation of DeepNL by the International Advisory Committee, to provide a basis for the development of the upcoming fourth Call for proposals (Call 2b). The evaluation was based on a self-evaluation report and encompassed the midterm progress of the eight projects from DeepNL Call 1a (period 2019-2022) and to what extent they form, together with ten projects from Call 1b and Call 2a, a coherent set of projects contributing to the goals and envisioned targets of the overall DeepNL programme. The IAC had a first online meeting in June 2022 and delivered their report in November.

The IAC sees DeepNL as a timely and forward-looking research programme to bring together and strengthen the Dutch geoscience community and build knowledge and tools to understand the deep subsurface in order to address questions associated with the energy transition, the extraction of natural resources, geological storage, and associated hazards. The IAC is positive about the progress that has been made since the start of DeepNL, despite the COVID-related restrictions.

For the second phase of the DeepNL, the committee advocates a strong focus on collaboration and integration within the programme and on jointly delivering the key outcomes that the programme was aimed at and that are important for non-academic stakeholders. For the upcoming final DeepNL call, the IAC recommends to identify key knowledge gaps and to avoid further widening of fundamental research, and instead concentrate on what research is needed to consolidate work and demonstrate applicability to Groningen and other reservoir operations, leaving problems that require further capacity building to follow-up funding opportunities. Other recommendations concern a stronger coordination with theme leaders within the programme, to set up repositories to share data and codes within the programme, and to consider how the programme and its outcomes could gain larger visibility to stakeholders and the wider public by, for example, collaborating with partner organisations on outreach. Finally, the IAC strongly supports further pursuing the discussions for follow-up funding initiatives that will allow consolidating and building on the current successes of DeepNL.

Scope and procedure DeepNL Call 2b

The fourth and final Call for proposals is to be published in February 2023. The call is also open to researchers who are not (yet) involved in DeepNL projects. A maximum of €1,000,000 can be applied for, and an application must at least include one temporary scientific position (PhD or postdoc). The proposed research should be tailored to achieve as much as possible the overall targets originally outlined in the DeepNL programme, and to provide added value with respect to the ongoing DeepNL projects. Specifically, proposals are required to contribute to one or more of the following key goals:

1. Consolidation and optimal utilisation of the Groningen region as a study area;
2. Strengthen the path to application;
3. Relevance to future subsurface activities.

The procedure consists of two phases and guides the process towards a coherent set of projects. In phase one, the applicants submit an expression of interest. The expressions of interest will be shared with all applicants and serve as a starting point for a workshop. The goal of the workshop is twofold: (1) to outline the aim and assessment criteria of the call, and (2) to align individual research plans. In this phase no selection is made by NWO.

In the second phase, applicants submit their elaborated proposal. An independent assessment committee will rank the proposals based on the assessment criteria and interviews. The board of the NWO Domain Science will take a decision about awarding or rejecting the proposals based on the advice from the assessment committee and the available budget. More information on the scope and the conditions can be found in the Call or Proposals on the NWO website.

Key dates:
- The deadline for submitting an expression of interest is 18 April 2023, 14:00:00 (CEST)
- On 25 May 2023, a mandatory workshop will be organised for the applicants involved in an expression of interest
- The deadline for proposals is 29 June 2023, 14:00:00 (CEST)
- The outcome of the Call for proposals is expected in November – December 2023
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 also advises on the design of new funding rounds and implementation of the reserved funds for opportunities and programme activities.

In 2022, the programme committee convened in three dedicated meetings. They discussed topics such as the overall progress of DeepNL research projects, the planning of events, the position of DeepNL in a broader national subsurface research landscape and plans for the next Call for proposals.

Dr Giovanni Bertotti
TU Delft

Prof. Arwen Deuss
Utrecht University

Prof. David Smeulders
Eindhoven University of Technology

Dr Hanneke Verweij
former TNO

em. Prof. Rinus Wortel (chair)
Utrecht University

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. The IAC provides recommendations to the research projects, programme committee and board of the NWO Science Domain for the duration of the DeepNL programme.

