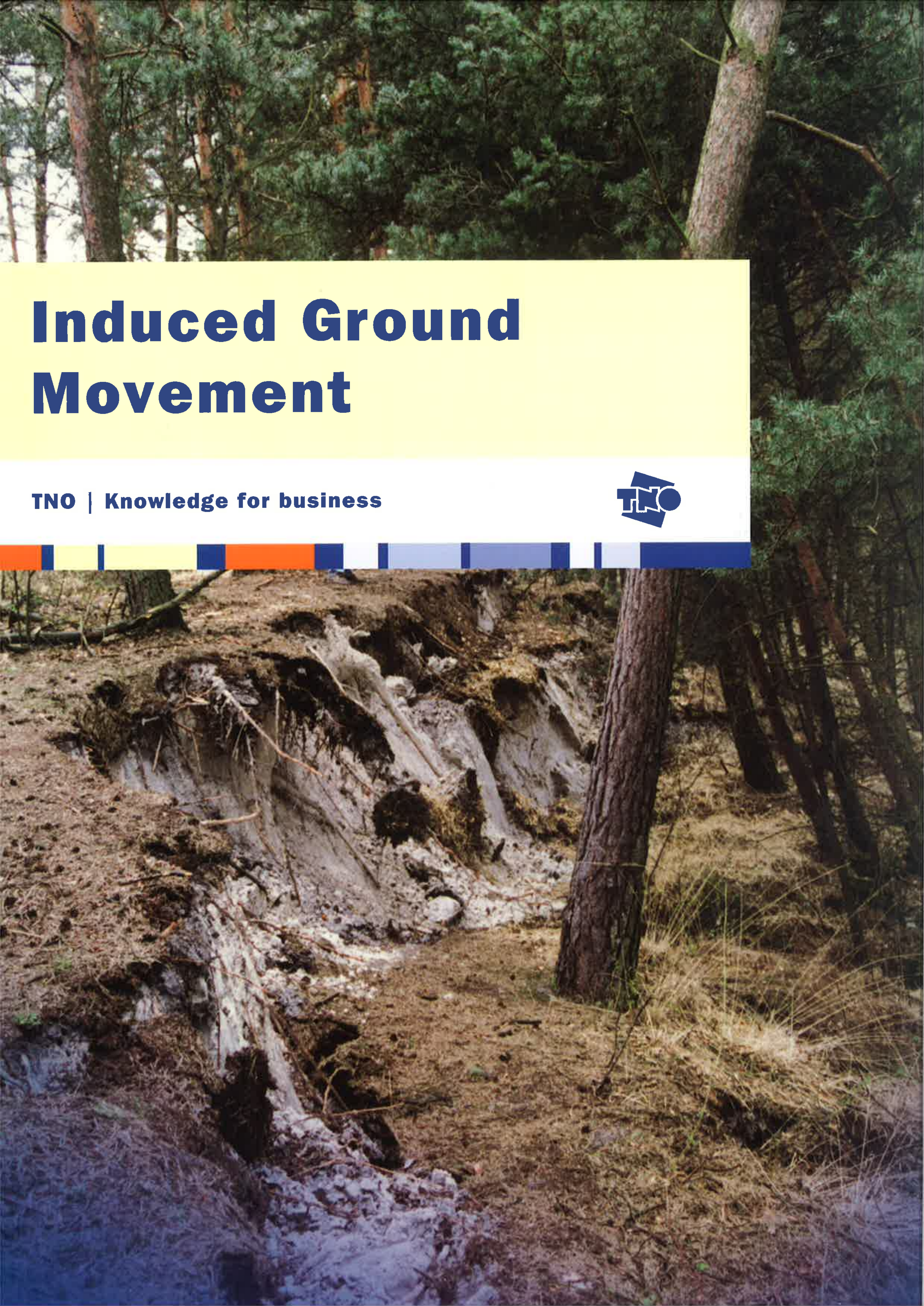

Induced Ground Movement

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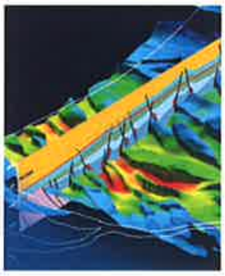
Exploration • Production • Induced Ground Movement • CO_2 Storage • Geobiology

Geo energy



Induced Ground Movement

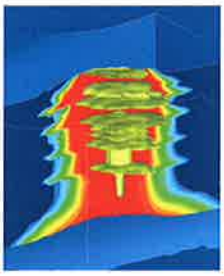
- LOFAR: The eyes of the Earth
- Integrated Subsidence Studies
- Prediction of Subsidence with Semi-Analytic Techniques
- Disentangling deep and shallow causes of subsidence
- Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands

Exploration

- Low Cost Sharing of 3D Basin Maps
- ExploSim:Exploration Portfolio Simulation tool for determining future productionand throughput profiles at production locations
- TNO conceptual framework for "E&P Uncertainty quantification and Technical-to-Business Integration for Improved Asset Investment Decision-Making"
- A Bayesian Belief Network approach for assessing the impact of exploration prospect interdependency
- Renewed interest in geothermal energy
- Petroleum Geological Atlas of the Southern Permian Basin Area (SPBA)
- NCP-2:Detailed 3D subsurface mapping ofthe Netherlands Continental Shelf
- Seismic velocity model building based on sonic data of boreholes in the Netherlands
- Reservoir and sealing characteristics of the Chalk Group in the Netherlands North Sea
- Probabilistic tectonic heatflow for basin modelling (PETROPROB)
- Integrated determination of reservoir porosity of the Dutch offshore NCP-2A region
- Basin subsidence mechanisms during the Carboniferous in the Netherlands
- Quantitative Modelling of the Hydrocarbonof Inverted Basins
- Interpreting anomalies indicating leakage
- Pressure and fluid dynamic study
- High-resolution quantitative reconstruction of Late Cretaceous-Tertiary erosion in the West Netherlands Basin using multi-formation compaction trends and seismic data

