NAM

Independent Review of Groningen Subsurface Modelling Update for Winningsplan 2016

with Opinion Letter

SGS Horizon B.V.

Datum June 2016

Editors Jan van Elk & Dirk Doornhof

General Introduction

The subsurface model of the Groningen field was built and is used to model the first step in the causal chain from gas production to induced earthquake risk. The model's main purpose is to model the pressure response in the gas bearing formations to the extraction of gas and water.

The reservoir model of the Groningen field was built in 2011 and 2012 and has a very detailed model of the fault zone in the field to support studies into induced earthquakes in the field. The model was in 2013 reviewed by SGS Horizon. The Opinion Letter of SGS Horizon prepared in 2013 was included in the Technical Addendum for Winningsplan 2013. Since then the model has been continuously improved. The model used for Winningsplan 2016 was therefore also reviewed and assured by SGS Horizon. This report describes the assurance review of the model used for Winningsplan 2016 and the conclusion.

This report contains first the "Opinion Letter" followed by the Main Report. The report by NAM describing the improvements for the subsurface model of the Groningen field for Winningsplan 2016 can be found at:

www.namplatform.nl/feiten-en-cijfers/onderzoeksrapporten

NAM

Title	**Independent Review of Groningen Subsurface Modelling Update for Winningsplan 2016 with Opinion Letter**	**Date**	June 2016
		Initiator	NAM
Author(s)	Staff of SGS Horizon BV	**Client**	Jan van Elk Dirk Doornhof
Organisation	SGS Horizon BV	**Organisation**	NAM
Place in the Study and Data Acquisition Plan	Study Theme: Prediction Reservoir Pressure based on gas withdrawal Comment: The subsurface model of the Groningen field was built and is used to model the first step in the causal chain from gas production to induced earthquake risk. The model's main purpose is to model the pressure response in the gas bearing formations to the extraction of gas and water. The reservoir model of the Groningen field was built in 2011 and 2012 and has a very detailed model of the fault zone in the field to support studies into induced earthquakes in the field. The model was in 2013 reviewed by SGS Horizon. The Opinion Letter of SGS Horizon prepared in 2013 was included in the Technical Addendum for Winningsplan 2013. Since then the model has been continuously improved. The model used for Winningsplan 2016 was therefore also reviewed and assured by SGS Horizon. This report describes the assurance review of the model used for Winningsplan 2016 and the conclusion. This report contains first the "Opinion Letter" followed by the Main Report.		
Directly linked research	1. Technical Addendum to Winningsplan 2013. 2. Groningen Field Review 2015, Subsurface Dynamic Modelling Report, by NAM Reservoir Engineering Team: Ulan Burkitov, Hank van Oeveren & Per Valvatne.		
Used data	Sub-surface data from the Groningen field; open-hole logs, core data, pressure data, production data etc.		
Associated organisation	Independent consultant SGS Horizon BV		
Assurance	This report contains the assurance review of the subsurface model of the Groningen field.		

SGS HORIZON

Nederlandse Aardolie Maatschappij B.V.
Ftao Mr. J. van Elk
Schepersmaat 2
9405 TA Assen
The Netherlands

Voorburg, 30 March, 2016

Dear Mr. van Elk,

Disclaimer

This opinion letter has been prepared by SGS Horizon B.V. ("**SGS**") for the exclusive use and benefit of Nederlandse Aardolie Maatschappij B.V. ("**NAM**") as the sole addressee. This opinion letter is an extract of a report addressed to NAM and is as such not itself a comprehensive report on the matters discussed in it. Third parties should be aware that SGS does not accept any liability towards them for the content of this opinion letter and that any form of taking knowledge of this report beyond this disclaimer is held to imply that such third party accepts this condition and those further restrictions stipulated below.

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The conclusions in this opinion letter are based on the underlying report, the findings and conclusions of which report have been established following every effort of SGS to follow good industry practice and its own quality management procedures in order to reach proper conclusions based on the data provided to it by NAM.

This opinion letter cannot be held to address - not by implication or otherwise - any matters related to seismicity or geomechanical modelling. Any liability in connection with this report towards NAM is subject to the contractual conditions applicable between NAM and SGS in relation thereto and the disclaimer comprised in the underlying report. This opinion letter and any dispute in connection therewith are exclusively governed by Dutch law.

Independent Review of Groningen Subsurface Modelling

To support the Winningsplan 2016, NAM has updated the static and dynamic subsurface models of the Groningen gas field. These models are used to, amongst others, generate forecasts of gas production and of reservoir pressure. NAM has made the updates to the models primarily based on comments from previous reviews for the Winningsplan 2013 by TNO-AGE / SodM and by SGS, as it was communicated by NAM to SGS.

NAM has requested SGS in May 2015 to carry out an independent review of the modelling work performed to support the Winningsplan 2016. The SGS review has been limited to the following aspects:

1. the technical quality level of the work and model,
2. the appropriateness of the model for preparation of production forecasts for the future reservoir pressure distribution over time in the field, based on depletion scenarios where the offtake may be variable between areas of the field.
3. the overall quality of the production forecasts for depletion of the field, with focus on the time span the most relevant for the Winningsplan 2016, i.e. the period 2016 to 2025.

The static model describes the Groningen gas reservoir and provides a distribution, both vertically and horizontally, of gas initially in place. The dynamic model simulates the movement of gas through the reservoir to the production wells and up these wells to the wellheads. For predictions of future gas production, the dynamic model is linked to a surface network model. The dynamic model also predicts the reduction in reservoir pressure as a result of the withdrawal of gas. The geomechanical aspects of the reservoir rock and any possible induced subsidence and seismicity effects were not part of the review scope, consequently SGS's report does not contain any conclusions regarding seismicity and subsidence as a consequence of NAM's gas production activities.

SGS approach

In order to carry out this review SGS has utilised the following criteria to judge the quality of NAM's work and the models:

1. Transparency: was the work done as stated in the reports, is there a clear auditable workflow?
2. Accuracy: does the model accurately represent the main reservoir processes?
3. Completeness: was all available data consistently incorporated?
4. Uncertainty: was the full range of uncertainty applied?

For the review of the subsurface modelling for the Winningsplan 2016, SGS has applied a structured approach:

1. Verification that elements that should not have been changed significantly in the static models between 2012 (used for the Winningsplan 2013) and 2015 / 2016 (as it has been stated by NAM) indeed are unchanged and require no further in-depth review. This has been carried out by both high level review and through detailed spot checks.
2. Evaluation of elements of the models that changed compared to the 2012 model (as it has been stated by NAM). SGS has carried out spot checks on key parameters / areas, has reviewed if techniques and workflows are appropriate and are applied in a consistent manner.
3. Multi-disciplinary integrated conclusions have been made by SGS, and are described in this letter.

The material used by SGS has been provided by NAM. We have assumed that the information is complete and representative.

The review as described in this opinion letter has been a continuation of the review performed by SGS in 2013, which was documented in an opinion letter of SGS of 29th November 2013. It is noted that the quality criterion of uncertainty was not further evaluated in the current review, as the review in 2013 covered this extensively and only a relatively very small amount of additional data has become available since.

The overall results of our work and the opinions offered are detailed here below.

Static Model

The overall approaches to the update of the static model are supported by SGS.

The main geological, geophysical and petrophysical features of the Groningen Rotliegend reservoir appear to have been correctly captured in the static model. The updates to the static model performed for the

Winningsplan 2016 are relatively minor, and can be considered as improvements compared to the models used for the Winningsplan 2013. The main recommendation from SGS made in 2013 has been followed up by NAM and implemented in the current model. New recommendations for further improvements to the modelling and suggestions for additional analysis and clarification are provided in the overall conclusions below.

Dynamic Model and History Match

The update to the dynamic model is supported by SGS.

The (computer assisted) history matching methodology, which employs Shell proprietary software, has been adapted to include subsidence data. This has resulted in an acceptable history matched reservoir model. A single history match realisation, which has been selected by NAM to be used to generate future production forecasts (predictions), has been presented to SGS for review. The two main recommendations from SGS made in 2013 have been followed up by NAM and implemented in the current model. New recommendations for further improvements to the modelling and suggestions for additional analysis and clarification are provided in the overall conclusions below.

Predictions

The production forecasting method is considered appropriate for predicting future reservoir pressure distribution over time in the field for the period 2016 to (and including) 2025, assuming the offtake schedule for the Groningen production clusters, as determined by NAM, will be realised.

