APPRAISAL OF THE LONG TERM SUBSIDENCE STUDY OF THE WADDEN SEA REGION

By

THE WADDEN ACADEMY

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1 Introduction

1.1 Background of the Study

In 2012 the Minister of Economic Affairs of the Netherlands determined that the *Nederlandse Aardolie Maatshappij* (NAM), within the regulations governing the extraction by NAM of natural gas from gas fields in the Wadden Sea Region, was required to carry out a detailed study of the gas extraction related subsidence in the Wadden Sea Region.

This study was to be carried out to the satisfaction of the Inspector General of Mines (the head of the State Supervision of Mines of the Netherlands), prior to 1 July 2015. The request was an official condition to the approval of three *Winningsplannen* (Moddergat, Lauwersoog, Vierhuizen Winningsplan, the Anjum Winningsplan as well as the Ameland Winningsplan). The aim of the study was to improve knowledge of the physical background of measured time-dependent effects of subsidence behaviour and its possible influence on expected subsidence in the long term.

The study should lead to a better understanding of the physical processes that explain the subsidence that has already occurred, with the aim of improving the forecasting of future subsidence. The study was to be based on generally accepted rules of physics, objective measurement data and proven scientific methods.

The Wadden Sea is an area with outstanding abiotic features that serves as a habitat for a very rich and varied flora and fauna. The trilateral Wadden Sea Region is a World Heritage Site. The

environmental sensitivity of the Wadden Sea places restrictions on the use of the area. Gas extraction related subsidence in the Wadden Sea Region is therefore an important concern for nature conservation organization, for socially responsible enterprises, for governmental entities and for citizens.

1.2 Terms of Reference for the Study

In 2012/2013 the NAM developed a "*Proposed Research Program for Higher Order Subsidence Modelling of The Netherlands Gas Fields*", which included:

a) Overview of Subsidence Modelling (The Need for Subsidence Modelling; The Geertsma and Van Opstal Concept; Discrepancies and Subsequent Modifications; Re-evaluating the Past Modelling Workflow).
b) Research Program (Data Quality Uncertainty and Statistics; Physical Models, Continuum Mechanics; Subsidence Data; Constitutive Laws; Validation and Testing; Salt Mechanics).
c) Deliverables.

While developing the Proposed Research Program, it was discussed in framing and brainstorming sessions within NAM, and in joint sessions with experts from the State Supervision of Mines and the Advisory Group of Economic Affairs (AGE).

1.3 Organizational Set-up of the Study

Because of the importance of improving the forecasting of future subsidence related to gas extraction in the Wadden Sea Region, the NAM and the Wadden Sea Society decided, in consultation with the Ministry of Economic Affairs, to establish an independent Steering Committee for the Study.

The NAM and the Wadden Sea Society then jointly decided to request the Wadden Academy to establish, facilitate and chair the Committee, to be known as "*The Scientific Steering Committee for the Long Term Subsidence Study in the Wadden Sea Region*" (SC LTS).

The Wadden Academy, established in 2008, has the task of providing a scientific basis for the management of the natural and social values represented by the Wadden Sea Region.

The Wadden Academy agreed to set up the Steering Committee (maximum of seven members including the chairperson), to chair the Committee and to provide the Committee with a technical secretary.

The actual cost and remuneration reasonably incurred of the activities of the members of the Steering Committee are paid for by NAM, with exception of these of the chairman (facilitating and taking charge of scientific committees on the Wadden Region comes within the remit of the Wadden Academy, which has an autonomous status).

The Wadden Academy agreed to the Steering Committee members proposed by the NAM and the Wadden Sea Society. However, the members would be appointed by the Wadden Academy *à titre personnel* and in their personal professional capacity. The technical secretary of the SC LTS would be seconded to the Wadden Academy for the duration of the Study.

The Study would be carried out by the NAM and various other parties (specifically universities and research laboratories) working on its behalf, with oversight by the Steering Committee.

