Bijlage 1

DeepNL

A proposal for an Integrated Programme to Understand Subsurface Dynamics Caused by Human Activities.

CONTENT

Bijlage 1

0. EXECUTIVE SUMMARY

Over recent years, the development of subsurface resources in the Netherlands has gradually become a major source of concern to the general public, locally, regionally and nationally. Subsurface activities such as gas production, geothermal energy production, geological storage of CO_2, geological storage of energy reserves and salt mining, can lead to undesired effects such as earthquakes, subsidence and leakage, which may lead to damage at the surface or pollution of groundwater, soil or air. A clear example is the public reaction to the tremors induced by the gas production in the Groningen field. Society is now demanding that such potential hazards are avoided and that the associated risks to people and assets are mitigated as far as possible. However, while the Dutch subsurface is relatively well characterised and the broad processes responsible for subsidence and seismicity in gas fields are qualitatively understood, quantitative predictive capability is as yet wholly lacking. As recognized by the Dutch Government in its reaction to the report of the Dutch Safety Board 2015, major advances in understanding of subsurface processes are required, enabled by fundamental and applied research as well as large-scale acquisition of relevant data over and above to what is already available.

The focus of the DeepNL research programme is on developing a quantitative, physics-based understanding of the subsurface response to activities such as resource production and geological storage. The programme aims to achieve this by integrating the expertise that exists in the Netherlands in the field of Solid Earth Sciences. The proposed programme will initially run over 6 years. A milestone evaluation will take place mid-term and a potential extension to a total of 10 years will depend on the results. Its initial focus will be to understand the surface effects caused by subsidence and induced seismicity in the Groningen Gas field.

The programme will develop a multi-scale, multi-physics, data-driven modelling methodology to investigate the response of the soil at the Earth's surface due to tremors at depth. A highly integrated effort involving geo-mechanics, seismic modelling techniques, rock physics, quasi-real time imaging tools, data at high sampling density, and massive and novel data processing capabilities is essential to achieve this goal. Existing monitoring infrastructure will be used for data acquisition, especially in the Groningen area. Large investments in infrastructure are not part of the initial programme, but may be defined on the basis of the scientific results.

The programme will reside under the umbrella of the NWO Exact and Natural Sciences domain, with day to day execution being overseen by a programme committee. This will be supported by a small programme office, residing at NWO. Stakeholders in the programme, such as scientific institutions, industry and governmental representatives, are involved via participation in a Stakeholder Advisory Board, which gives feedback on progress and direction of the research. Outreach to stakeholders and the general public is considered essential. Therefore a comprehensive programme covering education, knowledge-sharing and popularisation of relevant Earth sciences topics is foreseen, but is *senso stricto* not part of the scientific problem definition of the first 6 years.

Funding through the programme is open to Dutch knowledge institutes with project proposals to be submitted via thematic NWO calls. It is envisaged that the first call will be published in the second half of 2017.

1. BACKGROUND AND SCOPE

1.1 THE NEED FOR A RESEARCH PROGRAMME ON THE IMPACT OF SUBSURFACE ACTIVITIES

Triggered primarily by the recent increase in frequency and strength of induced earthquakes in the Groningen gas field, the development of subsurface resources in the Netherlands has become a major source of concern to the general public, locally, regionally and nationally. Subsurface activities such as gas production, geothermal energy production, geological storage of CO_2, geological storage of energy reserves, and salt mining can lead to undesired effects such as earthquakes, subsidence and leakage which may lead to damage at the surface or pollution of groundwater, soil or air. Although more than 100 years of subsurface activities in the Netherlands shows a track record of relative safety, developments over the last decade point to an urgent need for new and more advanced understanding of subsurface processes. Amongst these developments, the subsurface activity level has increased substantially, both in intensity and areal coverage. This need for knowledge will continue to increase in future, due to the need to develop and implement options ranging from CO_2 storage to energy storage and geothermal energy. Secondly, new activities such as injection of gases and liquids have not only resulted in changed conditions at reservoir level but also caused effects noticeable at the surface. Thirdly, and most importantly, as Dutch gas fields such as Groningen, and as operations like salt mining, have progressed into the mature and later stages of field life, phenomena such as subsidence and induced seismicity have been observed, which are relatively new in the Netherlands. Society is now demanding that these potential hazards are avoided and that the associated risks to people and assets are mitigated as far as possible. However, while the Dutch subsurface is relatively well characterised and the broad processes responsible for subsidence and seismicity in gas fields are qualitatively understood, quantitative predictive capability is as yet wholly lacking. As a result, a more deterministic basis for modelling and assessment of ground motion, which is the determining factor in assessing hazard and risk of earthquakes induced by gas production, is largely absent. As recognized by the Dutch Government in its reaction to the report of the Dutch Safety Board 2015, achieving this basis requires major advances in our understanding of subsurface processes, to be enabled by fundamental and applied research as well as large-scale acquisition of relevant data over and above what is already available.

The overall objective of the programme proposed here is to successfully develop a quantitative, physics-based understanding of how the subsurface responds to activities of resource production and geological storage, addressing in particular the issues of subsidence, induced seismicity and system integrity. The programme aims to achieve this by integrating the expertise and potential that exist in the Netherlands in the field of Solid Earth Sciences (seismology/seismics, rock and fault mechanics, tectonics/tectonophysics, computational geophysics, Earth materials, hydrogeology and geochemistry) in a concerted effort focused on addressing the hazards resulting from subsurface activities in the Netherlands, especially that of gas production from the Groningen Gasfield. Various Dutch research groups occupy internationally leading positions in the relevant geoscience fields, but are not necessarily focusing on integrated, quantitative approaches to study induced seismicity. This programme therefore provides an opportunity to integrate and improve this research power in the national interest, to investigate the hazards involved, thereby establishing a warranted science basis for risk assessment. Furthermore this programme aims to anchor the developed understanding in the scientific community in the Netherlands.