SGS has not critically reviewed the surface network model element of the production forecast models but is supportive of the methodology used to generate the forecasts, notably for the period 2016–2025.

The main recommendation from SGS made in 2013, regarding prediction in late field life, has been, at least partially, followed up by NAM and implemented in the current model. SGS has not reviewed this aspect in detail as it is not relevant for the period 2016–2025.

It is observed that the production plan of NAM is expected to lead to considerable differential depletion across areas of the field. Such high differential depletion has not occurred over the last 35 years.

Overall Conclusions

In general, the static and dynamic models meet the quality criteria, established above. The dynamic models are appropriate for preparing production forecasts of future reservoir pressure distribution over time in the field.

The items below are the main “exceptions” to the above supportive opinion, hence represent areas where SGS recommends further improvements to the modelling by NAM:

- While the use of seismic inversion for static modelling is supported by SGS, an improvement of the method for porosity determination from seismic in the water bearing part of the reservoir is recommended. The “porosity cube” from seismic inversion should be used instead of the “acoustic impedance cube” and the method to determine porosity from seismic needs to be properly validated.
- The difference in the gas volumes between the static and the dynamic model of the Groningen field is within the uncertainty range of 5% (range determined by NAM for the Winningsplan 2013), but more justification and reconciliation by NAM of the difference is desirable in future modelling.
- The pressure match in the peripheral areas of the field, outside the Groningen field production clusters, has been improved compared to the Winningsplan 2013 model. Further improvement is desirable, should a more accurate pressure prediction in those areas be required.
- The objective of the model, as communicated by NAM to SGS, was to predict reservoir pressure in the Groningen field. Therefore the model is not appropriate for predicting the reservoir pressures in some small adjacent fields which are included in the dynamic model area but are outside the Groningen field. This applies specifically for the adjacent fields Kiel-Windeweer, Feerwerd, Annerveen-Veendam, Bedum, Midlaren and the Zuidwending East area.

MB

Of lower importance, additional analysis and clarification by NAM would be beneficial on the following items:

- For future static modelling (seismic interpretation), provide an audit trail of the residual correction process and time to depth conversion of the final model. Detailed fault modelling in a few regions of the field requires attention.
- The detailed distribution of reservoir properties in the static model would benefit from additional analysis on regional trends and on the quality of input data used for modelling these reservoir properties.
- Clear documentation on the changes to the "Net-to-Gross" cut-offs, on the permeability model used and on the formation water parameters used.
- "Sensitivity analysis" on the dynamic modelling of the fault seals, the aquifer parameters, and the permeability model, to support the choice of parameters as used in the single history match realisation used for the forecasts of the Winningsplan 2016.

Kind regards,

Danilo Bandiziol

Managing Director

SGS Horizon B.V.

NAM

Independent Review of Groningen Subsurface Modelling – Update for Winningsplan 2016

30th March 2016

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This report has been prepared by SGS Horizon B.V. ("**SGS**") for the exclusive use and benefit of Nederlandse Aardolie Maatschappij B.V. ("**NAM**") as the sole addressee. Third parties should be aware that SGS does not accept any liability towards them for the content of this report and that any form of taking knowledge of this report beyond this disclaimer is held to imply that such third party accepts this condition and those further restrictions stipulated in the below as if that party were NAM.

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SGS has made every effort to ensure that the findings, conclusions and recommendations presented in this report are in accordance with good industry practice and its own quality management procedures. SGS does however not guarantee the correctness of same and shall not be liable or responsible for any damage incurred by anyone for the sole reason that any interpretation, finding, conclusion or recommendation in this report is incorrect.

This report is limited to the scope as stipulated in the SGS proposal with reference OGC/NL/HAG/2015/S1505-03 REV2, namely the independent review of the quality of the static and dynamic models used for production forecasting for the Groningen field Winningsplan 2016 (March 2016) of NAM, more specifically on the appropriateness of the model for the making of forecasts for the future reservoir pressure distribution over time in the field, based on depletion scenarios where the offtake may be variable between areas of the field.

The review was carried out by employing solely the methodology set forth by SGS in this report. No research has been carried out with another aim than fulfilling this scope and beyond the methodology set forth in this report. This report does not address - not by implication or otherwise - any matters related to seismicity or geomechanical modelling, unless such is explicitly stated in this report. The findings and conclusions of this report are based on the information provided by NAM, of which a non-exhaustive overview is provided in Appendix A and use of the methodology set forth by SGS in this report.

SGS has relied on the documentation and information provided for by NAM and assumed that all such information was complete and that there is no information relevant to the review carried out by SGS that was not provided, whether intentionally or unintentionally. Except where specifically mentioned in this report, SGS has not independently verified the accuracy and completeness of data and information provided by NAM.

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This report is subject to the qualifications contained herein and any liability in connection with this report towards NAM is subject to the contractual conditions applicable between NAM and SGS in relation thereto. This report and any dispute in connection therewith is exclusively governed by Dutch law.

Signed:

Maarten Slijkhuis
Project Manager

Date: 30 MARCH 2016

Danilo Bandiziol
Managing Director

Date: 29 March 2016

EXECUTIVE SUMMARY

Background and Objectives

The Groningen gas field has been producing for more than 50 years. Over the last few years, the production strategy of the field is being adjusted following induced earthquakes noticed above the field.

In the second half of 2013, SGS carried out an independent review of the static and dynamic subsurface / reservoir models as they were completed and documented in 2012 (GFR2012 model), and used for the Winningsplan 2013.

For, amongst others, the preparation of the Winningsplan 2016 and the “Hazard and risk analysis”, NAM has been performing an update to the static and dynamic reservoir models for the Groningen field. These models are used to, amongst others, generate forecasts of gas production and of reservoir pressure. NAM has updated the models primarily based on comments from previous reviews for the Winningsplan 2013 by TNO-AGE / SodM and by SGS, as it was communicated by NAM to SGS.

As communicated by NAM to SGS, the updated models will specifically be used for:

1) forecasts for the future reservoir pressure distribution over time in the field, based on depletion scenarios where the offtake may be variable between areas of the field,
2) as input into an investigation of earth tremors
3) as input for a subsidence prognosis.

Secondary uses for the model may be:

a) basis for investment decisions, including installation of additional compression, the development of infill well locations and the development of several peripheral blocks,
b) to predict future production capacity of the Groningen Field,
c) input for reserves reports and business plans.

NAM has requested SGS in May 2015 to carry out an independent review of the modelling work performed to support the Winningsplan 2016. It was mutually agreed that the SGS review was limited to the following aspects:

1. the technical quality level of the work and model
2. the appropriateness of the model for preparation of production forecasts for the future reservoir pressure distribution over time in the field, based on depletion scenarios where the offtake may be variable between areas of the field
3. the overall quality of the production forecasts for depletion of the field, with focus on the time span the most relevant for the Winningsplan 2016, i.e. the period 2016 to 2025.

NAM has performed the modelling work in a phased approach. As agreed between NAM and SGS, after each phase SGS independently reviewed an aspect of the modelling, as made available by NAM, and summarised its findings to NAM. At the end of the current review, which took place between 1 September 2015 and 30 March 2016, SGS has prepared an opinion letter (sent separately) and a report (this document). This report only documents the findings by SGS of the static and dynamic models as used for the Winningsplan 2016, and does not include the findings on intermediate modelling steps.

NAM has given SGS access to its study reports, data sets, static models (Petrel software, 2 updated versions), and dynamic models (MoReS software, 2 updated versions). A summary of the main reports and models used for this analysis is listed in Appendix A. SGS has assumed that the information is complete and representative.

SGS Approach

In order to carry out the review in 2013, SGS has utilised specific criteria to judge the “quality” of NAM’s work and the models, which also have been applied in the current review:

- Transparency: was the work done as stated in reports, is there a clear auditable workflow?
- Accuracy: does the model accurately represent the main reservoir processes?
- Completeness: was all available data consistently incorporated?
- Uncertainty: was the full range of uncertainty applied?

The current review by SGSH has been building on the 2013 review. For the review of the subsurface modelling for the Winningsplan 2016, SGS has applied a structured approach:

1. Verification that elements that should not have been changed significantly (as it has been stated by NAM) in the models between 2012 and 2015 / 2016 indeed are unchanged and require no further in-depth review. This has been carried out by both high level review and through detailed spot checks.
2. Evaluation of the elements of the models that changed compared to the 2012 models (as it has been stated by NAM). SGS has carried out spot checks on key parameters / areas, has reviewed if techniques and workflows are appropriate and are applied in a consistent manner.
3. Multi-disciplinary integrated conclusions have been made by SGS, and are described in this report.

