

## Projectleider



**prof. dr. ir. Kees Wapenaar**  
Technische Universiteit Delft  
Expertise: seismic methods

## Co-projectleiders



**dr. ir. Deyan Draganov**  
Technische Universiteit Delft  
Expertise: seismic interferometry



**dr. Kees Weemstra**  
Technische Universiteit Delft / KNMI  
Expertise: seismic inversion



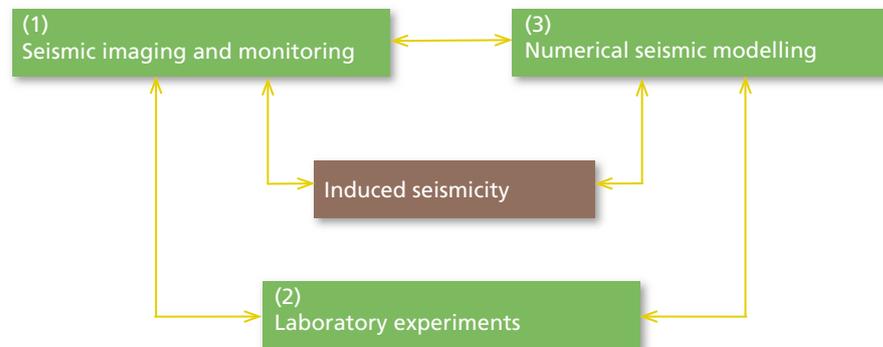
**dr. Auke Barnhoorn**  
Technische Universiteit Delft  
Expertise: rock mechanics

## 5.8 | DeepImage: multi-scale geophysical imaging, monitoring and forecasting of induced seismicity (prof. dr. ir. Wapenaar)

### Prognose van de bodembeweging in Groningen

Met dit onderzoek willen we een betere prognose kunnen maken van de bodembewegingen in Groningen, veroorzaakt door mogelijke toekomstige aardbevingen. Dit vereist inzicht in het ontstaan van seismische activiteit in de diepe ondergrond, de voortplanting van seismische golven door de verschillende aardlagen en hoe die golven tot bodembewegingen leiden. Hiertoe ontwikkelen we een nieuwe prognosemethodologie, die laboratoriumexperimenten met seismische modellerings- en monitoringstechnieken combineert. Met dit onderzoek leveren we een bijdrage aan een beter begrip van de relatie tussen menselijk ingrijpen in de ondergrond en de effecten daarvan aan het aardoppervlak.

“Dit project biedt ons de mogelijkheid seismische monitorings- en modelleringstechnieken op veldschaal te integreren met metingen in het laboratorium.”



*Integrated system for imaging and monitoring induced seismicity and forecasting the occurrence and effects of possible future induced earthquakes.*

“Op laboratorium-schaal kunnen we seismiciteit zien aankomen voordat deze met passieve technieken kan worden waargenomen. Dit project zal inzicht verschaffen in hoeverre dit kan worden opgeschaald naar seismiciteit op veldschaal.”



dr. Ranajit Ghose  
Technische Universiteit  
Delft  
*Expertise:* wave  
propagation

“Met ons onderzoek verwachten we betere prognoses te kunnen maken van bodem-bewegingen, veroorzaakt door mogelijke toekomstige aardbevingen.”

Werkpakket 1	
Development of seismic imaging and monitoring methodology	
<p>Methodology for layer-specific imaging and monitoring (MLSIM)</p> <p>PhD 1 Technische Universiteit Delft <i>Expertise:</i> seismic imaging</p> <p><i>Coördinatie:</i> Deyan Draganov / Guy Drijkoningen (promotor) / Kees Wapenaar (promotor)</p>	<p>Full-waveform inversion of active and passive data (FWIAPD)</p> <p>PhD 2 Technische Universiteit Delft <i>Expertise:</i> seismic inversion</p> <p><i>Coördinatie:</i> Kees Weemstra, Láslo Evers (promotor) / Kees Wapenaar (promotor)</p>
Werkpakket 2	Werkpakket 3
<p>Laboratory experiments: early detection of stress changes, failure and seismicity in rocks using acoustic techniques</p> <p>PhD 3 Technische Universiteit Delft <i>Expertise:</i> rock mechanics</p> <p><i>Coördinatie:</i> Auke Barnhoorn, Evert Slob (promotor) / Kees Wapenaar (promotor)</p>	<p>Numerical seismic modelling</p> <p>PhD 4 Technische Universiteit Delft <i>Expertise:</i> wave propagation</p> <p><i>Coördinatie:</i> Ranajit Ghose (promotor) / Wim Mulder (promotor)</p>

“DeepNL zal een belangrijke bijdrage leveren aan het inzicht in de relatie tussen menselijk ingrijpen in de ondergrond en de effecten daarvan aan het aardoppervlak.”