1.2 NATIONAL AND INTERNATIONAL POSITIONING

KNMI has been engaged in monitoring induced seismicity in the province of Groningen since the 1990's. Similarly, TNO is actively involved in performing reservoir modelling to quantify subsidence and seismic hazard due to gas extraction in the Groningen and other Dutch gas fields. Both undertake these tasks mostly upon requests from EZ (Ministry of Economic Affairs) and SodM (Staatstoezicht op de Mijnen), or from NAM.

Some seismic and ground motion monitoring infrastructure has been put in place by NAM over the years, with a major upgrade being implemented in 2015, but more may be needed. The impact of this improved infrastructure, in terms of data already collected and future data potential, have not been fully evaluated yet. Nonetheless, the infrastructure now available, along with further developments in future, offer a major opportunity for the success of the proposed programme.

Internationally, many researchers and national laboratories[1] are involved in monitoring induced seismicity due to gas production, water injection, enhanced geothermal systems, fracking and CO_2 storage. In comparison with these and other monitoring programmes, DeepNL will go much further by addressing the processes that operate at depth in the Earth's crust (i.e. up to 5-6 km) in response to fluid extraction or injection, via integration of input from the disciplines of seismology (source physics and seismic imaging) and geomechanics (Figure 1). Key enabling (sub-)disciplines and methodologies include rock physics, quantitative process modelling, up- and down-scaling, multi-phase fluid flow studies, and data processing (i.e. pattern recognition techniques). Through integration of these elements, DeepNL should lead to a deterministic capability for modelling and assessment of ground motion. The results of the scientific programme will be communicated with the stakeholders via workshops, outreach sessions, symposia and open day events at the participating research organisations. Moreover, in the final years of the initial programme, stakeholders and scientific partners will jointly work on applying the results of the fundamental science programme to solve practical problems.

[1] see for example http://earthquake.usgs.gov/research/induced/ or http://esd1.lbl.gov/research/projects/induced_seismicity/ or https://scits.stanford.edu/about or http://www.brgm.eu/project/microseismic-risks-arising-from-stimulation-of-deep-geothermal-wells

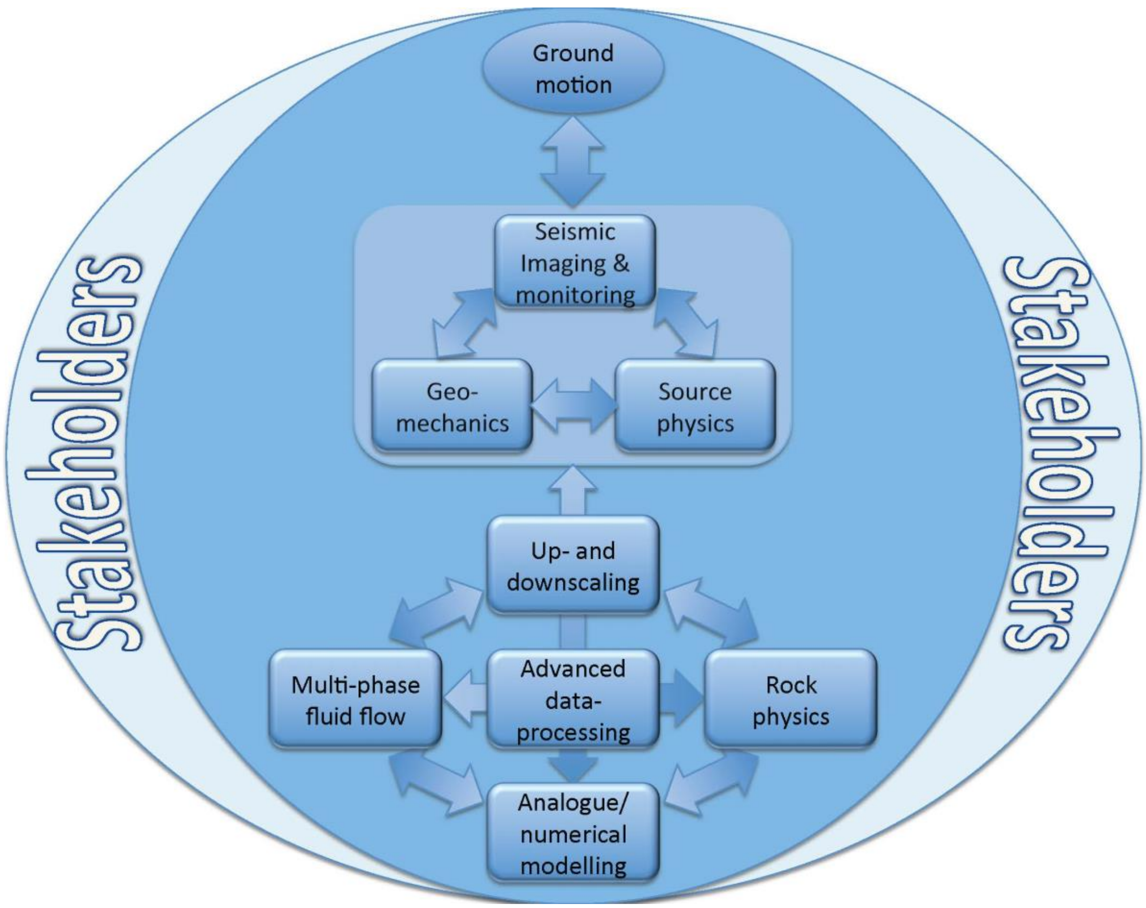

Figure 1: Scientific fields (sub-discipines, methodologies) and their interactions. The core fields are shown in the rectangle, the enabling fields are depicted below. The main stakeholders are KNMI, TNO, EZ, SodM and the local population in areas displaying induced subsidence and seismicity.