The NAM would be responsible for providing the State Supervision of Mines of the Netherlands and the Ministry of Economic Affairs with information on the Study's progress and for involving their representatives in the Study.

The Wadden Academy was tasked with familiarizing the Members of the SC LTS and the technical secretary with the "*Code for the prevention of improper influence due to conflicts of interest*" (Royal Netherlands Academy of Arts and Sciences/KNAW, January 2012) and the "*Declaration of Interests*" included in the Royal Academy's Code. The SC's chairperson would ask the members and the technical secretary of the SC LTS whether they could participate in the SC LTS "*independently of any outside influence*".

Where necessary, the Steering Committee would consider the most appropriate follow-up after finalization of the Study (on 1 July 2015) and communication concerning its findings, in consultation with the NAM. All communication by the Committee with the outside world would be the chairperson's responsibility.

1.4 The Steering Committee

The Steering Committee comprises the chairperson, six members and the technical secretary.

- Dr Hessel Speelman (Vice Chair, Wadden Academy, Geoscience portfolio; Chairman of the Steering Committee)
- Prof. Patrick Baud (School and Observatory of Earth Sciences, University of Strasbourg)
- Prof. Ramon Hanssen (Civil Engineering and Geosciences, Technical University Delft)
- Prof. Ryszard Hejmanowski (Mine Areas Protection, Geoinformatics and Mine Surveying; AGH University of Science and Technology Krakow)
- Prof. Rune Martin Holt (NTNU – Norwegian University of Science & Technology, Trondheim)
- *Ir.* Adriaan Houtenbos (Independent Subsidence Analyst)
- Prof. Robert Zimmerman (Earth Science & Engineering, Imperial College London)
- Dr Bogdan Orlic (Senior Scientist TNO; technical secretary on behalf of Wadden Academy)

1.5 Experts from the State Supervision of Mines and Advisory Group of Economic Affairs

Representatives from the State Supervision of Mines of the Netherlands and the Ministry's advisory group participated in the Steering Committee's meetings.

- *Ing.* Rob van Lieshout (Senior Inspector, State Supervision of Mines, Ministry of Economic Affairs)
- Dr Annemarie Muntendam-Bos (Senior Inspector, State Supervision of Mines, Ministry of Economic Affairs)
- Dr Hans de Waal (Deputy Department Head Geo-Engineering, State Supervision of Mines, Ministry of Economic Affairs)
- Dr Jaap Breunese (Principal Advisor, Advisory Group of Economic Affairs)

2 Execution of the Long Term Subsidence Study

2.1 Researchers Involved in the Study

The research was executed largely by NAM and Shell researchers, and to a lesser extent by researchers at Utrecht University, Delft University, Heriot-Watt University (Edinburgh) and the National Oceanographic Centre (Liverpool).

- Dr Antony Mossop (Principal Investigator, NAM)
- *Ir.* Ruud van Boom (Cluster Development Lead Onshore, NAM)
- Dr Hermann Bähr (Researcher Geodesist, NAM)
- Dr Pepijn Kole (Researcher Petrophysicist, NAM)
- *Dipl. Ing.* Fritz Seeberger (Principal Investigator Reservoir Engineering, NAM)

- Dr Stijn Bierman (Researcher Statistician, Shell)
- *Ing.* Ab Coorn (Researcher, Shell)
- Dr Sander Hol (Principal Investigator Experimental Geomechanics, Shell)
- *Ing.* Arjan van der Linden (Researcher, Shell)
- *Drs*. Fons Marcelis (Researcher, Shell)
- Dr Tim Park (Researcher Statistician, Shell)
- *Ing.* Pedro Zuiderwijk (Researcher, Shell)

- Dr Taco Broerse (Faculty of Geosciences, Utrecht University)
- Prof. Rob Govers (Faculty of Geosciences, Utrecht University)
- Dr George Marketos (Researcher, Faculty of Geosciences, Utrecht University)
- Prof. Chris Spiers (Faculty of Geosciences, Utrecht University)