Production

- ISAPP Integrated System Approach PetroleumProduction
- Reservoir permeability estimation from production data
- Coupled modeling for reservoir application
- Toward an integrated near-wellbore model
- TNO conceptual framework for "E&P Uncertainty quantification and Technical-to-Business Integration for Improved Asset Investment Decision-Making"
- Production forecasting with uncertainty quantification
- Full Value Chain Gas Market Simulation
- Underground Gas Storage Studies
- Time Lapse Seismic Activities
- A Fast Model for the Productivity of Complex Wells
- Re-use of E&P-boreholes for geothermal energy production
- New prediction method for oil phase saturations
- Training Courses on Decision and Risk Analysis
- Dynamic Fault Seal Behaviour in Petroleum Reservoirs



CO_2 Storage

- CO_2 ReMoVe
- Risk Assessment for analysing the safety of geological CO2 sequestration operations in the deep subsurface
- CO_2 storage pressure in finite saline aquifers
- Interpreting anomalies indicating leakage
- Time Lapse Seismic Activities
- Synthetic modelling of time-lapse seismic data versus real data at the Sleipner CO_2 injection site
- K12-B, CO_2 storage andenhanced gas recovery
- CO_2 storage in underground coal seams while simultaneously enhancing CBM production (RECOPOL)
- Natural gas migration to the near-surface environment as an analogue to potential leakage of CO_2
- The mechanical impact of CO_2 injection

Geobiology

- Why the past is a key to the future
- Towards a Rotliegend Biostratigraphy
- Palynomorph EcoGroup & Automated Palynodebris Analysis
- Finding the right pollen to find the oil - The role of palynology in the onshore exploration programme of Suriname
- Petroleum Exploration - Analytical methods
- Applied paynology (Geobiology team)
- Managing the Fossil Record

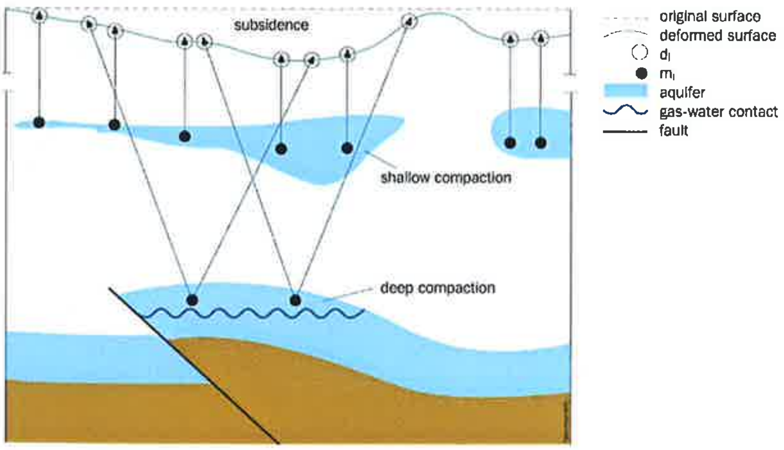
Disentangling deep and shallow causes of subsidence

Subsidence is an important social issue in the Netherlands and elsewhere. Some of the anthropogenic causes, like construction of buildings, roads and tunnels, oxidation of peat, clay compaction and withdrawal of groundwater, occur at or near the surface. Others primarily affect the deep subsurface: extraction of hydrocarbons, salt mining and geothermal production. Until now inversion programs, which aim to quantify the subsurface processes based on subsidence measurements, have focused on either deep or shallow causes. If contributions from these processes are comparable, however, neglecting one of them may lead to erroneous parameter estimations. We have therefore devised a procedure to objectively disentangle the shallow and deep causes of surface movement. The procedure employs the Bayesian approach of parameter estimation for the combined effect of the deep and shallow causes of subsidence. Additional information is added, such as knowledge about the expected compaction levels and spatial correlations.

Inverse Model

With an appropriate forward model, subsidence can be calculated from given compaction levels. The subsidence is the sum of the contributions due to deep and shallow causes, but the range of influence of deep causes is larger than the range of influence of shallow causes (Figure 1). The inverse problem of the compaction determination from subsidence can be formulated as the search for the compaction levels with the largest likelihood, given the subsidence data and the *a priori* knowledge. This *a priori* knowledge is instrumental because without it the inverse process is usually ill-conditioned: small changes in the data result in large variations in the calculated compaction. We have created a tool in which the *a priori* knowledge is incorporated in the form of a combination of the expected compaction, the variance in it and the covariance. The covariance gives information about spatial correlations within and between compaction levels.

*Figure 1. Sketch of shallow and deep causes of compaction (**m**) resulting in surface subsidence (d). Arrows denote the area of influence of individual compaction sources ($\mathbf{m}_i$).*



Demonstration of the Method

In the first artificial example we combined the effects of a shallow and a deep compaction grid. The shallow compaction consisted of a linearly increasing, regional east-west trend (Figure 2a). This may be considered to represent compaction of an idealized eastward-thinning peat layer that pinches out at the eastern area boundary. The shallow compaction was modelled with a combination of peat oxidation and shallow compaction. The pre-defined deep compaction grid resembled a rectangular-shaped gas reservoir with sharp boundaries (Figure 2b), as may be the case in faulted areas. As a forward model, we used a linear, semi-analytic approach designed to account for layering. With the two forward models, the calculated surface movement was a combination of the east-west trend induced by the shallow compaction and a subsidence bowl related to deep compaction (Figure 2c). In the central part of the area surface movement was controlled to approximately the same extent by shallow and deep compaction.