2. Scientific Problem

For the public, the most important questions related to deep subsurface extraction and storage activities, such as gas production in Groningen, are: what effects can these activities cause at the surface and what can the impact be on personal safety and property? For industry, economic institutions and government, a key question is: how can operations such as gas production be adjusted to avoid or minimise surface effects while remaining economic?

Of course, a crucial aspect underlying these questions is at what spatial and temporal resolution these questions can be answered? In particular, to be relevant in economic and societal context, the spatial and temporal resolution and accuracy of ground motion predictions must be improved over what can be achieved by present, conventional methods. Via a more deterministic, physics-based approach, coupled with the detailed geological and production data available for the Groningen field, as well as continuous data recording using the recently upgraded monitoring systems installed there, more accurate and higher resolution predictions (based on past as well as future production scenarios) should be possible. Importantly, the Groningen reservoir offers a uniquely defined situation allowing scientists to quantitatively integrate and validate fundamental aspects of geophysical, geomechanical and geological research to advance understanding of earthquake rupture processes in a manner that is not easily possible in other gas fields or in natural seismically active areas.

From a scientific perspective, the questions posed by society, government and industry regarding the surface impact of subsurface operations translate to the issue of how do subsurface systems respond to the changes in stress field that are induced by these operations, whether they be gas production, geothermal energy production, salt production or geological storage. For example, in the case of gas production from the Groningen reservoir, depletion of the reservoir results in vertical compaction of the reservoir rock, which becomes increasingly stressed, plus accompanying surface subsidence. Understanding the behaviour of such a system means understanding the stress-strain response of the reservoir and of its over- and underburden. At the same time, it is crucial to understand whether and how the evolving stress field within the subsurface system leads to fault reactivation and fracturing, where this will occur and whether the resulting motion may be seismic or may lead to losses in system integrity. If seismicity occurs, an essential requirement is to be able to constrain the likely ground motion, the maximum magnitude and to characterize frequency-magnitude relationships.

The problem accordingly reduces to determining the quasi-static stress-strain and stored (elastic) energy fields in the subsurface system and the resulting displacement field at the surface, as caused by changes in stress following fluid extraction or injection at depth, or by other activities that may modify stress state. Crucial here is to determine the distribution of stored strain energy versus dissipated mechanical work within the deforming subsurface system, as this determines the energy available for seismic release; the timescales of dissipation are of key importance. On the basis of such data, the potential for fault reactivation, unstable rupture propagation, stress-drop and associated seismicity and seismic energy release can be computed. Locally, we thus need to know the rock and fault mechanical properties, including elastic, inelastic, time-dependent creep and failure properties, which depend on temperature, lithostatic pressure, fluid pressure and chemical conditions. The elastic constants can be measured in the laboratory and an equation of state can be formulated to determine them at the relevant P-T-V conditions. They can also be obtained from geophysical imaging (mostly seismic). In neither case, however, are the elastic constants obtained at the relevant scale, and the difficult problem of up- or down-scaling needs to be addressed. Similar scaling is needed regarding other rock and fault properties.

If the rock and fault properties are known at the appropriate scales, advanced (dynamic) geo-mechanical and geophysical modelling can calculate the wave field and surface displacement or ground motion caused by seismic fault rupture, by forward propagating the stress or strain. This problem too can only be tackled if the properties of the affected rock mass are known in sufficient detail (fractures, fluid content, poro-elastic moduli) and in conjunction with data on in-situ temperature, pressure, stress and strain at points sampled as densely as possible. Currently, such data are obtained via monitoring of induced seismicity, but can be further constrained by direct downhole measurements, for example of temperature and stress state, and by petrophysical measurements made on core material. However, we need to remain aware that we can only ever access certain medium averages, and proper up- and down-scaling needs to be an integral part of any qualitative inference.

To answer the question of how a subsurface system responds to stress changes caused by a given activity, and in particular to understand how a seismic rupture nucleates, propagates and generates seismic waves, we have to understand the dynamics of the problem, which unfortunately are not directly observable. Statistics of earthquakes are usually taken as a proxy for unobservable dynamics using various assumptions. Conversely, seismological data and surface motion data provide crucial tools to critically test and validate forward models addressing the dynamics of subsurface stress-strain evolution, fault reactivation, rupture propagation and ground motion . The recently upgraded seismic infrastructure by NAM offers a unique opportunity to test such models and thus to realise the aims of this programme.

This deterministic approach is essential to provide physical understanding of the effects of subsurface activities, to constrain interpretation of seismic and surface deformation data obtained from field monitoring, to assess hazards and to design mitigation strategies. However, it inevitably relies on geomechanical, rupture propagation, wave propagation and ground motion modelling methods that are based on (at least) locally averaged effective medium properties and simplified structural and material property models. This means that the true complexity and variability of subsurface processes and their surface impact can never be captured in detail. It therefore remains crucial to the present programme to combine the deterministic approach with statistical inference methods based on continuous monitoring of seismicity and ambient noise. These data-driven methods provide important alternatives for predicting ground motion, which can likely be further improved by applying deterministic understanding to physically interpret monitoring data.