The committee was appointed by the NWO Domain Science Board in June 2022. The IAC had three online meetings in the context of the Midterm Evaluation of the DeepNL programme and three members attended the DeepNL Scientific Meeting on 18 November in Utrecht.

Prof. Torsten Dahm
GFZ German Research Centre for Geosciences Potsdam

Prof. Saskia Goes (chair)
Imperial College London

Prof. Inga Moeck
University Göttingen / Leibniz Institute for Applied Geophysics

Prof. Francesca Verga
Politecnico di Torino

Prof. Robert Zimmerman
Imperial College London

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. The coordinators act as secretaries for the programme committee, assessment committees and the international advisory committee.

Dr Niels van den Berg
Coordinator

Margit de Kok
Communication advisor

Ajita Ramautar
Programme assistant

Cindy Remeijnse-Schrader
Coordinator

Overview of DeepNL researchers

Stephen Akinremi
University of Twente
- PhD researcher: Deep, deeper, deepestNL: Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM)

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

Zhuldyzay Baki
University of Twente
- PhD researcher: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

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.

Hilmi Bayraktaroglu
TU Delft
- PhD researcher: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.

Wietseke Brouwer
TU Delft
- PhD researcher: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Marc Bruna
TU Delft
- NWP: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.
Dr Ylona van Dinther

- PhD researcher: LabQuakeAI - AI-driven production 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-sensor observables (DICTUM).

Eldert Fokker

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

Young DeepNL organising committee

Dr Ranajit Ghose

- TU Delft - Project leader: 3D-Soil: 3D soil variability in Groningen for accurate, local site response analysis.

Dr José Léon González Acosta

- TU Delft - Postdoctoral researcher: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.

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.

Dr Rens Elbertsen

- Utrecht University - PhD researcher: LabQuakeAI - AI-driven production and monitoring of laboratory earthquakes from passive and active acoustic data.

Dr Hadi Hajibeygi

- TU Delft - Associate project leader: Science4EiGee: a scientific basis for production and injection strategies to minimize induced seismicity in Dutch gas fields.

Dr Suzanne Hangx

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

Dr Rhys Hawkins

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

Vincent van der Heiden

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

Dr Rob Govers

- Utrecht University - Project leader: Quantitative constraints on pre-production reservoir stresses in Groningen. Associate project leader: Monitoring and Modelling the Groningen Subsurface based on an integrated Geodesy and Geophysics: Improving the space-time dimension.

Prof. Ramon Hanssen

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

Dr Janneke de Jong

- Utrecht University - PhD researcher: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: Improving the space-time dimension.

Dr Jose León González Acosta

- TU Delft - Postdoctoral researcher: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.

Prof. Michael Hicks

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

Dr Rob Govers

- TU Delft - Project leader: Quantitative constraints on pre-production reservoir stresses in Groningen. Associate project leader: Monitoring and Modelling the Groningen Subsurface based on an integrated Geodesy and Geophysics: Improving the space-time dimension.

Prof. Jan Dirk Jansen

- TU Delft - Project leader: Science4EiGee: a scientific basis for production and injection strategies to minimize induced seismicity in Dutch gas fields.

Dr Chien-Cheng Hung

- Utrecht University - PhD researcher: Probing the micromechanics of small magnitude earthquake slip.

Mr. Malek Jaran

- University of Twente - Postdoctoral researcher: Science4Steer: A multi-scale, multi-physics framework for modeling the geomechanical response of sandstone reservoirs to pore fluid extraction.

Prof. Cristina Jommi

- TU Delft/Politecnico di Milano - Associate project leader: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Janneke de Jong

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

Dr Muhammad Hamza Khalid

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

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Dr Janneke de Jong

- Utrecht University - PhD researcher: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: Improving the space-time dimension.
DeepNL annual report 2022

Dutch gas fields.