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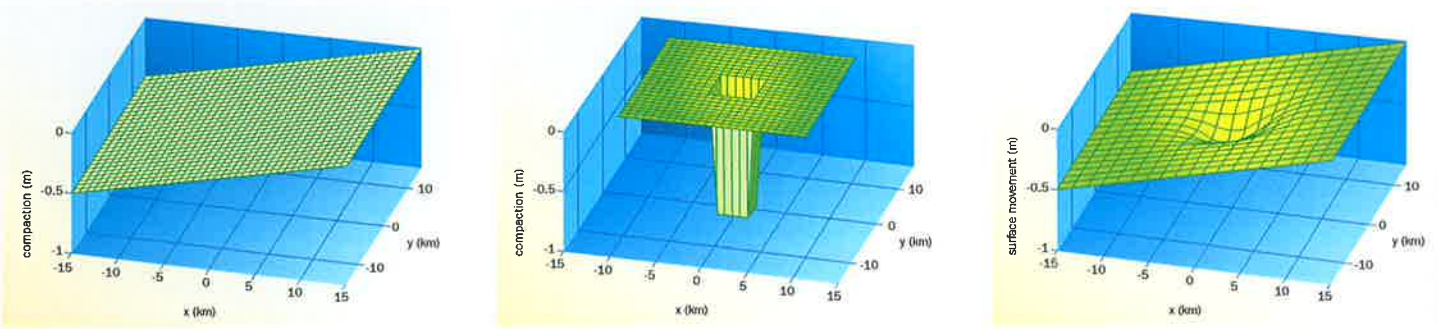

Figure 2. Forward calculation – a) Shallow compaction (40x30 grid) increases linearly from 0 cm at the eastern boundary to 50 cm at the western boundary; b) Deep compaction (25x25 grid) of 1 m within the rectangular shaped reservoir; c) Resulting surface movement prediction (20x20 grid).

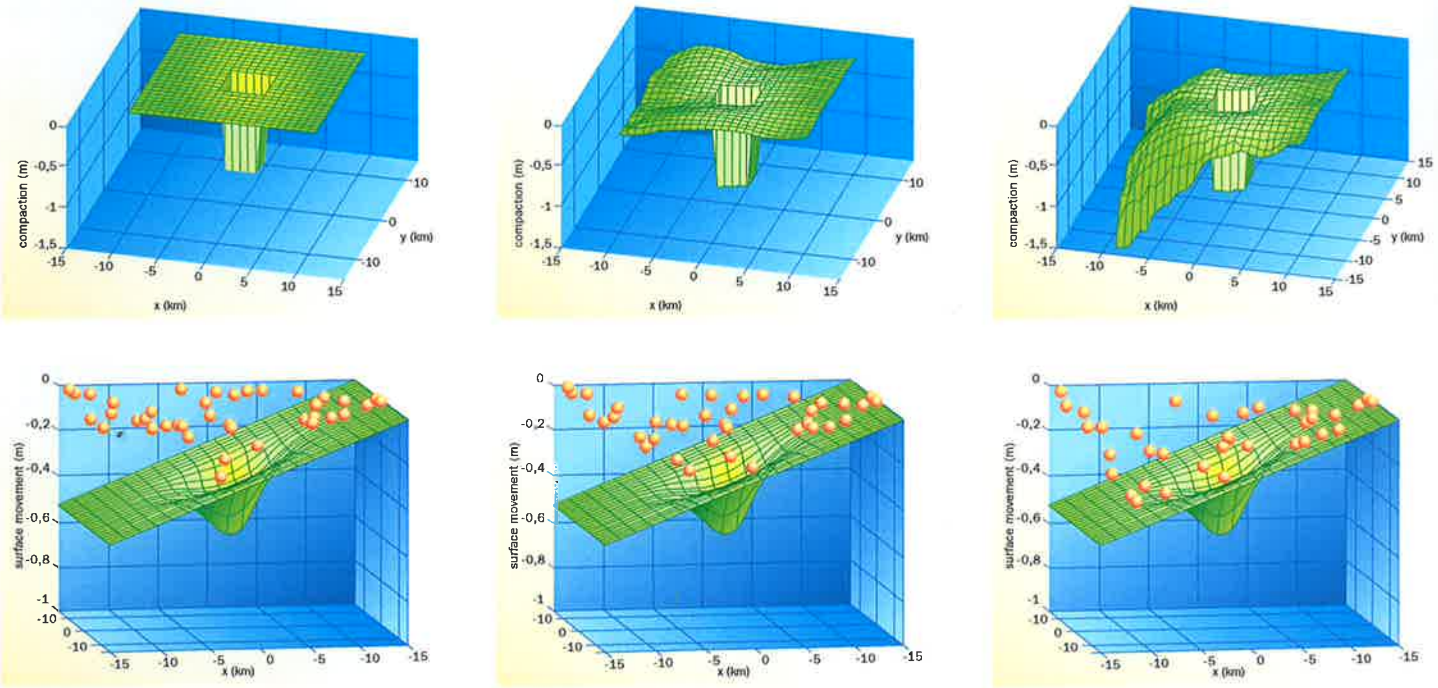

Figure 3. Inverse calculation results assuming only deep compaction. Top: Best estimate of deep compaction for a σ^2 of the initial deep compaction of 0.01, 0.1 and 1 respectively. Bottom: Original subsidence data (mesh) and the best estimate of the subsidence (dots at locations where synthetic subsidence data are available), based on forward modelling using the deep compaction estimates shown in the top row.