It is noted that the quality criterion of uncertainty was not further evaluated in the current review, as the review in 2013 covered this extensively and only a relatively very small amount of additional data has become available since.

It is further noted that the quality criterion of transparency was less extensively evaluated in the current review compared to the 2013 review, since the updated models have not been documented by NAM to the same standard as in 2013. As a consequence, a number of the main recommendations from SGS as a result of the current review are to improve the clearness of the documentation.

The static and dynamic models for the Winningsplan 2016 are based on the same seismic data set as used for the Winningsplan 2016, while the area of static modelling was slightly extended outside the limits of the Groningen field. It was initially envisaged by NAM to include additional geophysical data (a reprocessed seismic data set), NAM decided later not to incorporate that for the Winningsplan 2016. Some recommendations made by SGS in this report are for the future use of additional geophysical data in the modelling.

The overall results of the SGS evaluations and the opinions from SGS are presented here below.

Static Model

The overall approaches to the update of the static model are supported by SGS.

The main geological, geophysical and petrophysical features of the Groningen Rotliegend reservoir appear to have been correctly captured in the static model. The updates to the static model performed for the Winningsplan 2016 are relatively minor, and can be considered as improvements compared to the models used for the Winningsplan 2013. The main recommendation from SGS made in 2013 has been followed up by NAM and implemented in the current model. New recommendations for further improvements to the modelling and suggestions for additional analysis and clarification are provided in the overall conclusions below.

Dynamic Model and History Match

The update to the dynamic model is supported by SGS.

The (computer assisted) history matching methodology, which employs Shell proprietary software, has been adapted to include subsidence data. This has resulted in an acceptable history matched reservoir model. A single history match realisation, which has been selected by NAM to be used to generate future production forecasts (predictions), has been presented to SGS for review. The two main recommendations from SGS made in 2013 have been followed up by NAM and implemented in the current model. New recommendations for further improvements to the modelling and suggestions for additional analysis and clarification are provided in the overall conclusions below.

Predictions

The production forecasting method is considered appropriate for predicting future reservoir pressure distribution over time in the field for the period 2016 to (and including) 2025, assuming the offtake schedule for the Groningen production clusters, as determined by NAM, will be realised.

SGS has not critically reviewed the surface network model element of the production forecast models but is supportive of the methodology used to generate the forecasts, notably for the period 2016–2025.

The main recommendation from SGS made in 2013, regarding prediction in late field life, has been, at least partially, followed up by NAM and implemented in the current model. SGS has not reviewed this aspect in detail as it is not relevant for the period 2016–2025.

It is observed that the production plan of NAM is expected to lead to considerable differential depletion across areas of the field. Such high differential depletion has not occurred over the last 35 years.

Overall Conclusions

In general, the static and dynamic models meet the quality criteria, established above. The dynamic models are appropriate for preparing production forecasts of future reservoir pressure distribution over time in the field.

The items below are the main “exceptions” to the above supportive opinion, hence represent areas where SGS recommends further improvements to the modelling by NAM:

- While the use of seismic inversion for static modelling is supported by SGS, an improvement of the method for porosity determination from seismic in the water bearing part of the reservoir is recommended. The “porosity cube” from seismic inversion should be used instead of the “acoustic impedance cube” and the method to determine porosity from seismic needs to be properly validated.
- The difference in the gas volumes between the static and the dynamic model of the Groningen field is within the uncertainty range of 5% (range determined by NAM for the Winningsplan 2013), but more justification and reconciliation by NAM of the difference is desirable in future modelling.
- The pressure match in the peripheral areas of the field, outside the Groningen field production clusters, has been improved compared to the Winningsplan 2013 model. Further improvement is desirable, should a more accurate pressure prediction in those areas be required.
- The objective of the model, as communicated by NAM to SGS, was to predict reservoir pressure in the Groningen field. Therefore the model is not appropriate for predicting the reservoir pressures in some small adjacent fields which are included in the dynamic model area but are outside the Groningen field. This applies specifically for the adjacent fields Kiel-Windeweer, Feerwerd, Annerveen-Veendam, Bedum, Midlaren and the Zuidwending East area.

Of lower importance, additional analysis and clarification by NAM would be beneficial on the following items:

- For future static modelling (seismic interpretation), provide an audit trail of the residual correction process and time to depth conversion of the final model. Detailed fault modelling in a few regions of the field requires attention.
- The detailed distribution of reservoir properties in the static model would benefit from additional analysis on regional trends and on the quality of input data used for modelling these reservoir properties.
- Clear documentation on the changes to the “Net-to-Gross” cut-offs, on the permeability model used and on the formation water parameters used.
- “Sensitivity analysis” on the dynamic modelling of the fault seals, the aquifer parameters, and the permeability model, to support the choice of parameters as used in the single history match realisation used for the forecasts of the Winningsplan 2016.

Limitation

The geomechanical aspects of the reservoir rock and any possible induced subsidence and seismicity effects were not part of the review scope, consequently this report does not contain any conclusions regarding seismicity and subsidence as a consequence of NAM’s gas production activities.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

The Groningen gas field has been producing for more than 50 years. Over the last few years, the production strategy of the field is being adjusted following induced earthquakes noticed above the field.

In the second half of 2013, SGSH carried out an independent review of the static and dynamic subsurface / reservoir models as they were completed and documented in 2012 (also called “GFR2012 model”), and used for the Winningsplan 2013.

For, amongst others, the preparation of the Winningsplan 2016 and the “Hazard and risk analysis”, NAM has been performing an update to the static and dynamic reservoir models for the Groningen field. These models are used to, amongst others, generate forecasts of gas production and of reservoir pressure. NAM updated the models primarily based on comments from previous reviews for the Winningsplan 2013 by TNO-AGE / SodM and by SGS, as it was communicated by NAM to SGS. An overview of the main updates, as understood by SGS, is listed in section 1.4.

As communicated by NAM to SGS, the updated models will specifically be used for:

1) forecasts for the future reservoir pressure distribution over time in the field, based on depletion scenarios where the offtake may be variable between areas of the field,
2) as input into an investigation of earth tremors
3) as input for a subsidence prognosis.

Secondary uses for the model may be:

a) basis for investment decisions, including installation of additional compression, the development of infill well locations and the development of several peripheral blocks,
b) to predict future production capacity of the Groningen Field,
c) input for reserves reports and business plans.

1.2 SCOPE OF THE SGS CURRENT REVIEW (SEPTEMBER 2015 TO MARCH 2016)

NAM has requested SGS in May 2015 to carry out an independent review of the modelling work performed to support the Winningsplan 2016. It was mutually agreed that the SGS review was limited to the following aspects:

1. the technical quality level of the work and model
2. the appropriateness of the model for preparation of production forecasts for the future reservoir pressure distribution over time in the field, based on depletion scenarios where the offtake may be variable between areas of the field
3. the overall quality of the production forecasts for depletion of the field, with focus on the time span the most relevant for the Winningsplan 2016, i.e. the period 2016 to 2025.

NAM has performed the modelling work in a phased approach. As agreed between NAM and SGS, after each phase SGS independently reviewed an aspect of the modelling, as made available by NAM, and summarised its findings to NAM. At the end of the current review, which took place between 1 September 2015 and 30 March 2016, SGS has prepared an opinion letter (sent separately) and a report (this document). This report only documents the findings by SGS of the static and dynamic models as used for the Winningsplan 2016, and does not include the findings on intermediate modelling steps.

NAM has given SGS access to its study reports, data sets, static models (Petrel software, 2 updated versions), and dynamic models (MoReS software, 2 updated versions). A summary of the main reports and models used for this analysis is listed in Appendix A. SGS has assumed that the information is complete and representative.

1.3 PREVIOUS REVIEW (2013) BY SGS HORIZON

In 2013, SGS carried out a review of the static and dynamic models as they were completed and documented in 2012. That review consisted of an independent review of the work done, split into three phases, and with objectives as follows:

Phase 1 Review of the existing static model and history match of this model.
SGS comments on:
1. the technical quality of the work and model,
2. the appropriateness of the model for preparation of production forecasts of depletion processes and reservoir pressure maintenance processes.