The route that needs to be followed to address the problem of how the subsurface responds to human activities is therefore clear. At present, though, our understanding and capabilities are far too limited and qualitative to provide the answers needed. The present programme accordingly needs to open with an initial phase of fundamental scientific research designed to begin to rectify this, followed by a second phase in which stakeholders will be involved to realise application. As already indicated, the programme will focus on Groningen in the initial period. In this context, the main emphasis will be placed on improving predictions of subsidence, seismicity, magnitude-frequency statistics and ground motion hazard resulting from gas production.

3. Aim

Against the background given above, the aim of the DeepNL programme is to make major fundamental advances in establishing an integrated, multi-scale, multiphysics- and chemistry-based understanding of the response of the subsurface (upper crust and surface) to activities such as gas production, geothermal energy production, well stimulation, CO_2 storage, salt mining, energy storage and storage of wastes. The intention is to stimulate the development of a frontier-breaking, quantitative, forecasting capability to serve as an Earth Science basis for assessment of hazards posed by induced surface subsidence or heave, induced and triggered seismicity, fluid leakage and aquifer contamination. Initially, the focus of the initiative will be to improve modelling and prediction of ground motion effects due to gas production operations in the Groningen reservoir. The advances in methodologies achieved and understanding gained in this initial part of the programme will also provide a more general platform. At later stages, a broadening – based on this platform - towards other subsurface settings will be considered. The scientific motivation for a focus on the Groningen Gas Field is mainly based on the already available surface and subsurface data as well as the future data acquisition and monitoring plans in place for the reservoir. This is in addition to the societal and economic relevance that the results of such a hazard oriented study would have on earthquake risk analysis in the Groningen area.

Pre-requisite to advances in understanding and modelling such complex systems and phenomena is access to large-scale data handling, processing and computational facilities and methods, as well as to cutting-edge field and laboratory instrumentation. Coupling the scientific aims with developing this research infrastructure may well lead to a unique Dutch lead in integrated computational geosciences capability, which may be called upon, not only in the national interest but internationally, for practical expertise in assessing the critical subsurface factors underpinning hazard and risk analysis.

4. What is needed?

To achieve the aims defined above in relation to the Groningen Gas Field and beyond, a multi-scale, multi-physics/chemistry (deterministic) modelling methodology must be developed to investigate the response of the subsurface to resource exploitation and to model wave propagation and ground motion at the surface due to point excitations at depth (forward and inverse). This will need to be combined with statistical approaches to seismic hazard analysis. Intimate integration of new modelling techniques, rock physics data, quasi-real time imaging tools, monitoring data obtained at high sampling density, and massive and novel data processing capabilities is essential here, as well as regular communication with and involvement of stakeholders via comprehensive scientific/technical and popularization outreach activities. Integration of the multiple new data sources and new collaborations targeted in the programme will be key to synergizing new advances.

Specific needs that must be fulfilled and issues that must be addressed by the programme, to develop the intended capability and new approach to ground motion modelling, for Groningen and in general, are as follows:

1. Access to a state of the art seismic measurement and monitoring system, with potential for surface deformation and downhole stress, temperature and fluid pressure measurement at a given site. This underpins the choice of the Groningen field as the first scientific target of the proposed programme. Access to such a system as that in place (and potentially to be developed further) in Groningen is crucial to establish the required understanding and modelling of the main factors determining risk and hazard analysis.

2. Development of (or access to) accurate regional and site-specific seismic wave velocity models. Development of new seismological methods for accurate subsurface imaging, earthquake location and event interpretation, and for detecting fluids and their motion (seismology/seismics). While much progress has recently been made in the area of event location, work is needed, for instance, in shear wave imaging, focal mechanism characterisation and imaging the time evolution of subsurface processes and effects.

3. Numerical modelling of in-situ temperature, fluid pressure and especially pre-production stress state at regional and site-specific scales. Modelling studies of regional tectonic stress field have been conducted previously but have not addressed the Dutch subsurface at scales relevant for evaluating induced seismicity hazards.

4. Determination of rock and fault mechanical properties and the controlling physical and chemical processes, at true in-situ conditions, via intensively instrumented rock-physics experiments, micro-scale process observation and microphysical modelling Much previous work has been done on the deformation/compaction behaviour of reservoir and other sedimentary rocks and on the frictional behaviour of faults systems, in a generic sense. However, little attention has been paid to effects of temperature, pore fluid chemistry and loading rate or time, all of which are now emerging as playing an important role under conditions relevant for fields such as Groningen. Moreover, the physical mechanisms controlling mechanical behaviour are poorly understood, as are the effects of experimentally applied boundary conditions, so that extrapolation of existing lab data to the field is fraught with uncertainties. In addition, virtually no data exist on the partitioning between elastic and permanent deformation, i.e. on elastic (seismic) energy storage versus (aseismic) dissipation, in upper crustal rocks.

5. Development of theory and methodology for up-scaling lab data to length scales on the modelling mesh and field scales (10-1000 m). It is widely recognized in the rock mechanics and earthquake science literature that scaling relations need to be found to apply laboratory data on rock and fault properties confidently in numerical models and at the field scale. This problem is often circumvented by tuning numerical models to both lab and field data, and has been quite successful in modelling tectonic earthquake cycles. In the context

of induced crustal deformation and seismicity, however, a firmer basis for upscaling and for evaluating uncertainties is needed.

6. Large-scale computational modelling of the -(quasi-static) geomechanical response of reservoir-systems to subsurface activities, including stress-strain field evolution, fault and fracture (re)activation, surface deformation and fluid migration. Codes with this capability in 3-D are now becoming available, but have yet to be tailored to incorporating state-of-the-art descriptions of rock and fault mechanical behaviour.