- *Ir.* Sami Samiei-Esfahany (Researcher, Civil Engineering and Geosciences, Delft University of Technology)

- Prof. Sebastian Geiger (Heriot-Watt University, Edinburgh)
- Prof. Gabriel Lord (Heriot-Watt University, Edinburgh)
- Dr Robert Annewandter (Heriot-Watt University, Edinburgh)

- Dr Simon Williams (Researcher, National Oceanographic Centre, Liverpool)

2.2 Steering Committee Working Method

The Wadden Academy organized a series of Steering Committee meetings/workshops, discipline meetings and teleconferences attended by the members of the Steering Committee, NAM researchers and researchers from other organizations working on behalf of the NAM, representatives of the State Supervision of Mines, and representatives of the Advisory Group of Economic Affairs.

The technical secretary prepared the memoranda of all the meetings. Draft minutes were circulated for comments within four weeks; submitted comments and revised minutes were circulated before adopting the final version of minutes. The minutes, presentations given at meetings, progress

reports and other technical documents produced in the course of the Study were stored at the SharePoint accessible to all the parties involved in the study.

An abbreviated version of the minutes was made available to the public in July 2014 on the Wadden Academy website (http://www.waddenacademie.nl/).

Steering Committee meetings/workshops were held twice yearly between April 2013 and June 2015. The purpose of the meetings was to have the NAM update the Steering Committee on progress over the past six months, to review the results, and to give the NAM feedback and direct the activities planned for the next six months. In total, five two-day meetings were held: 1st Steering Committee meeting in Amsterdam (at the Royal Academy's headquarters on 18-19 April 2013); 2nd meeting in Leeuwarden (at the "*Huis voor de Wadden*" on 28-29 October 2013); 3rd meeting in Delft (at Delft University of Technology on 3-4 April 2014); 4th meeting in Utrecht (at hotel Karel V on 1-2 December 2014); and 5th meeting in Assen (at the NAM's offices on 11-12 May 2015). Attendance was excellent: all members of the Steering Committee attended three meetings, while one member joined in on the phone or excused himself at the other two meetings.

To prepare for the Steering Committee meetings, the NAM was requested to prepare progress reports and make pre-reading documents available for circulation two weeks ahead of the meeting date.

In an early phase of the Study (2013), a technical workshop took place during the 2nd meeting in Leeuwarden, with all the parties involved in the Study attending to discuss various hypotheses possibly relevant for a better understanding of time-dependent subsidence. Each member of the Steering Committee and a representative of the State Supervision of Mines gave their own view on the possible causes of anomalous production-related subsidence. The workshop presentations are publicly available on the Wadden Academy website (http://www.waddenacademie.nl/).

Besides Steering Committee meetings/workshops, several discipline meetings took place: (i) geodetic meeting (at TNO Utrecht on 21 January 2014); (ii) rock mechanics meeting (in Minneapolis, during the ARMA conference, on 2 June 2014); (iii) rock mechanics meeting (in Amsterdam on 17 June 2014); (iv) geodetic meeting (in Assen on 7 July 2014). Discipline meetings were attended by some members of the Steering Committee and a smaller number of researchers than at the Steering Committee meetings. In some cases bilateral meetings and teleconferences were held between a member of the Steering Committee and NAM/Shell researchers.

The most frequently used tool for communication in-between the meetings was email.

Draft reports were reviewed by the members of the Steering Committee in the period between 1 and 18 June 2015. Reports were revised for submission to the Ministry of Economic Affairs before the deadline on 1 July 2015.

2.3 Overview of Stakeholders Meetings

The Wadden Academy organized a series of stakeholder meetings to inform the stakeholders about the project's progress and to answer their questions. At the request of stakeholders, abbreviated versions of minutes of the Steering Committee meetings were made available to the public on the Wadden Academy website (http://www.waddenacademie.nl/). Attending the stakeholder meetings were representatives of nature conservation and public organizations (Wadden Sea

Society, It Fryske Gea, Dutch Forestry Commission, Ministry for Infrastructure and the Environment), the members of the Steering Committee, NAM/Shell researchers, representatives of the State Supervision of Mines and representatives of the Advisory Group of Economic Affairs. Stakeholder meetings were typically organized on the second day of the Steering Committee meetings to ensure the presence of and direct communication with the members of the Steering Committee. In one case the stakeholder meeting had to be rescheduled owing to unavailability of many stakeholders, and held on a later date.