Phase 2 Review of the dynamic modelling of depletion based production scenarios
SGS comments on:
1. the technical quality level of the work and model,
2. the overall quality of the production forecasts for depletion of the field,
3. the uncertainty around the expectation/base forecast.

Phase 3 Review of the dynamic modelling of pressure maintenance based production scenarios
SGS comments on:
1. the technical quality level of the work and the model,
2. the overall quality of the production forecasts for depletion of the field,
3. uncertainty.

Phase 1 and Phase 2 have been executed concurrently in 2013, followed by Phase 3 afterwards. SGS issued to NAM full reports on their findings and in addition SGS issued “opinion letters” which have been made public.

In order to carry out the review in 2013, SGS utilised specific criteria to judge the “quality” of NAM’s work and the models:
1. Transparency: was the work done as stated in reports, is there a clear auditable workflow?
2. Accuracy: does the model accurately represent the main reservoir processes?
3. Completeness: was all available data consistently incorporated?
4. Uncertainty: was the full range of uncertainty applied?

1.4 MODEL UPDATES BY NAM FOR THE WINNINGSPLAN 2016

As it was communicated by NAM to SGS, the updates to the models by NAM have primarily been driven by comments from previous reviews for Winningsplan 2013 by TNO-AGE / SodM and by SGS.

The static and dynamic models for the Winningsplan 2016 are based on the same seismic data set as used for the Winningsplan 2016, while the area of static modelling was slightly extended outside the limits of the Groningen field. It was initially envisaged by NAM to include additional geophysical data (a reprocessed seismic data set); NAM decided later not to incorporate that for the Winningsplan 2016.

Based on the information provided by NAM and the current review by SGS, on the following elements changes to the static model (compared to GFR2012, reviewed in 2013) have been made:

- inclusion of 3 new wells
- top reservoir map
- fault model – adjusted fault pattern regionally
- extension of the model area grid to cover an area carrying no hydrocarbons in the West and Southwest (model area from about 1000 km^2 to about 1300 km^2)
- static model reservoir architecture in relation to sequence stratigraphy
- porosity distribution – acoustic impedance from seismic was used to guide property distribution (a major new approach)
- cut-offs used for Net to Gross (based on Vclay)

- porosity-permeability relationship
- saturation – height modelling
- dynamic model matched with new CAHM (computer assisted history match) approach, with as additional matching constraint the measured subsidence.
- vapour water from the gas included in the dynamic model (will also affect vertical lift performance in well prediction)
- more aquifers in dynamic model
- additional adjacent fields in dynamic model
- deliverability modelling changed from based on cluster to based on wells; more emphasis on achieving a match of well deliverability to available pressure data at surface
- relative permeability and capillary pressure parameters in dynamic model
- updated surface network model

1.5 SGS APPROACH TO CURRENT REVIEW

The current review by SGSH has been building on the 2013 review, applying the same specific criteria to judge the “quality” of NAM’s work and the models (see section 1.3).

For the review of the subsurface modelling for the Winningsplan 2016, SGS has applied a structured approach:

1. Verification that elements that should not have been changed significantly (as it has been stated by NAM) in the models between 2012 and 2015 / 2016 indeed are unchanged and require no further in-depth review.
2. Evaluation of elements of the models that changed compared to the 2012 model (as it has been stated by NAM). SGS has carried out spot checks on key parameters / areas, has reviewed if techniques and workflows are appropriate and are applied in a consistent manner. A limited amount of sensitivity analyses using the models has been performed to test robustness to changes. Further methods may be included to support the findings by SGS.
3. Multi-disciplinary integrated conclusions have been made by SGS, and are described in this report. Included are recommendations by SGS on improving the static and dynamic modelling when further updates are pursued by NAM. SGS included recommendations on more clear reporting of the modelling.

It is noted that the quality criterion of uncertainty was not further evaluated in the current review, as the review in 2013 covered this extensively and only a relatively very small amount of additional data has become available since.

It is further noted that the quality criterion of transparency was less extensively evaluated in the current review compared to the 2013 review, since the updated models have not been documented by NAM to the same standard as in 2013. As a consequence, a number of the main recommendations from SGS as a result of the current review are to improve the clearness of the documentation.

The static and dynamic models for the Winningsplan 2016 are based on the same seismic data set as used for the Winningsplan 2016, while the area of static modelling was slightly extended outside the limits of the Groningen field. It was initially envisaged by NAM to include additional geophysical data (a reprocessed seismic data set), NAM decided later not to incorporate that for the Winningsplan 2016. Some recommendations made by SGS in this report (notably in section 3.5) are for the future use of additional geophysical data in the modelling.

Some initial recommendations made by SGS during the current review assumed that the additional geophysical data would be used in the modelling.

NAM has provided SGS for review of the forecasts for the Winningsplan 2013 with a single static model and with a single history matched realisation of the dynamic model based on this static model, which has been selected by NAM to be used to generate future production forecasts (predictions). SGS has performed very limited sensitivity analysis to this model.

NAM has provided SGS with a single production forecast based on a single offtake schedule for the Groningen production clusters, as determined by NAM. SGS has not critically reviewed the surface network model element of the production forecast models but SGS has checked that the offtake schedule is sufficiently realistic based on the MoReS model considering the period 2016–2025.

1.6 CLARIFICATION ON CONCLUSIONS AND RECOMMENDATIONS

In the following chapters 2 to 6, observations, intermediate detailed conclusions and suggestions for further modelling and data analysis are presented.

However, the full integrated conclusions and recommendations are documented in chapter 7. In case any unclear statements or contradictions may appear to be present in chapters 2 to 6, the SGS conclusions and recommendations in chapter 7 are overriding those.

It is noted that the integrated conclusions and recommendations in chapter 7 correspond to those in the opinion letter.

2 STRUCTURAL MODEL

In 2013 the seismic interpretation for the Groningen field was reviewed and validated by SGS [1]. In 2015 an extended interpretation of the Top Rotliegend was carried out by NAM, which NAM has denoted as "1st pass" (May 2015) and "2nd pass" (August 2015) respectively. The 2nd pass model has been used, according to NAM, for the static and dynamic models used for the Winningsplan 2016.

The SGS review documented in this report is for the structural model of the 2015 2nd pass model. Whilst, as stated by NAM and as verified by SGS, the changes between 2012 and 2015 top reservoir structural model are minor, the current review and report focus on the comparison between the 2012 and 2015 (2nd pass) models as well as the differences on GRV and Closure volume of those models.

The impact of any structural modelling issues on the dynamic modelling results has not been evaluated by NAM nor SGS.

2.1 ITEMS REVIEWED

The main items reviewed are, as provided by NAM to SGS:

- Top Rotliegend horizon (from Petrel 2nd pass Geomodel)
- Rotliegend well tops (same as 2015 1st pass)
- Fault model (from Petrel 2nd pass Geomodel)

No report was provided along with the 2015 structural model, so there is no information on how the top structure surface was created and on residual corrections applied by NAM. The seismic interpretation and depth conversion for the 2015 static model was therefore assumed to be very similar to that in 2012. It was verified by SGS that the differences were small.

In 2015 an extended area was modelled compared to 2012. No information was provided on the process to generate the surfaces in the model over that extended area. Such lack of information has limited the amount of review performed by SGS in that area.

2.2 FAULT MODEL

The major field boundaries, defined by faults, seem consistent in both 2015 and 2012 interpretations and only relatively minor differences were observed.
Some of the major fault polygons were extended into aquifer regions (to the West of the Groningen field), while other faults of limited to medium lateral extension were taken out of the 2015 model.