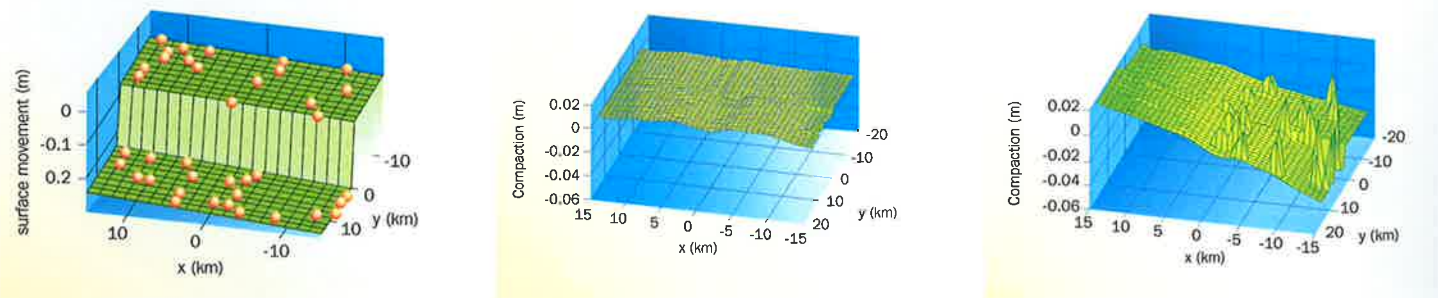

Figure 4. Forward calculation of shallow compaction (40x30 grid) of 1 particular realisation after 15 years in which clay thickness decreases from 0.5 m to 0.24 m. The inversion is based on the synthetic measurements in the dots. B and C: Difference between inverse calculation results and original compaction for the best estimate of shallow compaction using the median of the Monte Carlo simulation (Fig. 5C). In B, the full covariance matrix is used; in C only the variance.

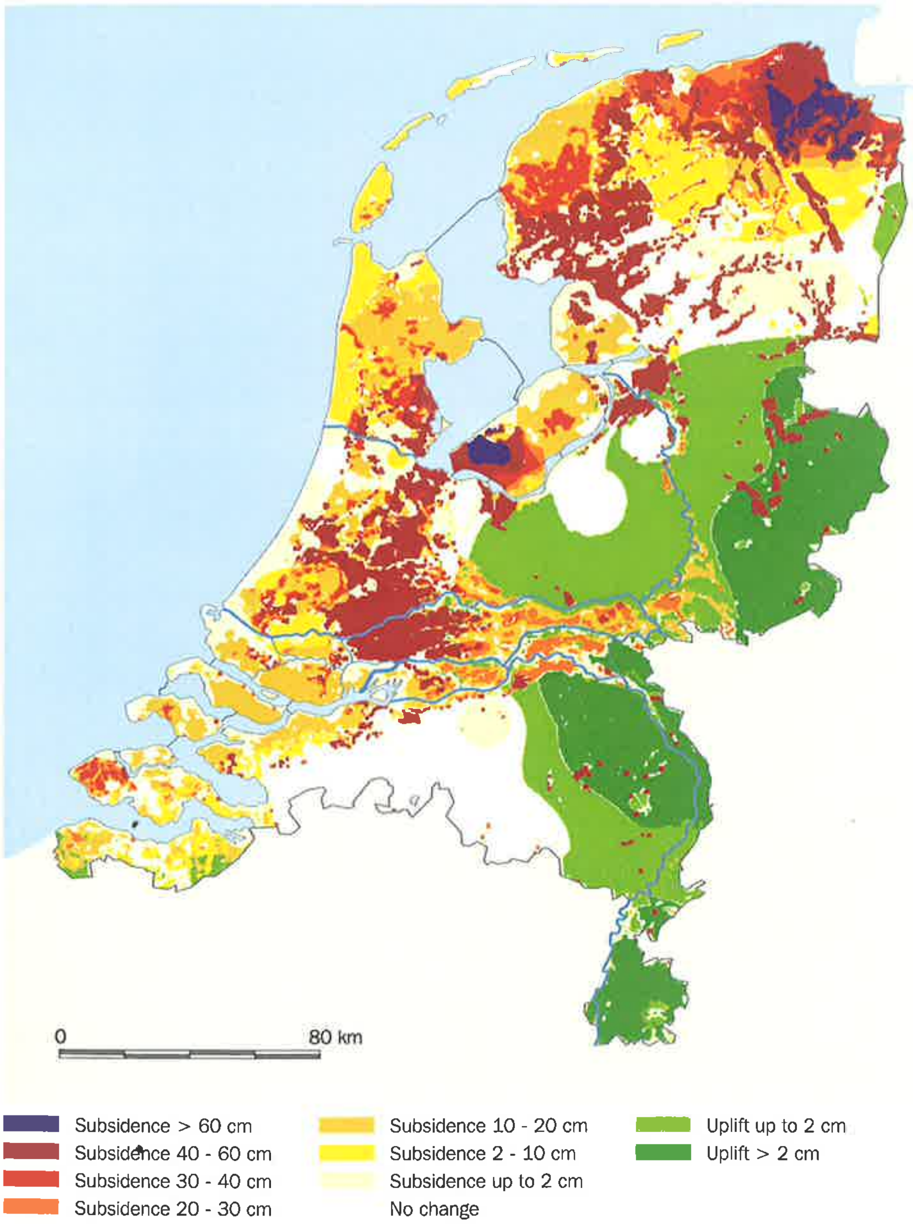

Figure 5. Expected subsidence and uplift of the Dutch surface up to 2050. This is a superposition of surface movements induced by natural and anthropogenic causes. The figure clearly shows that the expected subsidence is largest in the northeast (around the Groningen gas field), but the expected subsidence in the relatively young Flevoland polder is also striking. The expected subsidence around the rivers in the east results from thick clay and peat packets in the area. Source: Ed F.J. de Mulder et al.: "De ondergrond van Nederland" (The Netherlands Subsurface), TNO, 2003, p. 67.