Strategies to minimise induced seismicity in

Scientific basis for production and reinjection

Reservoirs to pore fluid extraction.

Geomechanical response of sandstone

Multi-physics framework for modelling the

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

Dr Mohammad Hadi Mehranpour

Utrecht University

Postdoctoral researcher: Making digital rocks: a scientific basis for production and reinjection strategies to minimize induced seismicity within the Groningen gas field using large scale field observations.

Dr Hanneke Paulssen

Utrecht University

Associate project leader: Comprehensive monitoring and prediction of laboratory earthquakes from passive and active acoustic data.

Dr Oliver Plümper

Utrecht University

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

Dr Ivan Pires de Vasconcelos

Utrecht University

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

Dr Helen King

Utrecht University

Associate project leader: Making digital rocks: a scientific basis for production and reinjection strategies to minimize induced seismicity within the Groningen gas field using large scale field observations.

Dr David van Lieshout

TU Delft

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

Prof. Chris Spiers

Utrecht University

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

Prof. Esther Stouthamer

Utrecht University

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

Dr Kathrin Smetana

Stevens Institute of Technology

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

Prof. Mark van der Meijde

University of Twente

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

Dr Johannes Miocic

University of Groningen

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

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.

La Ode Marzujriban Masfara

TU Delft

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

Dr Mandy Korff

TU Delft/Deltas

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

Meng Li

Utrecht University


Dr Samantha Kim

TU Delft

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

Dr Mohammad Hossein Khoeini

Eindhoven University of Technology

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

Dr Dr Helen King

Utrecht University

Associate project leader: Making digital rocks: a scientific basis for production and reinjection strategies to minimize induced seismicity within the Groningen gas field using large scale field observations.

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Utrecht University

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

Postdoctoral researcher: Science4Steer: a scientific basis for production and reinjection strategies to minimise induced seismicity in Dutch gas fields.

Dr André Niemeijer

Utrecht University

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

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University of Twente

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

Dr Johannes Miocic

University of Groningen

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

Dr Tamayaa Mishra

University of Twente

Project leader: uFALST: scaling friction from micro-contacts to faults at the reservoir scale.

Sebastian Mulder

University of Groningen

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

Mladen Naderloo

TU Delft

PhD researcher: 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 laboratory earthquakes from passive and active acoustic data.

Aleksei Novikov

TU Delft

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

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Utrecht University

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Utrecht University

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

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Utrecht University

Postdoctoral researcher: Making digital rocks: a scientific basis for production and reinjection strategies to minimize induced seismicity within the Groningen gas field using large scale field observations.

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Postdoctoral researcher: Making digital rocks: a scientific basis for production and reinjection strategies to minimize induced seismicity within the Groningen gas field using large scale field observations.

Dr Dr Mohammad Hadi Mehranpour

Utrecht University

Postdoctoral researcher: Making digital rocks: a scientific basis for production and reinjection strategies to minimize induced seismicity within the Groningen gas field using large scale field observations.
Overview of former DeepNL researchers

Michael Volk
- Utrecht University
  - Postdoctoral researcher: Probing the micromechanics of small magnitude earthquakes slip.

Dr Femke Vossepoel
- TU Delft
  - Associate project leader: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence.
  - Associate project leader: Monitoring and Modelling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

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.

Prof. Kees Wapenaar
- TU Delft
  - Postdoctoral researcher: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Dr Kees Weemstra
- TU Delft / KNMI
  - Associate project leader: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Prof. Jan-Diederik van Wees
- Utrecht University/TNO
  - Associate project leader: PhysiMinX: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling.

Gjøs Wensink
- Eindhoven University of Technology
  - PhD researcher: 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.