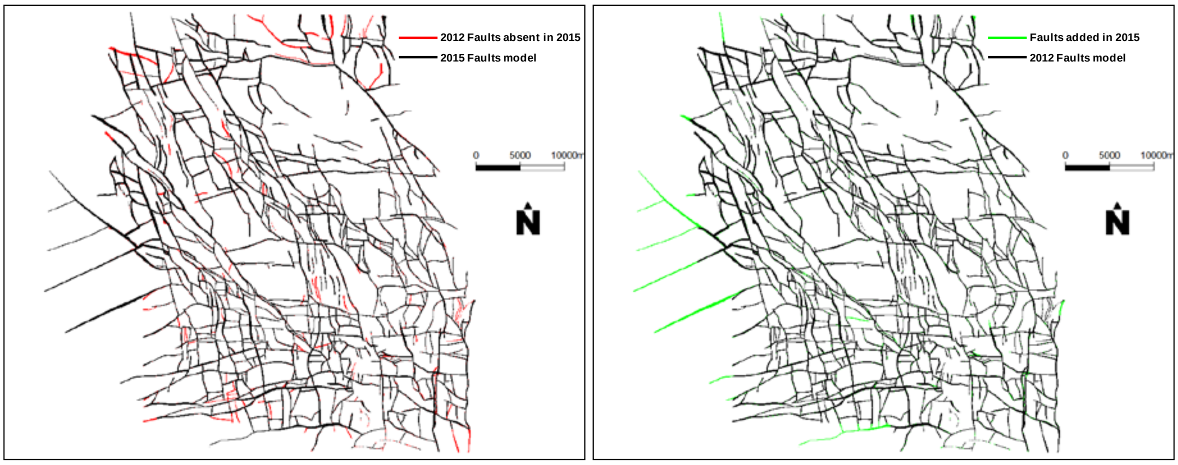


Figure 2-1 **Faults model for 2012 and 2015 static models. Left highlights in red 2012 faults not present in 2015. Right highlights in green fault extension to the West in the 2015 static model**

It is observed by SGS that some of the faults included in the 2012 model were not included in the 2015 model, while these show prominent throws on seismic. Figure 2-2 and Figure 2-3 show portions of Inlines 8747 and 8483, N-S oriented, showing respectively two and three of those faults, reflected in 2012 and not included in the 2015 structural model. No justification for removing these faults has been provided by NAM. Also no sensitivity analysis on the dynamic model is available to SGS to judge if these faults have a noticeable effect on the history match of the dynamic model.

Another observation is that the fault density over the extended area is much lower than over the Groningen field. As communicated by NAM to SGS, the fault pattern was defined as such to support the dynamic modelling of the aquifers to the Groningen field. From a geological point of view, SGS considers the fault density too low in this area.

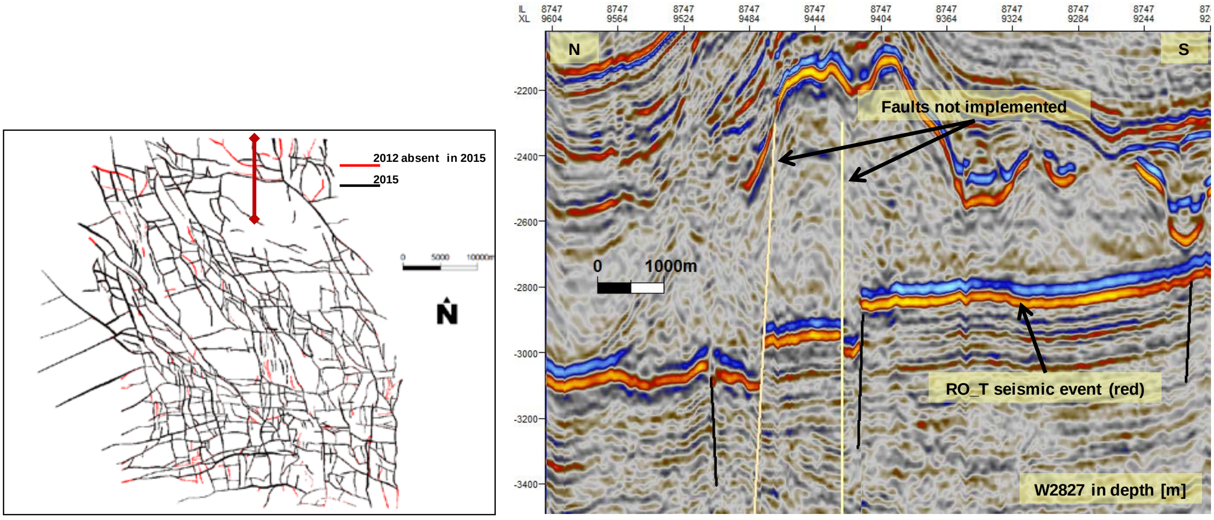


Figure 2-2 **Portion of Inline 8747, N-S oriented, and two faults with prominent throw, reflected in 2012 and not present in the 2015 model**

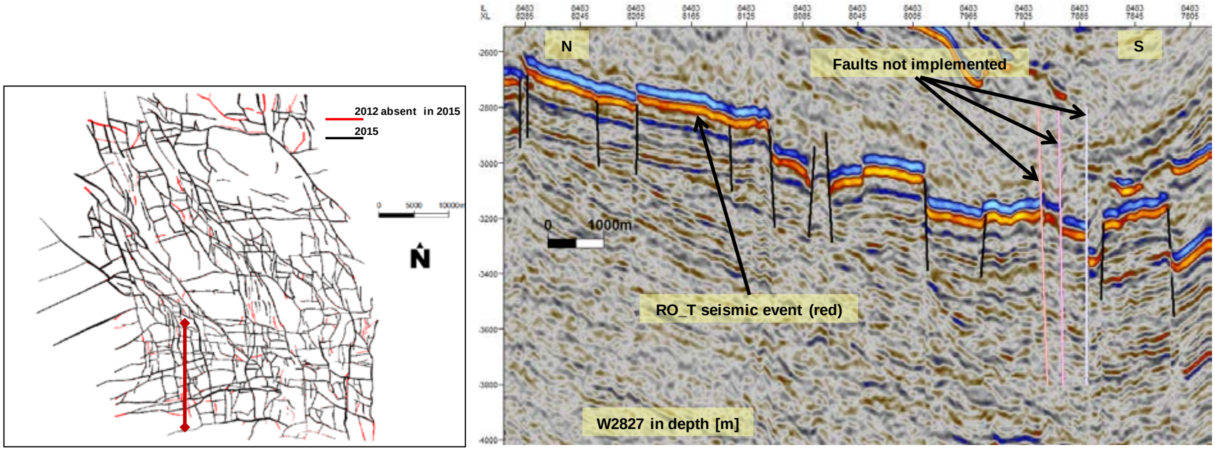


Figure 2-3 **Portion of Inline 8483, N-S oriented, and three faults with prominent throw, reflected in 2012 and not present in the 2015 model**

2.3 DEPTH MAPS (TOP ROTLIEGEND)

In the 2012 model, 104 wells were excluded of the tying process, potentially leading to issues during the distribution of seismic velocities and potentially reservoir properties, besides off-depth perforations in the dynamic model. The 2015 static model includes all wells (except 5 wells cut by faults) in the tying process of the Top Rotliegend. The latter model approach is therefore considered more robust to prevent/correct well-seismic mis-ties.

One observation for the 2015 static model is that despite the inclusion of more deterministic data, the method used for well-seismic tie created local bull's eyes. This is a drawback if compared to the 2012 model where the surfaces seem to exhibit a more geologically consistent surface. Figure 2-4 shows a portion of inline where Top Rotliegend tying does not honour the well top. That kind of mismatches creates a few bull's eyes in the depth maps, as observed in the same figure.

Other minor issues are a few spikes that were observed at the cluster KPD, thought by SGS to be produced by proximity amongst the well tops. The impact of those spikes is likely negligible for dynamic modelling, but no sensitivity analysis has been made on this subject.

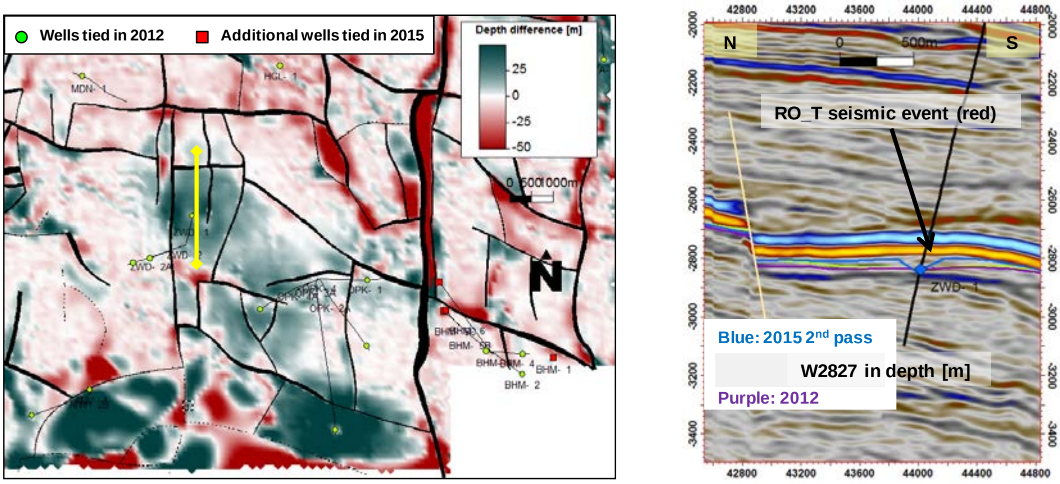


Figure 2-4 Portion of a N-S section shows that Top Rotliegend tying is locally not satisfactory. Where correction is large it creates bull's eyes. The 2012 surface showed a more geologically consistent surface

The Top Rotliegend horizon in the current, 2015, structural model is very similar to the 2012 version. Differences in the gas in place volume due to the structural model changes are therefore expected to be small. The differences have been checked by SGS, as is described below.