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

Project leaders: Prof. Kees Wapenaar (TUD),  
Dr Auke Barnhoorn (TUD), Dr Deyan Draganov (TUD)  
and Dr Kees Weemstra (TUD/KNMI)

In the Deep Image project we develop an integrated methodology for seismic imaging and monitoring of the Groningen subsurface and its induced seismicity. The aim is that this methodology will improve the forecasting of occurrence and effects of possible future induced seismicity. This requires a thorough understanding of induced seismic sources (their cause, location and radiation characteristics), the complex propagation of the seismic waves from these sources to the surface, and the resulting ground motion experienced at the surface. We aim to accomplish this by developing an integrated system consisting of (1) advanced seismic imaging and monitoring methodology, (2) innovative scaled experiments in our rock-mechanics laboratory and (3) advanced numerical seismic modelling modules. The research is organized in three interrelated workpackages along these lines. The progress for each of these workpackages is briefly described below.

WP1a: Methodology for layer-specific imaging and monitoring. As part of WP1, we will develop tools based on seismic interferometry and Marchenko redatuming for monitoring velocity and quality-factor changes in the Groningen subsurface. For this task, PhD student Faezeh Shirmohammadi started her PhD project in November 2019. We started the research for this task by numerical-modelling tests for the retrieval of non-physical reflections using seismic interferometry. We are investigating the retrieval quality of zero- and multiple-offset ghost reflections, in case of inclined layers, for layer-specific velocity monitoring. The first results will be presented at the March 2020 NAC meeting in Utrecht. The methodology developed in this package will be applied to active-source surface reflection data, borehole data, and the combination of the two, but also to induced earthquakes.

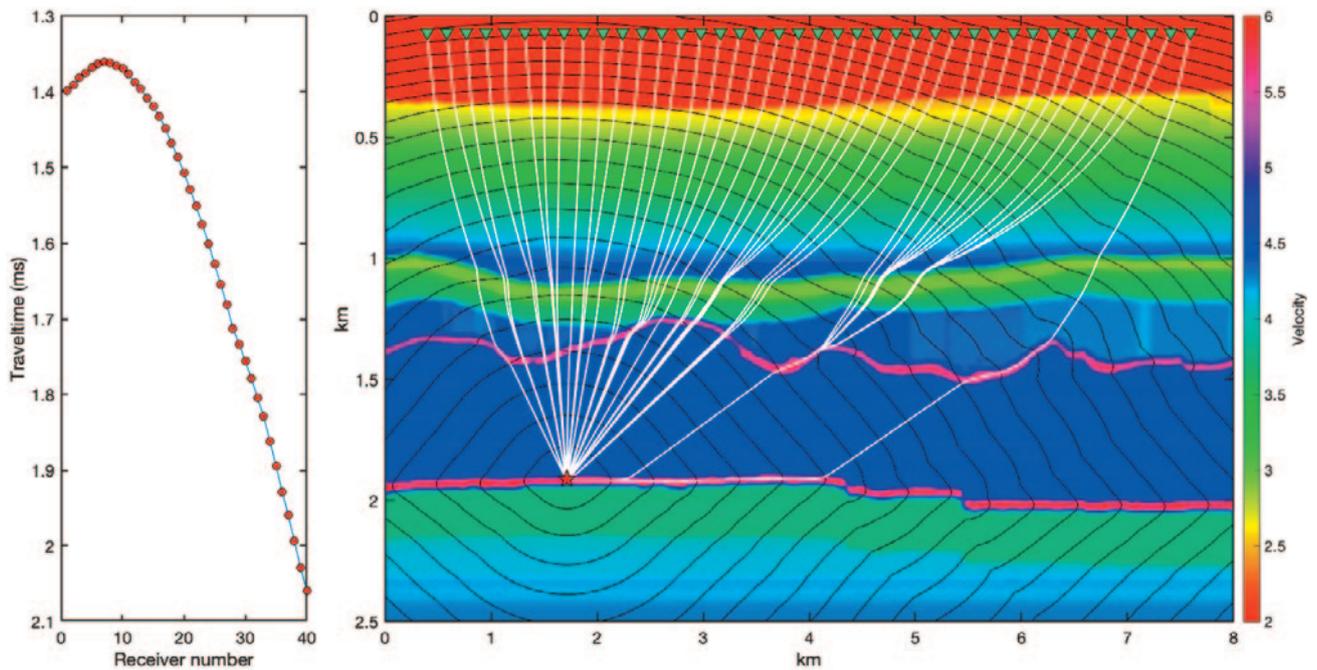
WP1b: Full-waveform inversion of active and passive data. Differences between computed seismograms and recorded seismograms are, in general, the result of a combination of an inaccurate structural model (including velocities and dissipative properties) and inaccurate source parameters