A total of six stakeholder meetings took place: five meetings were organized in conjunction with the Steering Committee meetings and one additional, special stakeholder meeting was held separately. The stakeholder meetings were as follows: 1st stakeholder meeting in Amsterdam (at the Royal Academy's headquarters on 19 April 2013); 2nd meeting in Leeuwarden (at the "*Huis voor de Wadden*" on 29 October 2013); 3rd meeting in Delft (at Delft University of Technology on 4 April 2014); 4th special meeting in Assen (at the NAM's offices on 22 May 2014); 5th meeting scheduled in Utrecht (at hotel Karel V on 2 December 2014) was rescheduled in Assen (at the NAM's offices on 20 February 2015); 6th meeting, also in Assen (at the NAM's offices on 12 May 2015). Attendance at the 1st meeting was good, poor at the 2nd and 3rd meetings, and good at the 4th, 5th and 6th meetings.

The Wadden Sea Society and other nature conservation organizations commented on the Long Term Subsidence Study, asking that: a) a problem analysis be performed, and b) the scope of the study be extended to cover several questions put forward by the stakeholders.

Regarding a) the problem analysis, it is important to explain the background of the Study. The Study was ordered by the Minister of Economic Affairs. Under the regulations governing the extraction plans for the Dutch Wadden Sea area, the NAM is required to carry out a detailed study prior to 1 July 2015, to the satisfaction of the Inspector General of Mines, to improve knowledge of the physical background of measured time-dependent subsidence and possible implications for expected subsidence in the long term. The relevant topics and possible hypotheses were identified and discussed prior to the Study in framing and brainstorming sessions within the NAM, and in joint sessions with the representatives of the State Supervision of Mines and the Advisory Group of Economic Affairs. The research topics thus identified were subsequently included in the Terms of Reference (Section 1.2). After the study scope had been defined, an open debate arose when the Wadden Sea Society raised additional questions. Not all the questions could be included in the Study, as its scope was to better understand the physical processes behind the subsidence that had already occurred, with the aim of improving forecasting of future subsidence. However, while the Study was under way, the members of the Steering Committee were continuously asked to recommend new topics or hypotheses beyond the ToR that would improve the forecasting of future long-term subsidence. The NAM honoured most of the Steering Committee's requests to expand the scope of the Study, for example: (i) to study the time effects of aquifer depletion, and (ii) to study the correctness of Geertsma's model for subsidence prediction. Some requests were not honoured, such as: (i) a formal problem analysis, for the reasons already explained in this paragraph, and (ii) a field test with different subsidence models, which has been recommended as a follow-up study (see Recommendations in Section 3a).

Regarding b) the additional questions, the Wadden Sea Society compiled two lists of questions: a list of 38 questions which was circulated ahead of the 3rd Steering Committee meeting held in Delft

(on 4 April 2014) and a list of eight questions circulated ahead of the 5th steering committee meeting held in Assen (on 12 May 2015).

The first list of 38 questions was addressed at the 3rd stakeholder meeting in Delft (4 April 2014) and at the 4th special meeting in Assen (22 May 2014). The NAM presented a written proposal for addressing the different groups of questions: (i) questions falling within the scope of the Study (as agreed jointly by the NAM, the State Supervision of Mines and the Wadden Academy), which had to be addressed in the Study; (ii) questions beyond the scope of the Study that could be addressed in future research programs; (iii) questions that had to be answered at regular time intervals and reported to the State Supervision of Mines through the "*Meet en Regel protocol"* (M&R). A special stakeholder meeting was consequently held at the NAM's offices to answer the third group of questions related to the M&R.