7. Computational modelling of dynamic rupture and fracture, resulting seismic wave field and seismic ground motion, plus earthquake magnitude/frequency statistics and earthquake early warning signatures . Such modelling capability is now being developed and applied in relation to the modelling of both natural and induced earthquake rupture but is still requires major advancement for confident application in hazard analysis.

8. Laboratory-based validation and improvement of numerical models for subsurface response and fault rupture behaviour by comparison with massively instrumented (i.e. acoustic emission, acoustic CT and X-ray CT instrumented) analogue and scale model experiments. To date, virtually no studies of this type have been reported internationally, in the context of induced crustal deformation and seismicity.

9. Field-based validation and improvement of numerical models for subsurface response, surface deformation, fault rupture and seismicity by comparison with seismic monitoring data, down-hole monitoring data and surface-monitoring data. The focus of the first phase of the proposed programme on the well-characterised and newly instrumented Groningen Gas Field provides an unprecedented opportunity to achieve such validation, which will be of major value not only in the national context but to advancing earthquake science in general.

5. SCIENTIFIC FIELDS INVOLVED AND CHALLENGES

From the above, it is clear that processes in the Earth’s crust related to fluid extraction or injection involve complex interactions that can only be addressed by integrating efforts between the disciplines of seismology and geomechanics, with crucial input from the enabling fields of rock and fault physics, multi-phase fluid flow in porous media, applied mathematics and computational science (Figure 1). The key scientific methodologies needed include seismic imaging using (semi) continuous data streams, analogue and numerical modelling, experimental determination of rock mechanics parameters, up- and down-scaling, sensor development, and advanced data processing and visualization, including semi-automated (machine) learning methods (Deep Learning Principles).

5.1 SEISMIC DATA ANALYSIS, IMAGING AND MONITORING

Seismic imaging and monitoring form one of the main methodologies available for probing the geomechanical and fluid flow processes that operate in the deep subsurface. Traditionally the seismic method is applied with active sources (at the surface or in wells). In the past ten to fifteen years there have been exciting developments in the field of passive seismic imaging and monitoring. In this approach, instead of using active sources to generate the seismic wavefield, geophones and/or seismometers passively record ambient seismic noise, microseismicity, anthropogenic noise and the like. Using advanced data-analysis methods (commonly known as seismic interferometry), these recordings are turned into virtual seismic responses, i.e., responses that would be measured by the receivers if there were an active source at the position of any of the receivers. Passive seismic methods that employ surface-wave noise have proven to be particularly successful for monitoring minute changes in the constitutive parameters of the subsurface. Other exciting developments in the field of seismic imaging and monitoring are full wavefield inversion and so-called Marchenko imaging. Both methodologies employ the full seismic response rather than primary waves only, and therefore have the potential to image and monitor the Earth with much higher spatial and temporal resolution. New breakthroughs in the monitoring of geomechanical processes, fluid-flow processes and seismic source mechanisms in the deep subsurface, and in deterministic modelling and assessment of ground motion can be expected by combining these recent advances in seismic interferometry, full wave form inversion and Marchenko imaging. Several groups in the Netherlands (Delft, Utrecht) have played pioneering roles in these fields and are therefore very well equipped to accomplish the breakthroughs needed.

In the proposed programme, recent success in Deep Learning opens new possibilities to train neural networks to infer reservoir dynamics based on real-time ground motion observations, i.e. from seismometer records obtained at the surface. The surface ground motion is a causal expression of the dynamic processes operating within the reservoir. Dedicated rock physics experiments will be used to calibrate these relations and neural networks have the potential for isolating and interpreting ground motion observations, however complicated they may appear.

Challenges related to this programme component are:

1. Determining moment tensors and source mechanisms (in particular of induced seismicity).
2. Development of accurate regional and site-specific, time-dependent anisotropic seismic wave velocity models.
3. Accurate ground motion forecasting.
4. Development of new seismological methods for detecting fluids and their motion and fractures.

5.2 Rock and Fault Physics: Laboratory work and multiscale analogue/numerical modelling

Laboratory experiments, coupled with micromechanistic studies, analogue scale modelling, numerical modelling and upscaling methodologies, are crucial for characterizing and understanding the mechanical, wave transmission and fluid transport properties of rocks and faults at in-situ conditions. Few data are currently available on these properties at sufficiently deep subsurface conditions. Moreover, numerous uncertainties exist in extrapolating from the laboratory sample (cm or dm) scale to that of a geomechanical modelling mesh (1m-100m) and ultimately to the field scale. New multiscale data must therefore be produced to provide the input on rock properties and controlling processes needed for modelling geosystem response to fluid extraction/injection, including seismic rupture and ground motion, and for interpreting seismic data. Key challenges that must be addressed in the present programme, with its initial focus on induced seismicity in the Groningen Gas Field, are described below. To achieve the necessary advances, the experimental work highlighted will need to employ the latest, real time sample-scale structural and process monitoring methods including acoustic emission monitoring, wave velocity monitoring, ultrasonic tomography, X-ray tomography, intra-sample P-T measurements and pore fluid chemical sampling, alongside more conventional methods.

The main challenges are:

1. Experimental determination of the poro-elastic, inelastic and time dependent deformation behaviour of field-specific reservoir rocks, caprocks and underburden formations, under true in-situ pressure-temperature-stress and pore fluid (chemical) conditions, with the aim of producing mechanism-based constitutive laws.

2. Determination of the partitioning of deformation between elastic and permanent, inelastic deformation.

This is crucial for assessing the extent of elastic energy storage versus dissipation, and hence the energy available to drive seismicity in both reservoir and over/underburden rocks.