The map of difference of the 2012 and 2015 structure maps at Top Rotliegend, Figure 2-5, ranges between ± 50m. Extreme values are located toward the edges of the AOI. No audit trail is available on these changes.

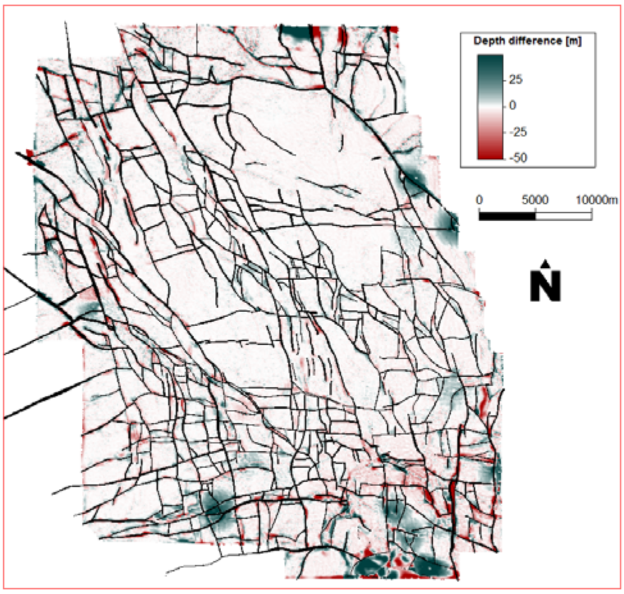


Figure 2-5 Top Rotliegend, map of depth difference between 2012 and 2015. Red color highlights where 2015 structure is deeper than 2012

2.4 GRV & CLOSURE VOLUME COMPARISON

A closure volume comparison was conducted for a window from Top Rotliegend to FWL. The map of differences for closure volume (Figure 2-6) highlights, in red, the areas where the 2015 static model has less volume than 2012. Similarly, Gross Rock Volume difference maps were created, Figure 2-7.

The difference between GRV and closure volume is that the GRV takes into account the difference between top structure and bottom reservoir (above the FWL), while the closure volume considers the entire volume between top structure and the FWL. The closure volume is therefore generally higher than the GRV, especially in the south of the field.

A summary of the differences for GRV and closure volumes, per segment, is provided by Table 2-1. For some segments, the percentual differences are considerable, but the absolute differences are minor. For some other segments, the absolute differences are considerable, but the percentual differences are small.

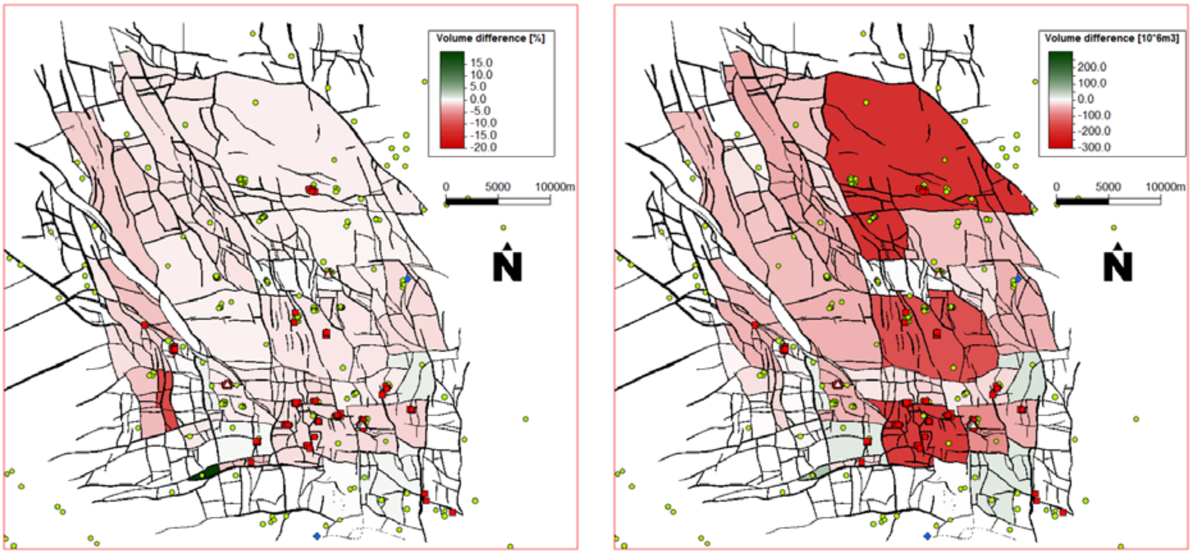


Figure 2-6 **Closure volume comparison of 2012 and 2015 models. Closure from Top Rotliegend to FWL. Left: Closure volume difference [%] per segment. Right: Closure volume difference [10^6 m^3] per segment**

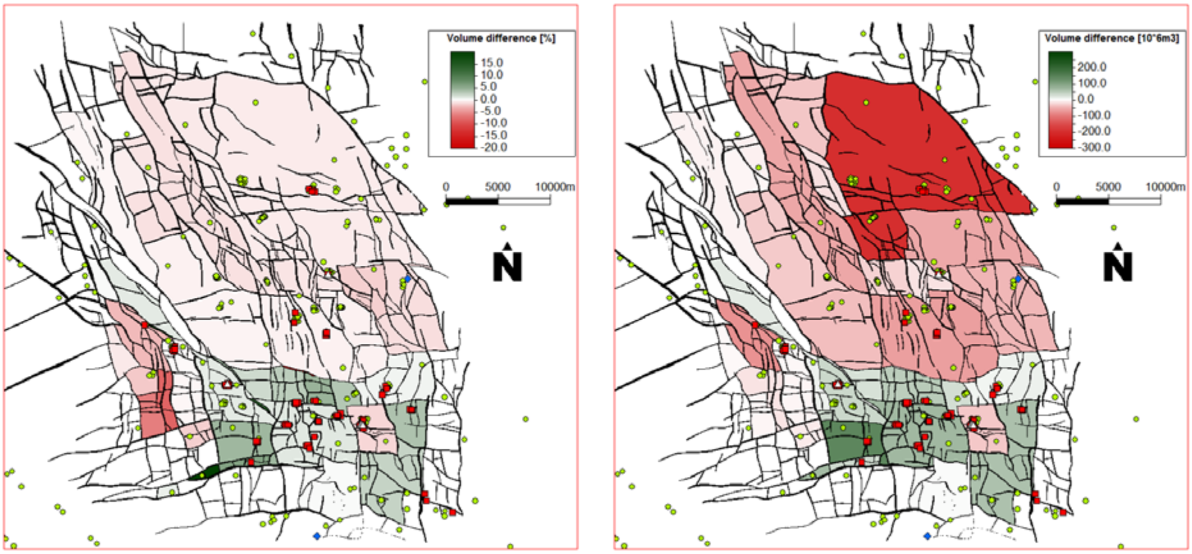


Figure 2-7 **GRV comparison of 2012 and 2015 models. Left: GRV difference [%] per segment. Right: GRV difference [10^6 m^3] per segment.**

The difference between 2012 and 2015 structure models are considered small for the summation over the model, 0.1% and 0.72% for GRV and closure volumes, respectively.

Overall it is concluded that the changes to the structural model from 2012 to 2015 have a minor effect on the overall modelling.