In practice only a rather small number of measurements are available to constrain the movement of the surface. The error created by neglecting shallow compaction (Figure 2a) is demonstrated in cases where the initial model of the deep compaction was correct (Figure 2b) and known within different degrees of certainty. Assuming a small variance in the *a priori* compaction data (Figure 3, left), the difference in subsidence displayed a clear east-west trend. Such a clear and deviating trend should serve as a warning that a significant process (shallow compaction) has been overlooked. If, on the other hand, the initial deep compaction model was assumed very uncertain (Figure 3, right), this effect was small, whereas the estimated deep compaction did extend well beyond expected reservoir boundaries and displayed a clear east-west trend: subsidence that was caused by shallow compaction was now attributed erroneously to deep compaction.

Inversion using Monte Carlo simulation

To demonstrate the strength of the incorporation of the spatial correlation with the covariance we created a more complex artificial case of shallow compaction (Figure 4a). It is a model with two polder units, separated along an east-west dike. The phreatic level in both polders was lowered by 0.3 m and the hydraulic head of the aquifer was lowered by 0.5 m. The subsurface consisted of peat that was covered by a layer of clay. At one boundary the clay thickness was 0.5 m, the opposite boundary had a clay thickness of 0.24 m. The resulting subsidence movement was resampled to provide a random set of 40 subsidence data points, Figure 4b. This set was used as input in the inversion.

In the inversion it was assumed that the set-up of the model was known. However, clay thickness was highly uncertain at the second boundary: it could be between 0 and 1 m thick. Fifty Monte Carlo simulations were performed to derive *a priori* estimates for the shallow compaction, its variance and covariance at every grid point. Alternatively, one could choose to simply use the realization of the expected average clay thickness of 0.5 m as the *a priori* estimate and then allow for a large variance in the model.

Inversion results of both alternatives are shown in Figure 4. Clearly, inversion using the Monte Carlo results approached the original compaction (Figure 4b) best. The result is remarkably smooth given the absence of a smoothness constraint. This is due partly to the reasonable *a priori* estimate and partly to the introduction of non-zero covariances. The non-zero covariance quantifies expected relations between grid points. In this particular case the grid points were sharing the same groundwater regime or had a similar clay cover thickness. In effect, each data point updated (at least partially) all other grid points with which it shared a non-zero covariance.

Simply using average clay thickness in combination with a high variance produced a lot of spikes and completely failed to reproduce the abrupt change in compaction in one of the polder units (Figure 4c).

Conclusions

We have successfully created and tested a Bayesian inversion scheme that disentangles the deep and shallow causes of subsidence. Assumptions on the shape of the subsidence bowl are not necessary, even when there is considerable uncertainty in the measurements. When the contributions to subsidence of deep and shallow compaction have a similar order of magnitude, the neglect of one of them leads to faulty conclusions. This has been demonstrated using a realistic artificial example.

A priori information and spatial correlations have been introduced through Monte Carlo simulations. Using Monte Carlo simulations for defining *a priori* estimates is clearly worthwhile. The explicit use of the covariance can be particularly advantageous in optimization problems: adding only a few more data points at carefully chosen locations which share a high covariance with many other grid points will significantly improve the solution.

Monte Carlo simulations can also be applied to compaction in depleting gas reservoirs. There is often knowledge available about spatial correlations, even when the absolute values of the *a priori* compaction data are quite uncertain. Then, the explicit incorporation of known *a priori* spatial correlations significantly improves the result.

Outlook

The method is suitable for monitoring reservoir behaviour and depletion zones lacking pressure measurements, such as lateral aquifers or undrilled reservoir blocks. Our method can also be applied in areas where the subsidence signal of reservoir depletion is distorted by unrelated shallow compaction.

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Discrimination between shallow and deep causes

Integrated subsidence studies

For the past year, as commissioned by the Dutch Ministry of Economic Affairs, TNO has been researching the causes of damage sustained by buildings near the town of Grou, in the middle of Friesland.
A consortium of two institutes, TNO and GeoDelft, was formed to bring together expertise on the structure of the deep subsurface and natural gas production, the structure of the shallow subsurface and soil characteristics, soil compressibility, groundwater, soil mechanics and damage assessment of buildings and foundations.

Figure 1. One of the farms in the Frisian peatlands that was part of the study.

In this region, there has been a general concern for years that the number of cases of damaged buildings, mostly farms, is apparently higher than average.
For more than ten years, people have surmised that the damage might be related to the production of natural gas in the region, which began around 1970.
The main line of reasoning was that the problems were attributable to land subsidence caused by compaction of the gas reservoir, located at a depth of 2000 m, or perhaps to possible induced earthquakes or to vibrations triggered by the operator's various industrial activities in the boreholes. Earlier research, published in 1990, found that the gas production played a negligible role in terms of the damage caused.
Since the unease in the region persisted nonetheless, in 2002 the Ministry asked TNO to perform more broad-ranging research to pinpoint exactly what, then, the cause of the damage could be.