3. Verification that laboratory-characterized rock deformation mechanisms actually operate in-situ, using state-of-the-art optical, electron-optical and petrophysical studies of reservoir and over/underburden core samples (e.g. taken before and after gas production in the Groningen field).

4. Experimental determination of the failure and frictional behaviour of realistic, field-specific rock and fault rock materials, again under true in-situ P-T-stress and pore fluid (chemical) conditions. Essential here is to determine the key parameters and mechanisms controlling seismic versus aseismic fault (re)activation in the rupture nucleation and dynamic rupture propagation regimes.

5. Determination of the elastic wave transmission properties of site-specific reservoir, cover and underburden rocks under in-situ P-T-stress and pore fluid conditions.

6. Development of advanced ultrasonic and X-ray CT imaging capability, alongside new DEM and grain-scale-FEM or "digital rock" modelling capability. This should be aimed at quantifying the microstructure, mechanical behaviour and wave transmission properties of reservoir and fault rocks, advancing DEM capability by incorporating lab-verified microphysical process laws operating at the grain scale.

7. Development and testing of rules and models for upscaling laboratory data to representative fault and rock mass scales, through multiscale lab experiments.

8. Development, testing and tuning of numerical models for subsurface response and fault rupture by comparison with massively instrumented (i.e. acoustic emission, acoustic CT and X-ray CT instrumented) analogue and scale model experiments.

9. Estimation of in-situ reservoir and over/underburden stress states by exploring the applicability of stress-sensitive petrophysical and microstructural indicators to core samples. Tectonic modelling may also offer constraints on tectonic stress states before field operation.

5.3 Geomechanics and ground motion modelling

Geomechanics forms one of the central disciplines of this programme. It encompasses modelling, at the scale of the reservoir system and beyond (to the extent required by the processes involved), of rock fracture and rock deformation, (re)activation of faults and fractures and the quantification of lateral and vertical subsurface stress and strain fields. Modelling, understanding and, ideally, influencing these phenomena involves the determination and monitoring of in-situ temperature, fluid pressure and the state of stress at regional and site-specific scales (using seismology, down-hole measurements, numerical and analogue tectonic modelling), and relies on experimental data on geomechanical rock properties for deterministic evaluation of fault movement. The challenge will be to combine laboratory-based constitutive laws with large-scale effective medium images into a quantitative modelling tool. Up- and down-scaling needs to be an integral part of such modelling as well as scale-dependent uncertainty analysis. While evaluating the impact of subsurface activities in producing subsidence and fault (re)activation lies in reservoir-scale numerical modelling of quasi static stress-strain field evolution, seismic rupture and dynamic wave field modelling, and hence ground motion and acceleration, require a fully dynamic modelling approach. This is presently in a relatively early stage of development, in part because of the massive computational intensity. An important challenge within the present programme will accordingly be to advance this field, drawing on both computational science and rupture modelling methods employed in natural earthquake simulations by groups in the US and Japan in particular. It is essential that this modelling is strongly data driven.

5.4 Multi-phase fluid flow

Geomechanical processes interact with fluid flow in heterogeneous porous and fractured media. Indeed, fluid pressure changes in the subsurface are the key drivers for changing the in-situ stress and strain field and hence for causing subsidence, heave, fault reactivation and induced seismicity. The study of multi-phase fluid flow in reservoir systems, including both physical and chemical effects, underlies understanding, predicting and influencing the effects of fluid injection and/or extraction of fluids. Fluid flow computations are therefore needed, alongside geomechanical modelling, to evaluate the effects of injection and extraction strategies. Moreover, multi-phase fluid flow modelling is of major importance for evaluating the integrity of potential future sequestration sites for liquids or gases, where the aim is to prevent leakage in the short term (e.g. natural gas or hydrogen fuel) as well as in the long run (e.g. Carbon Capture and Storage).

5.5 Mathematical up- and down-scaling

As mentioned at several locations above, to link the results of laboratory experiments and analogue modelling work to field-scale measurements and/or numerical experiments, mathematical up- and down-scaling methodology is required. Hence, in this programme ample attention needs to be paid to the development of theory and methodology for the up-scaling of laboratory data to length and time scales of the modelling mesh and field scales (10-1000 m) and vice-versa.

5.6 Advanced data processing

Large sensor networks (be it existing ones, like the sensor network of the Groningen gas field, or new networks to be developed outside this programme), will provide a continuous stream of 'big-data'. This requires a rethinking of data handling, processing and visualisation, including the development of new methodologies for this purpose. Pattern recognition techniques are likely to be essential to relate dense surface observations to sub-surface processes. Seismic interferometry, described in detail above, is one of the new data processing tools needed in this programme.

Another essential tool is Deep Learning. It has been shown that deep neural networks can learn any complicated relation, non-linear and/or multi-valued. Provided that sufficient pairs of observations and corresponding model parameters are available, these networks can be successfully trained and rapidly applied to future observations. This is ideal for the forecasting of seismic hazard, for instance. The difficulty in this programme lies in finding sufficient pairs for training. In the Groningen case, this could be achieved via two complementary routes: Use refined classical geomechanical modelling together with seismic imaging to create realistic synthetic pairs to train the networks, and, once trained, use it on real observations. This approach has been successfully applied by Utrecht researchers. Another approach is learning directly from the real data observations using calibrations from dedicated rock physics experiments.

5.7 Integration

To be successful DeepNL needs to be strong in innovation within each of the programmes components (projects, subdisciplines, methodologies) as well as in the integration of these components. This integration requires attention as soon as developments or results in individual components allow or call for it.

6. EXAMPLES OF INFRASTRUCTURAL NEEDS

6.1 DATA/COMPUTATIONAL INFRASTRUCTURE

It is not the purpose of this programme to make major infrastructural investments. However, limited project-based investments might be necessary for proofs-of-concept. Depending on the findings, major infrastructure investments should be found elsewhere.