The second list of eight questions was addressed at the 5th Steering Committee meeting in Assen (12 May 2015). Each member of the Steering Committee was invited to make his own observations and comments about the Study, in particular concerning: (i) how the research contributed to a better understanding of the physical backgrounds of measured subsidence; (ii) whether the NAM had followed his directions and advice; and (ii) recommendations for future research.

The Wadden Academy proposed holding a second special stakeholder meeting at the NAM's offices in August/September 2015 to discuss the second list of eight questions.

2.4 Results of the Study

The "*Long Term Subsidence Study of the Wadden Sea Region*" consisted of a number of constituent studies. The results of the discipline studies were presented in a series of technical reports and scientific publications[1]. Most of the research was conducted internally by NAM and Shell researchers, and to a lesser extent externally by researchers at Utrecht University, Delft University of Technology, Heriot-Watt University in Edinburgh, and the National Oceanographic Centre in Liverpool.

The report: "*Wadden Sea Long term Subsidence Studies – Overview report, 2015. NAM report* EP201506209625" provides an overview of the key results and conclusions of all the discipline studies.

The *Overview report* identified the following key hypotheses concerning the causes of apparent time-dependent subsidence behaviour:

- Time-dependent subsidence is an artefact and merely an apparent trend caused by the noise structure and uncertainty in the surveillance data.
- Time-dependent subsidence is caused by salt flow.
- Time-dependent subsidence is caused by slow depletion in underlying aquifers not captured in the reservoir simulation.
- Time-dependent subsidence is due to anomalous pressure diffusion which could have caused pressure equilibration to occur over longer time scales.
- Time-dependent subsidence is due to time-dependent poro-mechanical compaction in the reservoir rock.

[1] The papers have not been released due to copyright restrictions. They are accessible via digital libraries.

The key hypotheses have been addressed in the discipline studies. The results of discipline studies have been presented in a series of technical reports and scientific publications. The key areas, deliverables and main conclusions are given below.

- **Pressure depletion in the aquifer below and adjacent to depleting gas fields**

The results have been presented in three reports:

Seeberger, F.C., 2015. Predicting gas- and aquifer reservoir pressures in the Waddenzee gas field development area. NAM report EP201505216677.

Mossop, A., 2015a. Derivation of a scale dependent pressure diffusion equation. NAM report EP201506209300.

Geiger, S., Lord, G., Annewandter, R., 2015. Anomalous pressure diffusion in heterogeneous porous media – Interim report submitted to Nederlandse Aardolie Maatschappij.

The main conclusions and recommendations of this study are:
Uncertainties in the reservoir simulation of the pressure depletion field should be quantified for both the reservoir and the aquifer. The residual gas in the aquifer is also identified as a potential source of time dependent compaction. This improved insight will be used to bound the subsidence model predictions better. Further work will be carried out to update prediction of depletion levels and uncertainty ranges in the Wadden Sea fields.

- **Reservoir rock compaction in response to pressure depletion**

The results have been presented in two reports and a paper:

Hol, S., van der Linden, A.J., Zuiderwijk P.M.M., Marcelis F.H.M., Coorn A.H., 2015. Mechanical characterization of Permian reservoir sandstone from the Moddergat-3 well in the Dutch Wadden Area. Shell report SR.15.11614.

Hol, S., van der Linden, A.J., Zuiderwijk P.M.M., Marcelis F.H.M., 2015. Geomechanical experiments on Ten Boer rock samples from well Moddergat-3. Shell Report SR.15.11616.

Hol, S., Mossop, A., van der Linden, A., Zuiderwijk, P., Makurat, A.H., 2015. Long term compaction behavior of Permian sandstones – An investigation into the mechanics of subsidence in the Dutch Wadden Sea. ARMA Conference Paper. ARMA 15-618.