(location plus moment tensor). PhD student Iban Mafara started his PhD project in September 2019. We have so far focused on the inversion for the source parameters only. Currently, we are investigating probabilistic inversions for these parameters. In other words, we aim to quantify the uncertainty when it comes to the location and characteristics of the induced events in Groningen. In particular, we use a Hamiltonian Monte Carlo approach for this purpose. We are now at the point where we apply the scheme to a 2D velocity model of the Groningen subsurface for which synthetic data are generated. Comparing travel times for a large number of models (by means of the Hamiltonian Monte Carlo scheme) against the travel times extracted from the synthetic data, we obtain an estimate of the uncertainty on the locations and source characteristics of the induced events. These results will be presented at the March 2020 NAC meeting in Utrecht.

WP2: Laboratory experiments: early detection of stress changes, failure and seismicity in rocks using acoustic techniques. PhD student Aukje Veltmeijer started her PhD project in October 2019. Activities within this WP2 project have mainly centered around setting up, modifying and improving the experimental set-up to be able to do active acoustic monitoring and passive acoustic monitoring simultaneously. Passive acoustic sensors record the earthquakes, while the active acoustic sensors periodically send seismic waves through the material. By analysing the details in the changes of the active wave forms we aim to forecast when failure is occurring. Our initial efforts aim to integrate the newly acquired passive monitoring system into our established experimental protocol, as well as the understanding and data processing of the passively acquired seismicity data. The first results will be presented at the March 2020 NAC meeting in Utrecht.

WP3: Numerical seismic modelling. Quantifying and forecasting the effects of induced seismicity in and around Groningen requires modelling the entire chain of processes from the occurrence of induced earthquakes – considering the specific situation of the Groningen field, wave propagation through the different rock layers toward the ground surface, to site effects controlled by near-surface heterogeneities and distribution of soft sediments. PhD student Jingming Ruan started his project in September 2019. He has performed literature studies on the mechanism of seismicity in the Groningen gas field, existing fault distribution and the rupture models. A 4-year research plan was formulated and the primary impacts were defined. A computer

code (PFLOTRAN) has been installed for modelling the pore-pressure evolution. This was followed by installation of an up-to-date poro-elastic forward modelling code (Defmod) for fluid-induced dynamic faulting. This code was originally developed at MIT to model earthquakes in the Groningen gas field (Meng and Wang, *Computer and Geosciences*, 113, pp. 54-69, 2018). These two codes are now being used to model a fluid depletion scenario. In the near future, these codes will be adapted and tuned to model a more realistic situation.



Two-dimensional ray-based propagation for the purpose of source (parameter) inversion in WP1b. Synthetic data is created by placing a simple impulsive source (red star) at the depth of the top of the Gas reservoir. The velocity model is a two-dimensional vertical cross-section extracted from the three-dimensional velocity model of the NAM. Black lines represent lines of constant travel times, whereas the white lines represent the rays along which the energy between the source and each of the receivers traveled. The synthetic travel times are evaluated against travel times associated with source locations proposed by the Monte Carlo sampler (see description of WP1b). As such, a probability density of the location of the (synthetic) induced event is constructed.