The research was made up of two parallel components. First, potential disturbances to the deep and shallow subsurface were examined on a regional scale.
For the shallow subsurface, this meant also looking into spatial and temporal variations in groundwater levels.
The possible repercussions of natural gas production were re-examined. Second, more detailed research was performed on a local scale, at the sites of individual farms. At ten of these properties, supplementary in situ tests, using hand drilling, cone penetration, Begemann drilling and other methods, were done to determine the structure of the soil. Compression tests were later performed in the laboratory to quantify the soil's compressibility. The selected buildings were also inspected thoroughly by TNO and the structural damage analysed.

In the final stage of the project, the various research groups synthesised their findings; the research was completed in April 2003. Results indicate that the Holocene formation's inherent compressibility and its lateral heterogeneity have had a much

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greater impact than the extraction of natural gas from the subsurface. The lowering of the groundwater levels has compounded the soil's inherent compressibility, especially since as a result of these drawdowns, the Holocene peat layers have been left dry. Finally, the foundations of the buildings themselves are an important factor.
The farms that are built on a terp generally display little or no damage because the terps not only contribute to pre-loading of the soft Holocene soil but also distribute the loading more evenly. Detailed maps of the localised compressibility will help planners estimate the risk of settling, and hence damage, in local areas. Recommendations can be made with respect to the maintenance of higher groundwater levels in the future, and with respect to the type of foundations to be used for new buildings.

The project team was able to demonstrate that neither the small amount of subsidence (< 4 cm) nor induced seismicity resulting from gas production could be the cause for damage in this particular region. These findings were conveyed to the larger public at a public meeting in Grou.

Acknowledgements

This project was conducted under the guidance of the 'Technische Commissie Bodembeweging'.

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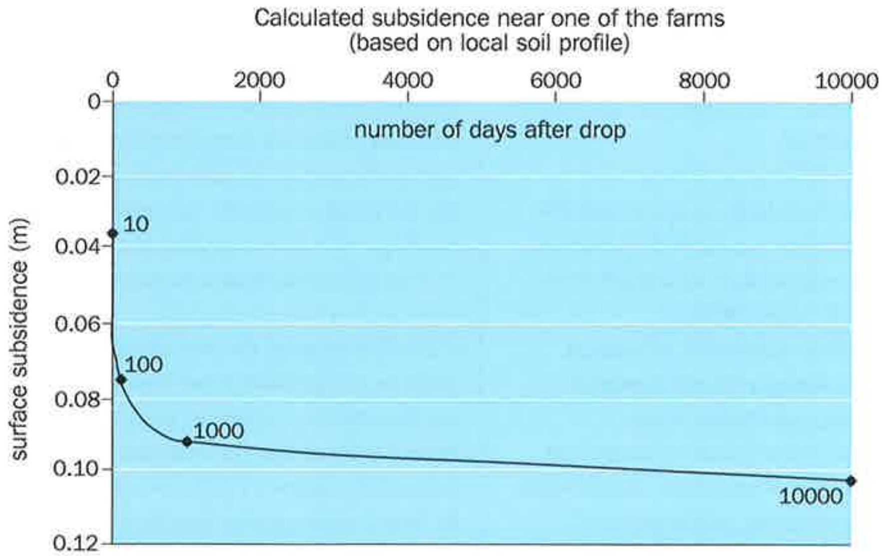
Figure 2. The impact of a drop in the groundwater table of 0.60 m on compaction of the holocene layer and subsidence at surface level. Most of the subsidence occurs in the first 1000 days. The amount of subsidence strongly depends on the local soil profile in the shallowest 4-5 meters of soft holocene deposits.



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Prediction of Subsidence with Semi-Analytic Techniques

The production of gas or oil from a hydrocarbon reservoir causes a change in the stress and strain field due to the reduction in pore pressure. The resulting compaction may cause subsidence of the surface which may well be serious in some cases. Examples are the Groningen gas field in The Netherlands and the Ekofisk field in the Norwegian sector of the North Sea.

Traditionally there have been two approaches to calculate subsidence for a given compaction: analytical and numerical. Existing analytical methods are restricted to one or two homogeneous layers. The Geertsma method, for example, is limited to homogeneous subsurface properties. An example of a numerical simulator is DIANA, a finite-element simulator for elasticity calculations. Numerical approaches may be comprehensive but are not always suited for quick sensitivity calculations or for scenario evaluations. Inversion is the reverse process. It is the extraction of reservoir data from subsidence measurements, and is usually performed with fast, analytic or semi-analytic techniques. Finite-element calculations often are too CPU-intensive to be used in inversion programs.

New method for subsidence prediction

TNO has developed a semi-analytic method in which a multi-layer subsurface with different elastic properties per layer are taken into account. The method starts by using the solution of a compacting 'nucleus of strain' in an infinitely extending homogeneous subsurface. This represents an amount of compaction concentrated in a point of the reservoir. To honour the layering of the subsurface, additional solutions are then added, containing free parameters which are adjusted to approximate the boundary conditions. The result is a subsidence bowl for one nucleus of compaction in a layered subsurface. Its quality can be improved by using more independent solutions with associated free parameters. The subsidence bowl for the actual compac-ting reservoir, finally, is determined by a process of integration over the reservoir.

Validation

We compared the new method with existing analytical and numerical packages. The comparison with analytical correlations, for a homogeneous subsurface, and for a finite-thickness subsurface on a rigid basement, yielded excellent agreement. Figure 1 gives a comparison with a finite-element simulator, DIANA. Here, a layer with deviating properties is introduced at a depth of 400 – 600 m. The top layer and the bottom layer are given an elasticity modulus of 1 GPa. Again, the agreement is excellent.