The main conclusions and recommendations of this study are:
Deformation experiments of Rotliegend reservoir core material under *in situ* conditions show that reservoir compaction involves a porosity-dependent inelastic deformation through grain cracking and an elastic (reversible) deformation. Volumetric compaction of the sandstone reservoirs could be responsible for the magnitude of the subsidence observed in the Wadden area, but it cannot directly explain the observed temporal relationship between the measured subsidence and reservoir pressure decline.

- **Improving the measurement of *in situ* compaction**

The results have been presented in a report:

Kole, P., 2015. In-situ compaction measurements using gamma ray markers. NAM report EP201506209302.

The main conclusions and recommendations of this study are:
In situ compaction data is only available in and around the Groningen field. The Groningen data can be used as an analogue for the Wadden fields. It is not recommended to install further gamma ray source compaction monitoring systems in future. Consider present day fibre optic based Real Time Compaction Monitoring systems instead as these are superior in resolution and spatial/temporal sampling.

- **Salt flow in response to compaction of an underlying gas reservoir**

The results have been presented in a report and two papers:
Marketos, G., Broerse, D.B.T, Spiers, C.J., Govers, R., 2015. Long-term subsidence study of the Ameland gas field: time-dependence induced by rock salt flow. Report UU.
Marketos G., Govers R.M.A., Spiers C.J., 2015. Surface subsidence induced by hydrocarbons extraction, and the potential for time-dependent ground deformations. ARMA Conference Paper. ARMA 15-375.
Marketos G., Govers R.M.A., Spiers C.J., in press. Ground motions induced by a producing hydrocarbon reservoir that is overlain by a viscoelastic rock salt layer: A numerical model. Submitted to *Geophysical Journal International*, March 2015.

The main conclusions and recommendations of this study are:
Salt flow in isolation appears not to be a plausible explanation for time-dependent subsidence. The temporal behaviour of the subsidence at the production location could not be fully explained by salt flow only. The width of the predicted subsidence bowl seems comparable to the field data, but the model predicts the subsidence rate will rapidly decrease in time, which is inconsistent with the field data.

- **Subsidence modelling (Geomechanics studies)**

The results have been presented in two reports:
Mossop, A., 2015b, Subsidence and compaction volumes. NAM Report EP201506209298..
Mossop, A., 2015c, Implications of hypoplastic compaction laws on subsidence modelling. NAM Report EP201506209299.

The main conclusions and recommendations of this study are:
The work addressed the apparent volumetric discrepancies in the standard geomechanical modelling approaches for subsidence calculations that have been used by NAM/Shell. A corrected solution has been derived in which an additional depth dependent term is included in the calculation of the reservoir volume strain. The error does not impact the calculation of subsidence, but the reservoir volume strain. In the Wadden Sea gas fields, the volume change correction factor will be small (< 10 %).

- **Improvements for processing and preparing subsidence measurements for geomechanical model calibration**

The results have been presented in two reports:

Samiei-Esfahany, S., Bähr, H., 2015. Research and development project for geodetic deformation monitoring. NAM report EP201505216980.
Williams, S., 2015. Description of GPS uncertainties within the Long Term Study on Anomalous Time-Dependent Subsidence. Nat. Oceanographic Centre, Liverpool.

The main conclusions and recommendations of this study are:
The time-dependent subsidence effect is real and not an artefact of noise and uncertainty in the geodetic data. The subsidence modelling precision can significantly be improved by taking correlation structures in the surveillance data into account. In addition, methods have been proposed for identifying and handling outlier measurements, data reduction techniques for large geodetic data sets, as well as improvements to include GPS data.

- **Statistical testing/validation procedures of model results versus observations**

The results have been presented in a report:
Park, T., Bierman, S., 2015. A Bayesian framework for validating and comparing models for prediction of surface displacements due to reservoir compaction. Shell report SR.15.11680.

The main conclusions and recommendations of this study are:
An improved and more formal statistical method based on a Bayesian framework is proposed to validate and test the quality of subsidence predictions against the survey data. The method can provide a coherent structure for the creation of initial models built on prior information, the objective updating of these models using collected geodetic data and the quantitative testing of future predictions. A prototype inverse modelling workflow has been developed.