### WP1a: Development of seismic imaging and monitoring methodology: methodology for layer-specific imaging and monitoring (MLSIM)

Supervision by Dr Deyan Draganov (TUD),  
Dr Guy Drijkoningen (TUD) and Prof. Kees Wapenaar (TUD)



**Faezeh Shirmohammadi**  
PhD student (TUD)

I obtained my master degree in Geophysics at Institute of Geophysics at University of Tehran and my bachelor degree in Geology at University of Tehran, Iran. In my master thesis, I worked on quality-factor tomography using earthquakes data, on seismic interferometry (SI), seismic hazard assessment, and seismic imaging. Now, as a PhD student in the section of Applied Geophysics and Petrophysics at the Department of Geoscience and Engineering at Delft University of Technology, I am working on a methodology for layer-specific imaging and monitoring in Work Package 1 of the project DeepImage. We will develop SI tools based on non-physical reflections and make use of Marchenko-redatuming tools for monitoring time-lapse changes in both P- and S-waves velocities and Q-factors in the Groningen subsurface. The SI tools will be developed for application to active-source surface reflection data, borehole data, and the combination of the two, but also to induced earthquakes.

### WP2: Laboratory experiments: early detection of stress changes, failure and seismicity in rocks using acoustic techniques

Supervision by Dr Auke Barnhoorn (TUD);  
Prof. Evert Slob (TUD) and Prof. Kees Wapenaar (TUD)



**Aukje Veltmeijer**  
PhD student (TUD)

In October 2019, I started my PhD in the section Applied Geophysics & Petrophysics at TU Delft. Before starting my PhD, I have a completed a bachelor in Applied Earth Science at TU Delft and the IDEA league joint master program in Applied Geophysics at TU Delft, ETH Zurich and RWTH Aachen. My project is part of DeepImage and about early detection of stress changes, failure and seismicity in rocks using acoustic techniques. The aim of my research project is to show precursory indicators for failure and slip along pre-existing faults in the laboratory, using acoustic measuring techniques. The other important component is to assess the feasibility of these monitoring techniques on larger field- and reservoir scale applications.

### WP1b: Development of seismic imaging and monitoring methodology: full-waveform inversion of active and passive data (FWIAPD)

Supervision by Dr Kees Weemstra (TUD),  
Prof. Láslo Evers (TUD/KNMI) and Prof. Kees Wapenaar (TUD)



**Iban Masfara**  
PhD student (TUD)

La Ode Marzujriban Masfara Rachman (Iban) obtained his bachelor's degree with a cum laude in Geophysics from the University of Hasanudin in Indonesia, and is highly passionate in Seismic Exploration and Inverse Theory. He then continued his study in a joint master's degree program of Applied Geophysics offered by the IDEA League (TU Delft, ETH Zurich, and RWTH Aachen) and graduated with distinction. During his master thesis, he worked under the supervision of Professor Andrew Curtis, Dr. Dirk Jan Van Manen and Hendrik Thomsen, M.Sc with the main topic of multi-scattering identifications in highly dispersive media in ETH Zurich Wavelab. In September 2019, he started as a Ph.D. student at TU Delft and has been working within Deep Image team, which is part of the DeepNL project. His main goal is to obtain a representative subsurface velocity model of the Groningen field. The project is under the supervision of Dr. Kees Weemstra with promotor of Prof. Kees Wapenaar.

### WP3: Numerical seismic modelling

Supervision by Dr Ranajit Ghose (TUD) and  
Prof. Wim Mulder (TUD)



**Jingming Ruan**  
PhD student (TUD)

Since 1st September 2019, I work as a PhD student in the Department of Geoscience & Engineering, TU Delft. I am responsible for research under Workpackage 3 of the DeepImage Project. Prior to this, I obtained my BSc degree from Sun Yat-sen University, China, majoring in marine sciences, and MSc degree in geophysics from Utrecht University. The topic of my MSc thesis was seismic wavefield reconstruction using sparsely sampled seismic data with spatial gradients. In my present research I am trying to numerically model the entire chain of processes related to induced seismicity in the Groningen gas field. This will involve modelling the evolution of pore-pressure to poro-elastic, dynamic faulting, seismic wave propagation and near-surface effects. The results will be useful to explain damages at the surface and forecast the effects of various production scenarios. The developed approach will be applicable to model both fluid injection- and depletion-induced seismic events.