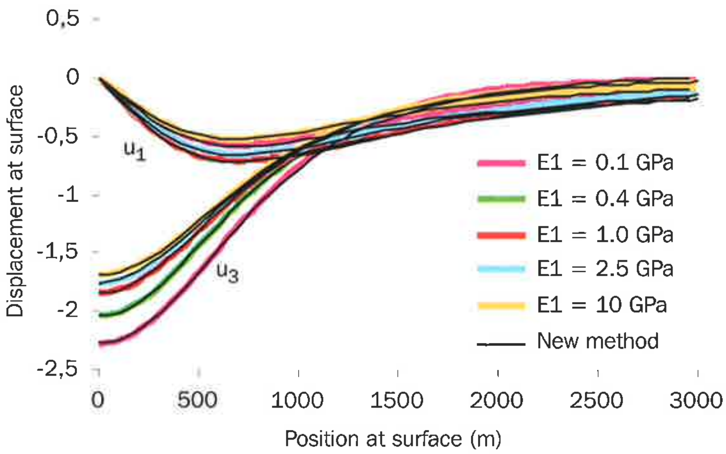

Figure 1. Validation of the new method with the finite-element simulator DIANA.

Demonstration

The new technique has been applied to a number of European and Asian oil and gas fields. One of the examples is the Ameland field in the Northern Netherlands. Over the past twenty years, subsidence in this closely monitored and well-documented field has been modeled using many different techniques. This has resulted in a range of predictions as to what the maximum subsidence will be in the year 2020. The maximum amount of subsidence due to the depletion of the Ameland field, expected for 2020, is 0.22 m. This value showed a variation of 20% depending on the elasticity

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parameters used in calculations. Three different studies by the operator had predicted a maximum subsidence of 0.27, 0.19, and 0.28 m. The present results are apparently in line with the earlier predictions.

A fast simulator

The new method has been built into a fast simulator, which can take account of a number of reservoirs at selected depths with a single vertical elasticity profile. The simulator first makes the "single-nucleus bowl" for each reservoir depth and then integrates the contributions of the complete compacting field. With an additional input for the original pore pressure and in-situ stress, the simulator can also evaluate the new stress regime against the Mohr-Coulomb failure criterion. This is of importance for the assessment of the risk that existing faults experience reactivation. A Windows representation of the software tool is given in Fig. 3.

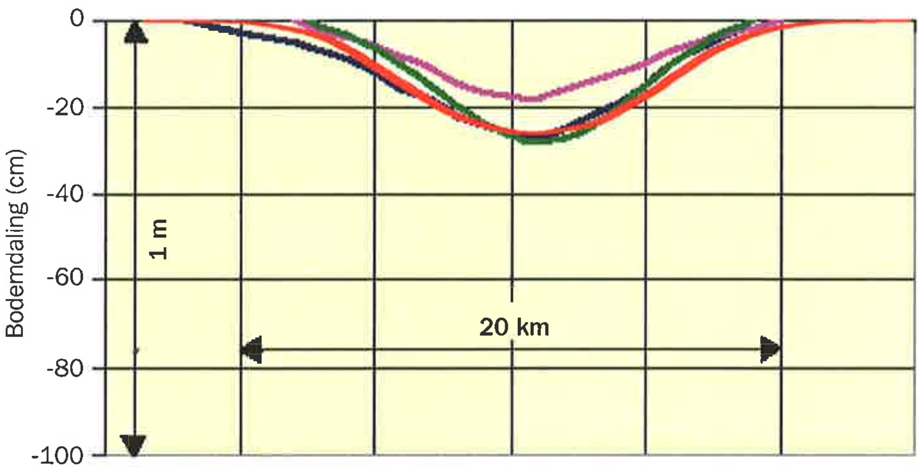

Figure 2. Subsidence profile over Ameland: comparison of operator predictions (blue, purple, green) and our semi-analytic simulations (red).

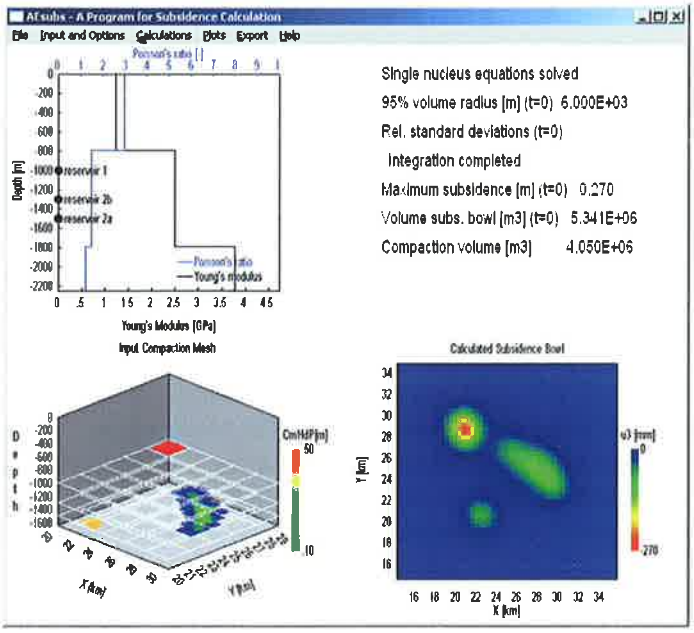

Figure 3. Windows realization of the subsidence program, showing the elasticity profile (left-top), the input compaction meshes of the reservoirs (left-bottom), numerical results (right-top) and the graphical representation of the subsidence bowl (right-bottom).

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LOFAR: The eyes of the earth

LOFAR is an ICT project that owes its origin to the ambitions of Dutch astronomers to observe the very beginning of the universe. Such an ambition requires a telescope one hundred times more sensitive than those we have today.