Table 2-1 **GRV comparison between the 2012 model and 2015 model (by segment in Petrel model). The calculation is based on the reservoir top structure map (Top Rotliegend)**

	GRV [10^9m3]				CLOSURE VOLUME [10^9m3]			
SEGMENTS	**2012**	**2015**	**Diff. [10^6m3]**	**Dif %**	**2012**	**2015**	**Diff. [10^6m3]**	**DIF %**
Amsweer	1.75	1.73	-15.8	-0.9%	1.86	1.87	1.8	0.1%
Borgsweer	3.83	3.79	-44.1	-1.2%	3.87	3.82	-48.3	-1.3%
Central Pop-up	0.02	0.01	-10.5	-197.4%	0.10	0.10	-0.4	-0.4%
De Eeker	2.26	2.22	-32.4	-1.5%	5.58	5.50	-79.7	-1.4%
De Paauwen	9.21	9.17	-39.5	-0.4%	9.66	9.61	-48.7	-0.5%
Delfzijl	2.56	2.52	-45.9	-1.8%	2.63	2.62	-16.9	-0.6%
Eemskanaal	1.90	1.90	-4.0	-0.2%	2.50	2.49	-5.7	-0.2%
Eemskanaal West	2.78	2.70	-74.5	-2.8%	2.98	2.93	-46.5	-1.6%
Ellerhuizen	0.23	0.24	0.5	0.2%	0.24	0.24	-1.8	-0.7%
Farmsum	7.71	7.66	-54.7	-0.7%	8.02	7.98	-35.7	-0.4%
Froombosch Pop-Up	0.07	0.08	11.7	13.9%	0.23	0.23	-3.9	-1.7%
Groningen SE (incl. Zuidwending East)	2.51	2.57	59.3	2.3%	4.25	4.27	19.1	0.4%
Harkstede	0.74	0.73	-15.5	-2.1%	0.73	0.71	-16.2	-2.3%
Harkstede-East	0.20	0.18	-15.0	-8.1%	0.22	0.20	-20.6	-10.4%
Harkstede-NW	0.45	0.45	-3.4	-0.8%	0.45	0.44	-4.9	-1.1%
Harkstede-South	0.08	0.08	-4.9	-6.2%	0.07	0.07	-2.0	-2.8%
Hoogezand	0.20	0.27	66.8	25.1%	0.18	0.24	56.7	23.8%
Kolham	0.61	0.60	-10.5	-1.8%	0.58	0.58	-4.4	-0.8%
Kolham-North	1.95	1.94	-4.9	-0.3%	2.05	2.05	-2.5	-0.1%
Kolham-West	0.00	0.00	-0.5	-51.5%	0.00	0.00	-0.1	-18.9%
Kooipolder Pop-up	0.13	0.13	5.1	3.9%	0.23	0.22	-2.6	-1.1%
Midlaren	0.04	0.04	0.2	0.7%	0.03	0.03	0.0	0.1%
Midwolda	1.71	1.77	60.3	3.4%	2.95	2.90	-48.5	-1.7%
Nieuw-Scheemda	0.91	0.94	29.2	3.1%	2.37	2.35	-11.6	-0.5%
Noordbroek	1.04	1.09	49.0	4.5%	1.78	1.75	-25.2	-1.4%
Oldorp	0.81	0.80	-7.8	-1.0%	0.79	0.79	-6.4	-0.8%
Oldorp West	0.89	0.89	-5.0	-0.6%	0.91	0.89	-14.5	-1.6%
Oostwold	2.12	2.13	11.4	0.5%	2.98	3.01	24.4	0.8%
Overschild	2.63	2.61	-25.5	-1.0%	2.75	2.75	1.7	0.1%
Sappemeer	3.21	3.35	142.2	4.2%	5.51	5.52	18.4	0.3%
Sappemeer-South	0.54	0.57	33.1	5.8%	0.85	0.83	-18.6	-2.2%
Schaaphok	1.21	1.22	10.3	0.8%	2.10	2.12	13.1	0.6%
Siddeburen-Oudeweg	13.22	13.15	-62.7	-0.5%	15.84	15.69	-147.5	-0.9%
Slochteren-Kooipolder	3.67	3.71	35.2	1.0%	6.27	6.22	-45.8	-0.7%
Spitsbergen-Tussenklappen	6.29	6.36	69.8	1.1%	15.01	14.83	-180.2	-1.2%
Ten Boer-North	1.65	1.66	17.4	1.0%	1.70	1.66	-40.5	-2.4%
Ten Boer-Pop up	0.03	0.06	33.3	51.5%	0.11	0.09	-11.6	-12.4%
Ten Post	6.62	6.59	-31.2	-0.5%	6.74	6.70	-40.0	-0.6%
Ten Post-North	2.79	2.76	-29.8	-1.1%	2.84	2.80	-34.1	-1.2%
Ten Post-West	2.14	2.14	-6.5	-0.3%	2.08	2.04	-39.0	-1.9%
tZandt-Bierum	30.22	30.02	-199.6	-0.7%	30.46	30.27	-195.9	-0.6%
Uithuizen	4.28	4.24	-33.5	-0.8%	4.26	4.23	-35.0	-0.8%
Zuidpolder	1.70	1.70	8.3	0.5%	3.31	3.29	-21.5	-0.7%
Zeerijp	5.18	5.12	-56.4	-1.1%	5.23	5.17	-53.4	-1.0%
Zeerijp-East	2.29	2.27	-17.0	-0.7%	2.29	2.27	-22.1	-1.0%
Zuiderveen	1.66	1.71	46.8	2.7%	2.14	2.12	-17.7	-0.8%
Zuiderveen-West	1.39	1.42	26.4	1.9%	1.82	1.81	-13.3	-0.7%
Zuidwending-Main	1.20	1.21	2.8	0.2%	1.76	1.76	1.2	0.1%
Zuidwending-South	0.00	0.00	0.0		0.00	0.00	0.0	100.0%
TOT	**1.39E+02**	**1.38E+02**	**-132.2**	**-0.1%**	**171.32**	**170.09**	**-1227.08**	**-0.72%**

2.5 DETAILED CONCLUSIONS & RECOMMENDATIONS

It is noted that the impact of any structural modelling issues on the dynamic modelling results has not been evaluated by NAM nor SGS.

Fault model:

- In general no larges differences were observed between the 2012 and 2015 structural models
- Several faults in the 2012 static model, from short to medium lateral extension, were not included in the 2015 static model
- Faults with a throw larger than ~ 100 m, or larger than local reservoir thickness, should be modelled
- Audit trail for fault modelling should be maintained by NAM and provided for future review
- Fault density over the extended area is likely underestimated.

Structure (Top Rotliegend):

- All wells (except 5 with fault cuts) are tied to the top structure. This is considered an improvement over the 2012 model
- The method used to tie the top structure to the wells created some local bull’s eyes and spikes
- For future modelling (new seismic interpretation), provide an audit trail of the residual correction process and time to depth conversion.

Rock volume

- The volume differences between the 2012 and 2015 models, related to Top Rotliegend map in the models, are negligible; 0.1% and 0.72% for GRV and closure volumes, respectively.

3 SEISMIC INVERSION

The objective of this review was to validate the methodology used in the seismic inversion executed by NAM in 2003 for the Groningen Field. The results of the seismic inversion have been used in the reservoir property modelling in static and dynamic models.

Furthermore, NAM stated that it was considering to update its models to include additional geophysical data (a reprocessed seismic data set). SGS below provides some considerations and recommendations on any future seismic inversion on this new data.

3.1 ITEMS REVIEWED

The items reviewed by SGS (see for more detail Appendix A) are a NAM report on the “Groningen field seismic inversion” from July 2003, a report on the “Groningen Field Jason Inversion of 3D Seismic Data” from Fugro-Jason of 2003, and maps from the “Promise” software. Use was made of the 2015 Petrel model, including well logs.

3.2 REVIEW OF INVERSION METHODOLOGY FROM NAM REPORTS

Two approaches for porosity modelling, which honour lateral heterogeneities captured by 3-D seismic, were performed at Groningen Field:

- A hard constrained sparse spike inversion (CSSI) was performed using Jason software. Porosity maps, for each reservoir unit, were estimated using the resulted acoustic impedance (AI) as trend through collocated cokriging.
- These porosity maps were used as input, together with other properties, in a stochastic inversion performed with Promise software in order to increase resolution. The outputs of this inversion were an AI volume, thickness, net-to-gross and porosity maps for each reservoir unit. Porosity*thickness*net-to-gross maps were back-tied to the wells using kriging with external drift (EDK).