Marius Wouters
- Utrecht University
  - PhD researcher: Monitoring and Modelling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Annika Greve
- Utrecht University

Dr Marcel Mizera
- Utrecht University

Floris Teuling
- Utrecht University

Ali Amootaghi
- TU Delft

Udit Asopa
- TU Delft

Jianye Chen
- Utrecht University / TU Delft

Mohsen Goudarzi
- Utrecht University

Appendix 1: Research output 2022

CLUSTER 1

Analysis of processes and conditions that lead to seismicity and subsidence

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

Presentations

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

Scientific publications

Presentations
Presentations

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

Scientific publications


Presentations


Other


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

Scientific publications


Presentations


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

Presentations


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

Presentations


Deepimage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity (Baarnhoorn et al.)

Scientific publications


• Shimohamadadi, F. D, Dragohov, and R. Ghose. (Submitted). The utilisation of geostatistics and seismic interferometry for large-scale characterisation of near-field surface data: Near Surface Geophysics.


Presentations


code/software


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

**Scientific publications**


• van Lieshout, M. N. M. (pre-print). Non-parametric adaptive bandwidth selection for kernel estimators of spatial intensity functions.


**Presentations**


**Code/software**


**Cluster 3 Subsidence and surface effects of seismicity**

**Scientific publications**


**Presentations**

Presentations


Other:

https://vimeo.com/773815746/b22d206741: In the framework of PhD of the Month UU-GEO: Short video of first measuring site, Neowalds Groningen

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

Scientific publications


Presentations


Appendix 2: List of abbreviations

ACT Accelerating CCS Technologies

AFM Atomic Force Microscopy

AGU American Geophysical Union

AI Artificial Intelligence

AWI Alfred Wegener Institute for Polar and Marine Research

CCS Carbon Capture and Storage

CPT Cone Penetration Test

CWI Dutch national research institute for mathematics and computer science

CYC-Doss Dynamic shear simulator for Organic Soft Soils

DEM Discrete Element Model

DSS Direct Shear Stress

EAGE European Association of Geoscientists and Engineers

EBN Energie Beheer Nederland

EGU European Geosciences Union

EZK Ministry of Economic Affairs and Climate Policy

FE Finite Element

FEM Finite Element Method

FWI Full Waveform Inversion

HPT Lab High Pressure and Temperature Lab

IAC International Advisory Committee

iGC inverse Gas Chromatograph

InSAR Interferometric synthetic aperture radar

KEM Knowledge Programme Effects of Mining

KNMI Royal Netherlands Meteorological Institute

LEFM Linear Elastic Fracture Mechanics

ML Machine Learning

NAC Netherlands Earth Sciences Congress

NAM exploration and production company

NARS Mobile seismic network operated by the seismology group of the Faculty of Geosciences, Utrecht University

NIOZ Royal Netherlands Institute for Sea Research

NORSAR Norwegian Seismic Array

NSF National Science Foundation

NWO Dutch Research Council

PI Principal Investigator

PPP public-private partnership

PSHA Probabilistic Seismic Hazard Assessment

QDM Quantum Diamond Magnetometer

RFEM Random Finite Element Method

RSF Rate and State Friction

RVO Netherlands Enterprise Agency

RUG University of Groningen

SBS Sea Bottom Seismometer

SCPT Seismic Cone Penetration Test

sEFVM smoothed Embedded Finite Volume Method

SEM Scanning Electron Microscopy

SHRA Seismic Hazard and Risk Assessment

SoDM Dutch State Supervision on Mines

TEM Transmission Electron Microscopy

TNO Netherlands Organisation for applied scientific research

TU Delft

TU/e Eindhoven University of Technology

UT University of Twente

UU Utrecht University

VS Velocity Strengthening

XRO X-ray Diffraction

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.

www.nwo.nl/deepnl
Dutch Research Council (NWO)
Domain Science (ENW)

NWO Den Haag
Laan van Nieuw Oost-Indië 300
The Hague

PO Box 93460
2509 AL The Hague
The Netherlands

deepnl@nwo.nl
www.nwo.nl/deepnl