Figure 1. Lofar antennas (foreground) at Westerbork (source: ASTRON).

LOFAR will be developing just such a radio telescope as a network of 10,000 sensors (Figure 1). The small antennas are distributed over an area some 350 km in diameter and linked to a supercomputer by a vast fibre optics network (Figure 2).

The ICT infrastructure that LOFAR will give rise to also holds great potential for non-radio astronomers, enabling them to make strides in accelerated monitoring. In the geosciences field, for example, it should be possible to extend the understanding of natural and induced seismicity, subsidence and water management. Advanced, wireless sensors will give agricultural researchers the tools they need to carry out precision agriculture and to understand how to optimise production processes.

The cost of realising LOFAR is estimated at 100 million euros and a further 48 million to fund the development of techniques on which LOFAR relies. Some of this financing is provided by the Dutch government in the form of a subsidy to stimulate the monitoring infrastructure. A consortium of 18 partners - universities, research institutions and companies - has been set up to achieve this aim. Together with TU Delft and the Royal Dutch Meteorological Institute (KNMI), TNO is participating in the application of LOFAR in the geosciences. Additional financing will be required for geoscientific research related to LOFAR and TNO is actively looking for sponsors in this respect.

Figure 2. 'The eyes of the Earth', Artists impression of the Lofar Network (source: ASTRON).

Scientific relevance

The fulfilment of the LOFAR project is awaited with great anticipation by the scientific community. Scientists are particularly interested in the instrument's new functionality. The LOFAR radio telescope is expected to be the first capable of observing signals from the first stars and galaxies to come into being from the Big Bang. These signals are very weak and receiving them will be a challenge for LOFAR's technology and its software, an enormous amount of which is required to steer the equipment and process all the data it gathers. The data make it worthwhile, however, providing valuable information about the formation and evolution of stars and star systems.

LOFAR will play a major role in an area in which Dutch astronomers enjoy a long tradition: the systematic mapping of large numbers of weak radio sources. The data LOFAR gathers will be particularly valuable when combined with the data gathered on other wavelengths, including those from telescopes such as the European Southern Observatory's Very Large Telescope in Chile and the Westerbork telescope.

Aside from radio astronomy, the LOFAR telescope will also offer research opportunities in adjacent scientific fields. It will gather a wealth of information about the ionosphere that for decades has greatly hindered observations on LOFAR's frequencies. If LOFAR is combined with a radar transmitter that may be built in the south of Sweden, it should be able to predict solar storms. These enormous gas explosions

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Figure 3. Distribution of seismicity in the Netherlands (source: KNMI)

on the sun's surface throw billions of tonnes of gas into space. When these geomagnetic storms reach Earth, they cause phenomena like the Northern Lights and wreak havoc with satellites, electricity networks and cordless radio communication. The advanced network of fibre optics will transport astronomical information and other measurement data.

The following are some of the activities the geoscientific participants in the consortium will be involved in:

- Recording natural seismicity by linking vibration sensors to the LOFAR network. This will mean using groups of multi-component motion sensors that will permanently monitor the seismic activity at the various LOFAR locations. Of particular interest will be areas subject to recent seismic activity (Figure 3).
- Monitoring induced seismicity, for example as a result of gas extraction, with the ultimate goal of linking observed seismicity to reservoir processes. This will also involve using a dense network of motion sensors.
- Monitoring reservoir characteristics via passive and active seismic observations taken with the seismic sensor networks mentioned above. The passive seismic response – i.e. the seismic observations made without explicit use of a seismic source – will be converted into a 'reflection seismic response' using daylight imaging techniques.
- Monitoring the receiver response functions. It may be possible to relate a changing response from seismic sensors to changes in the elastic characteristics of the shallow subsurface and to fluctuations in the water table.
- Monitoring subsidence. By linking GPS stations to LOFAR and continuing GPS observations with, e.g., INSAR altitude measurements, a detailed picture can be obtained of regional and local subsidence. Where subsidence occurs in the vicinity gas fields, it may be possible to study the relationship with induced seismicity (Figure 4).
- Linking (parts of) the groundwater monitoring network to LOFAR to enable 'real-time' monitoring of groundwater levels.
- Linking subsurface sampling to LOFAR. This would involve placing in-situ pressure and temperature sensors in boreholes, for instance.

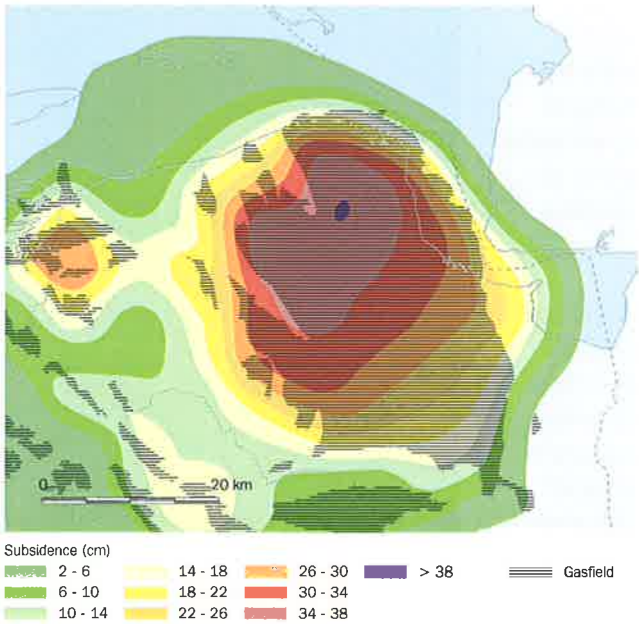

Figure 4. Subsidence in the north of the Netherlands

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