- **Overall conclusions**

The overall conclusions of the research activities carried out in the framework of the Long Term Subsidence Study of the Wadden Sea Region from mid-2012 to mid-2015 are:
Time-dependent creep behaviour is observed and predicted to be associated with different processes: (i) compaction of the sandstone in the gas reservoir; (ii) pressure diffusion and partial depletion of the aquifers; and (iii) flow of the overlying salt. Salt flow in isolation appears not to be a plausible explanation for time-dependent subsidence, while the compaction and pressure depletion models remain viable hypotheses within the possible uncertainty ranges.

The improved quantification of noise and uncertainties as well as the better understanding of the physical processes developed in this study will lead to an improved subsidence modelling, prediction and monitoring workflow.

In addition, outcome of this study has given rise to a number of more specific recommendations with respect to improving the subsidence modelling and monitoring workflow.

2.5 General Assessment of the Study

During the first meeting of the Steering Committee for the Long Term Subsidence Study in the Wadden Sea Region, at the Royal Academy's headquarters in Amsterdam in April 2013, the chairman articulated the Joint Ambition of the researchers executing the study and the members of the Steering Committee: "Realize a scientifically state of the art study that improves the

knowledge of the subsidence which has already occurred, with the aim of improving the forecasting of future subsidence in the Wadden Sea Region".

The overall conclusions of the series of constituent studies indicates that we now have a much better understanding of the subsidence that has already occurred and that the aim of improving the forecasting of future subsidence is in reach, based on an improved subsidence modelling, prediction and monitoring workflow. In particular, knowledge of the physical processes that may contribute to the observed time-dependent subsidence has improved. Research is still needed concerning the extent to which each process contributes to the overall subsidence in specific field conditions (see Recommendations in Section 3).

The series of constituent studies can generally be regarded as state of the art. A total of thirteen reports have been reviewed by members of the Steering Committee. At present, five peer-reviewed papers related to the Study have been submitted to scientific journals or accepted for presentation at scientific conferences. The Wadden Academy is particularly pleased that the vast majority of the Study's scientific work on the Wadden Sea Region is, or will be, in the public domain.

One criticism is that the set-up of several of the studies was initially delayed. Most of the scientific work was carried out in 2014 and 2015, and important findings were presented at later stages of the project. However, the principal researchers carrying out the various studies managed to integrate their main results and worked together on the "*Overview report*".

The Steering Committee's critical appraisal of the Study is given below. Following on from this appraisal are recommendations for follow-up research, presented in the next section.

- The problems posed by trying to understand and predict the subsidence in the Wadden Sea Region are scientifically non-trivial, and require data collection, as well as numerical and conceptual modelling.

- Much of the Steering Committee's effort and discussion was dedicated to geodetic study work. The observed time dependence of the subsidence is a real signal of physical origin; it is not an artefact of the survey data, which have a complex spatial and temporal correlation and noise structure.

- A number of possible mechanisms and physical processes were identified at the start of the study that could yield apparent time-dependent subsidence behaviour. The research focused on, but was not limited to, exploring those mechanisms and processes.

- Three main processes have been identified that contribute to time-dependent subsidence behaviour: compaction of the sandstone in the gas reservoir; pressure diffusion and partial depletion of the aquifers and tight layers; and flow of the overlying salt.

- The rock properties testing campaign was ambitious, well-conceived and carefully carried out, and has yielded very valuable data. Rock mechanical property data, which can only be obtained from laboratory measurements on cores, are crucial for future subsidence modelling. Extensive series of compaction tests, conducted at the *in situ* conditions, showed a porosity dependent inelastic deformation of reservoir sandstone, but no evidence of acceleration of deformation. Simple upscaling of the experimental-scale results

to the field scale indicates that we cannot reject the hypothesis that time-dependent subsidence could be due to time-dependent compaction.