The development of full-scale measurement networks lies beyond the scope of this scientific programme, which will, for instance, fully use the recently upgraded seismic network installed by NAM. However, limited-scale measurement networks for feasibility studies will be very useful, for testing the theories and methodologies developed under this programme and for verifying up- and down-scaling methods. The following are therefore examples of possibilities:

1. Development of a limited field-scale seismic network, designed for data-driven imaging, characterization and monitoring. Apart from standard multi-component sensors, this network could be supplemented with a glass fibre system (DAS: Distributed Acoustic Sensing), preferably a modified DAS for direct strain measurements.
2. Development of a limited field-scale facility for experiments with controlled dynamic production/injection strategies in a heavily instrumented reservoir. Ideally the seismic network, mentioned under point (1), would be combined with this facility.

In addition to facilities for field experiments, new lab facilities might for example be required in the long run as well:

1. High pressure-temperature equipment for investigating rock and fault failure phenomena under true in-situ P-T-Stress-Chemical conditions, and for testing numerical models of these phenomena, employing pervasive acoustic, ultrasonic CT and X-ray CT tomographic instrumentation for internal monitoring and imaging. This includes facilities for simulating, measuring and manipulating induced seismicity in the laboratory.

2. Analogue scale model facilities for simulating reservoir and field scale behaviour and for testing numerical models thereof, employing digital surface deformation mapping, acoustic emission monitoring, and ultrasonic CT and X-ray CT tomographic instrumentation for internal imaging.

The programme will need continuous access to computational facilities for big data processing, storage and imaging (data produced by seismic monitoring and massively instrumented laboratory and scale model experiments), as well as for large-scale numerical modelling and simulation. Computational infrastructure investments are not part of this programme, but proposals should demonstrate sufficient computational resources if required by the projects.

7. TIME SCHEDULE

These targets are formulated to stimulate and ensure progress in the programme and allow for evaluation thereof. Specifics obviously depend on the projects' nature; examples of such targets are given below, for some of the programme's components:

7.1 Targets after 2 years:

- Prototype software for data-driven seismic imaging and monitoring
- Prototype modelling software for visco-poro-elastic seismic data
- 3D seismic model from full waveform inversion using existing data
- Quasi real-time seismic hazard assessment based on Deep Learning
- Automatic event location and focal mechanism determination based on Deep Learning
- Existing lab facilities operational in addressing rock and fault physics and geomechanical properties of reservoir rock and faults.
- New lab facilities under construction and calibration.
- First lab data on overburden and underburden rock properties, with focus on potential inelastic effects.
- First recommendations regarding input data on reservoir rock and fault properties for geomechanical and wave-field modelling, based on previous work and results of present programme to date.

7.2 Targets after 5 years: (Indicative, but not definitive)

- Limited field-scale facilities, lab-facilities, and large-scale computational and data handling methods are in place.
- Three-dimensional software for data-driven seismic imaging and monitoring of micro-seismicity and fluid motion.
- Three-dimensional modelling software for visco-poro-elastic seismic data, with realistic induced source mechanisms.
- Measurement and understanding of in situ conditions, rock and fault properties and up-scaling thereof.
- Three-dimensional modelling software for coupled flow and geomechanical behaviour and for rupture modelling.
- Detailed data on and understanding of in situ stress-temperature-pressure-chemical conditions, reservoir rock and fault properties and preliminary up-scaling thereof, with mechanism-based constitutive laws and energy partitioning relationships relevant for true in-situ conditions
- System-theoretical basis for the development of operational protocols (dynamic production/injection strategies and optimization of well locations, with the aim to influence compaction and the chance of fault (re)activation.
- Integration of programme components and projects.
- Recognition of programme by societal stakeholders as reliable and independent.

Within 5 years after the start an (international) scientific evaluation of the results so far will be the basis for a decision on the second part of the programme.

7.3 Targets after 10 years: (Indicative, but not definitive)

- Lab-derived, mechanism-based, material behaviour models for all lithologies and fault rocks relevant to the Groningen field, with relevant and alidated upscaling.
- Full depletion-deformation-rupture-wavefield modelling capability validated against multi-scale lab and field data and with first forecasting capability.
- Integrated 'model-based feedback control approach', based on continuous measurements and fundamental understanding of source mechanisms, stresses and flow in the subsurface (from reservoir underburden to surface), to forecast and influence induced seismicity (spreading stored energy over multiple small events rather than a few large ones; optimal dynamic production/injection strategies for controlled build-up of stress in space and time).
- Quantitative evaluation of uncertainties of all measurements, models, and control measures.
- Results of all themes are available for embedding in the Dutch policy for the exploitation of the deep subsurface and in the definition of long term visions for energy supply, mitigation of emissions and supply of drinking water.

8. Budget

The budget of the programme will mainly be spent in two large calls. The proposed budget for the first call is 11.35M€, for the second call 9.5M€. For regular programme activities, such as workshops, outreach and organisation, a budget of 1.0 M€ is reserved. To allow for programme tuning and integration a further 1M€ is reserved for funding small projects in the course of the programme. The total budget is 23.75 M€, depending on the contributions of NAM (15M€), PPS-toeslag (3,75M€) and NWO (5M€). 6% of the private contribution is used to cover operational costs for NWO. The budget is summarised in the table below:

Contributions		**Expenses**	
NAM	15 M€	Subsidies	21.85 M€
NWO	5 M€	Programme activities	1.0 M€
PPS-toeslag	3.75 M€	Operational cost NWO	0.9 M€
Total:	**23.75**	**Total:**	**23.75**

9. A well-integrated programme to achieve the objectives

The programme will run under the umbrella of NWO within the science domain and in is part of the NWO contribution to the top sector energy (TKI gas). It has many connections to the Nationale Wetenschaps Agenda (NWA) in particular NWA questions 23, 55, 112 and 124. The programme will make use of existing, state-of-the-art infrastructure in terms of data acquisition and processing capability (NAM seismic network, laboratory equipment in many universities and the computational infrastructure of SURFSara and the universities). To achieve the objectives, a strong, effective and transparant governance structure is needed.

9.1 Governance

The governance of the programme can be seen in two phases: prior to the start of the research (call-phase) and after the start of research (research-phase)

For the call-phase the board of the NWO Science domain (DB NWO-ENW) will appoint a Programme Committee (PC) composed of the expertise needed to prepare a coherent programme in keeping with the high NWO standards of integrity and quality. The PC will advise the board on the procedure and possible members for an international assessment committee (IAC) which will have the task of evaluating all applications and of advising the board concerning the granting of an integral research programme based on the applications. The advice of the IAC should not merely be a ranking of the projects, but should be a comprehensive programme consisting of (parts of) the applied projects with the goal to make sure all topics which are required to reach the goals of the programme have excellent projects. This process will be further described in the calls.

During the research-phase the Programme Committee will be responsible for the day-to-day running of the programme. They will organize regular workshops for all scientists carrying out the research with the aim to develop a vibrant research environment in The Netherlands on the topics of the programme. The PC will commission a scientific evaluation of the programme. In the programme budget M€ 1,0 is reserved for the organisation of the activities of the programme committee and M€ 1,0 is reserved for granting small projects which have the aim of increasing the coherence and quality of the programme.

The Programme Committee and the International Assessment Committee will be assisted by a programme office provided by NWO-ENW for the logistics around the calls, project management, evaluation, workshop organization etc.

For the second call in the programme both the PC and the IAC will advise the NWO-ENW Domain Board if any changes to the (scope of the) call should be made.

In the research phase the IAC will take the form of an international advisory committee. It will evaluate the progress of the programme and suggest redirections to achieve the objectives more efficiently. The committee should be invited to the workshops, which will be instruments of community building and evaluation tools at the same time.

Industry, although a stakeholder, will not be part of any decision-making. They can be asked for advice and can be invited to the workshops to be informed of on-going progress. They may also be part of an internship programme in the context of PhD training.

9.2 Nature of the calls:

The programme will be mainly focussed around two large calls. The first call will consist of two parts: one for projects up to 1.5M€ and one for new scientific staff and tenure trackers. Scientific quality and potential for - and commitment to - innovative integration will be important criteria for selection. Infrastructure/equipment (see examples above) demands could be part of the proposal, with a clear demonstration how the infrastructure/equipment will be used. It will be up to the evaluation panel to advise on the infrastructure allocation, which should not be the main aim of this programme. If the allocated budget is not used in the first call (due to a lack of qualifying proposals), this can be used in future calls within the DeepNL context.

The nature of the second call will be decided upon depending of the result of the first call. The expectation is that the second call will have a large focus on integration of activities and filling areas were not enough high-quality proposals were available.

Other than the two main calls there is a possibility for smaller calls with specific purposes, such as visiting scientists, integration with (inter)national programmes, utilisation etc.

9.3 OUTREACH

In view of the societal relevance of the programme, a pro-active outreach strategy is chosen. Although the purpose of this programme is one of fundamental science, the results will be of direct interest to a wide spectrum of stakeholders, such as applied science institutes (TNO and KNMI), policymakers (EZ, SodM), industry (Shell, NAM), engineering companies and, last but not least, the general public. Given this diversity, the way the intentions, progress and outcomes of the scientific program are communicated should be tailored to common practices employed by different target groups. Most institutional, industrial and governmental stakeholders are expected to be members of the Stakeholder Advisory Board and will be informed on at least an annual basis regarding the intentions, progress and deliverables of the programme. Interested stakeholders will also be invited to the scientific workshops, where they can share their expertise in the relevant fields.

Given the sensitivity of the general public to risks and uncertainties associated with subsurface activities, a dedicated outreach programme is envisaged in collaboration with relevant national programmes, aimed at familiarization of the scientific results, both in terms achievements and shortcomings. This will be done by regularly and pro-actively approaching or employing the media (e.g .science pages in newspapers, television features, social media etc). Special focus should be placed on educational aspects via input to physics lessons at schools and contributions to science musea, such as Naturalis. Dedicated symposia can be considered, preferably in cooperation with local organisations such as provinces and municipalities.

It should be noted that the outreach programme is not only aimed at popularizing the Earth science results, but also serves as a vehicle to receive input and questions from stakeholders and society at large, in order to ensure appropriate embedding of the DeepNL programme.

For the outreach program to be successful, the scientists involved will need to have the right skills to be able to translate their research methods and results into layman's terms. If necessary the set up of a training programme could be considered, in particular for junior researchers. Also specific communication expertise needs to be available for the programme.

In parallel with the above, the scientific results will be published via standard channels, such as peer reviewed articles in magazines and contributions to international conferences. In order to avoid unnecessary delay in the sharing of knowledge and results between programme participants because of publication delays, a protocol for data sharing and dissemination needs to be developed.

If the decision of continuing the programme for the second term is made, a significant part of the budget will be reserved for a proof-of-concept programme (similar to the one pioneered by ERC). In this context, a stakeholder, together with a scientific partner, can make a joint proposal on how a component of fundamental science can be used to solve a practical problem.