- Slow depletion of (Ten Boer) shale as a candidate for time-delayed subsidence has not been fully addressed in the study. Follow-up research should asses and quantify the impact of slow depletion of the cap rock (Ten Boer), in addition to the slow depletion of tight layers, and bottom and lateral aquifers.

- When regarded in isolation, salt flow appears not to offer a full explanation of the observed temporal behaviour of subsidence. The time scale of salt response is difficult to constrain due to the wide range of possible material property values and the large compositional and microstructural variability in the Zechstein sequence. Mining literature may provide useful data but appears not to have been sufficiently consulted in this study.
- The research is generally of high quality and should be anchored in the scientific community and, in particular, integrated with previous work.

- The practical value of this research needs to be demonstrated in a field case study.

- The NAM, Shell and university researchers have generally been receptive to advice and steering by the members of the Steering Committee.

Following its assessment, the Steering Committee has made recommendations for both short-term and long-term follow-up studies.

3 Recommendations for Follow-up Studies from 1 July 2015 Onwards

The Steering Committee made the following recommendations to the NAM and the State Supervision of Mines:

a) Ameland field case study and instalment of a Review Panel for this study
The Steering Committee strongly recommends testing of various hypotheses developed in the LTS-study in an Ameland field case study. This follow-up study should start shortly, within a few months after 1 July 2015, and be completed preferably by the end of 2016. The Committee recommends forming an international independent Review Panel under a similar organizational setup as for the LTS-study. The role of this Review Panel would be to advice on, and review NAM's project plan, and to review the interim and final results of the field-scale implementation of the LTS-study results in an Ameland field case study.

b) Follow-up study of the time-dependent subsidence
The members of the Steering Committee gave a number of recommendations for potential follow-up research related to time-dependent subsidence:

    - Use experimental and theoretical methods to make a link between inelastic behaviour and creep of reservoir rocks, and incorporate this knowledge into the prediction of subsidence.

    - Clarify the impact of slow depletion zones within the reservoirs (aquifers, shales).

- Analyse the time-dependent subsidence in very mature onshore Rotliegend gas fields, e.g. Suawoude and Roden, as a means to gain insight in late field life subsidence behaviour potentially relevant for the Wadden Sea gas fields.

- Reduce the uncertainty in the rheological properties of the salt rock by using the existing data from the salt mining industry and conducting additional rock mechanics tests on the salt rock.

- A single overall finite element model, combining the various processes that have been individually investigated thus far (salt flow, anomalous diffusion, creep, *etc*.), should be developed as to yield a single "best estimate" of subsidence rate and magnitude, with appropriate error bars.

The Committee recommends to discuss the above mentioned recommendations for follow-up research with the key parties (NAM, Wadden Sea Society, State Supervision of Mines, Advisory Group of Economic Affairs and Wadden Academy) in parallel with new insights to be gained from the Ameland field case study (a). It is recommended to assemble a Steering Committee/Review Panel under similar terms and conditions to those proposed for the Ameland field case study.

4 Advice for Wadden Sea Research Topics

The Wadden Academy's tasks are:

- To identify gaps in cross-domain knowledge in order to assist in the sustainable development of the Wadden Sea Region.
- To promote a coherent research programme at regional, national and international level.
- To promote information supply and knowledge exchange within and between research institutes, government, industry and social organisations.

In 2009 the Wadden Academy published a research agenda for the Wadden Sea Region: "Knowledge for a sustainable future of the Wadden".

Part of this research agenda has been completed (see e.g. the Wadden Academy's annual reports and its website).

In 2014 it was decided to develop a trilateral research agenda (Denmark, Germany and the Netherlands) for the Wadden Sea Region/Wadden World Heritage Site. This agenda will be completed in 2017 and presented by the "ministers of research" of the three countries at a conference in the Netherlands. This agenda includes geoscience, ecology, society and cultural heritage, social and spatial economics, climate and water.

Parties and individuals who are interested in participating in the development of the trilateral research agenda are welcome to contact the Wadden Academy.