3.2.1 JASON INVERSION

Regarding the Jason inversion report, several aspects were reviewed by SGS:

- <u>Wells tied to the seismic</u>: Good qualitative correlations are observed (Figure 3-1) between the synthetic seismograms and original seismic traces in the 35 wells shown. Well-seismic ties are considered consistent.

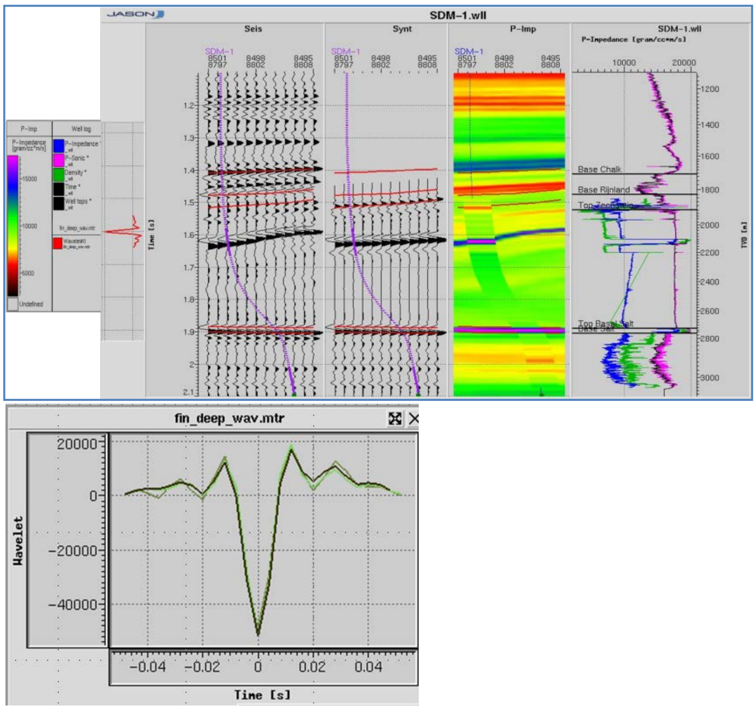


Figure 3-1 Well-seismic tie (Wells SDM-1) and extracted wavelet.

- Wavelet extraction: A deterministic laterally varying wavelet was estimated using 18 wells at the reservoir interval. The wavelet is almost symmetric zero phase which is considered good for the inversion process. The wavelet is considered reliable because of its deterministic nature, symmetry and amplitude variation due to lateral changes within the reservoir.

- Low frequency model (LFM): It is observed that the horizons used in the construction of the LFM are not introducing lateral error during the interpolations of the AI logs (Figure 3-2). The frequencies above 5 Hz were filtered out and the seismic has a bandwidth between approximately 8 to 60 Hz. This means that the LFM is not introducing artifacts to the resulted AI volume. The LFM is considered reliable.

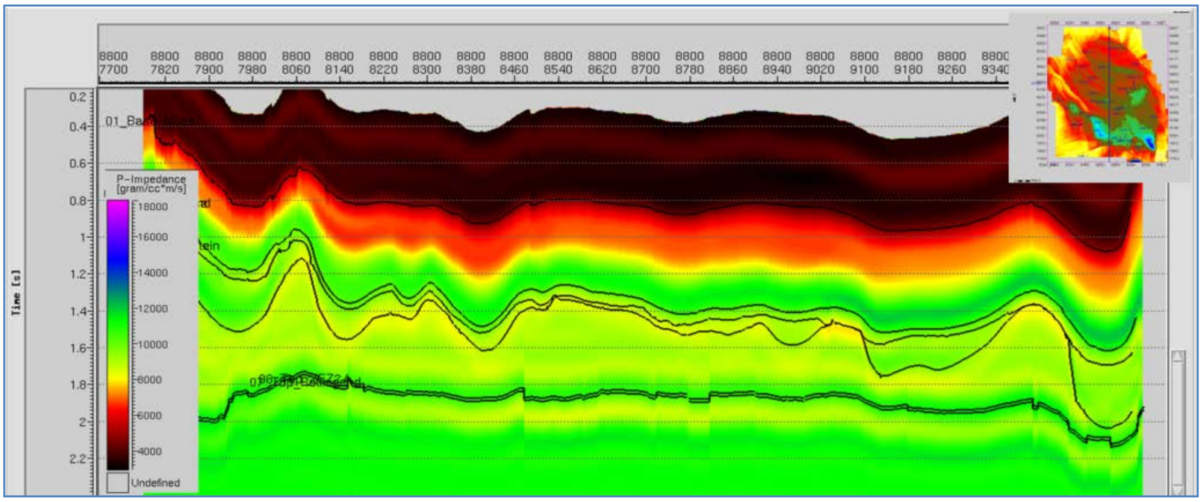
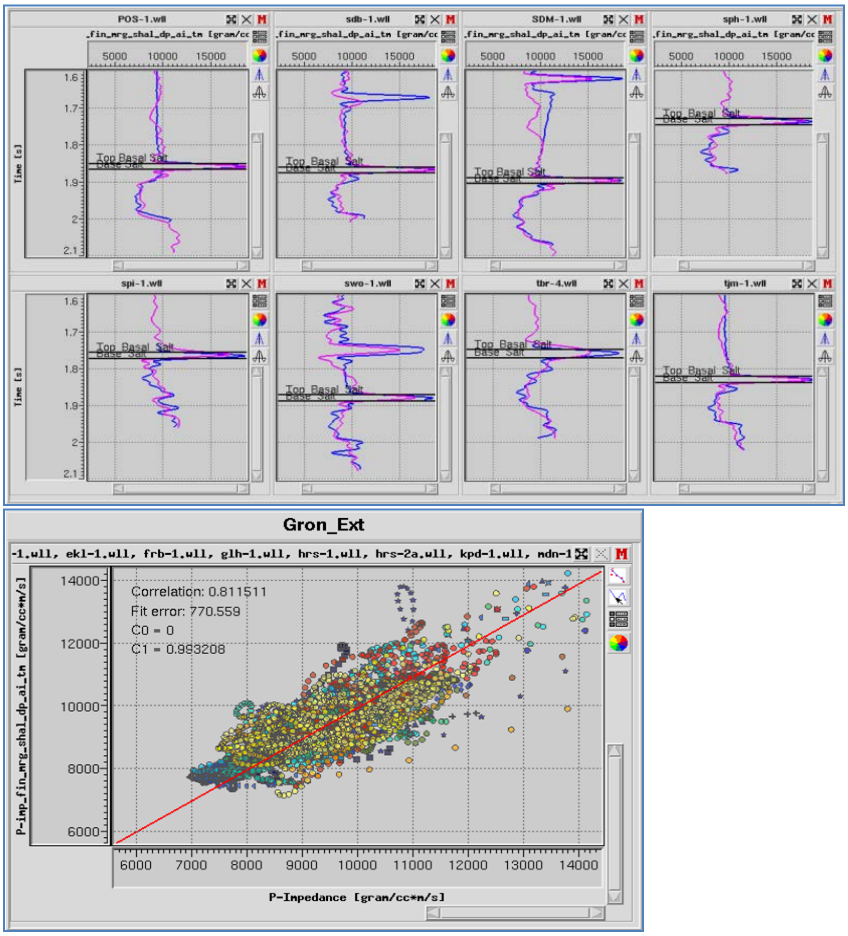


Figure 3-2 Low frequency model (high-cut filtered at 5 Hz)

- Inversion analysis at well locations: Qualitatively, a good match is observed between the AI logs and the modeled AI from the inversion at well locations. Quantitatively, a crossplot of modeled AI versus AI logs at reservoir interval (Figure 3-3) shows a linear trend (intercept = 0, slope = 0.99) with a correlation coefficient of 0.81, which is considered high enough. In general, the resulting AI volume from the sparse spike seismic inversion performed with Jason is considered to be of a good quality.



Correlation: 0.811511
Fit error: 770.559
C0 = 0
C1 = 0.993208

Figure 3-3 **Comparison between acoustic impedance from logs and acoustic impedance from the inversion (reservoir unit intervals)**

- Porosity estimation from AI: Porosity maps from each reservoir unit were generated using the resulting AI from Jason through collocated cokriging with nugget effect. The Jason report describes that a poor correlation exists between well porosities and the modeled AI if the unit thickness is less than about 30 meters; the correlation increases when bigger intervals are used. This is most likely due to the limited resolution of the inverted AI, as acknowledged by SGS.

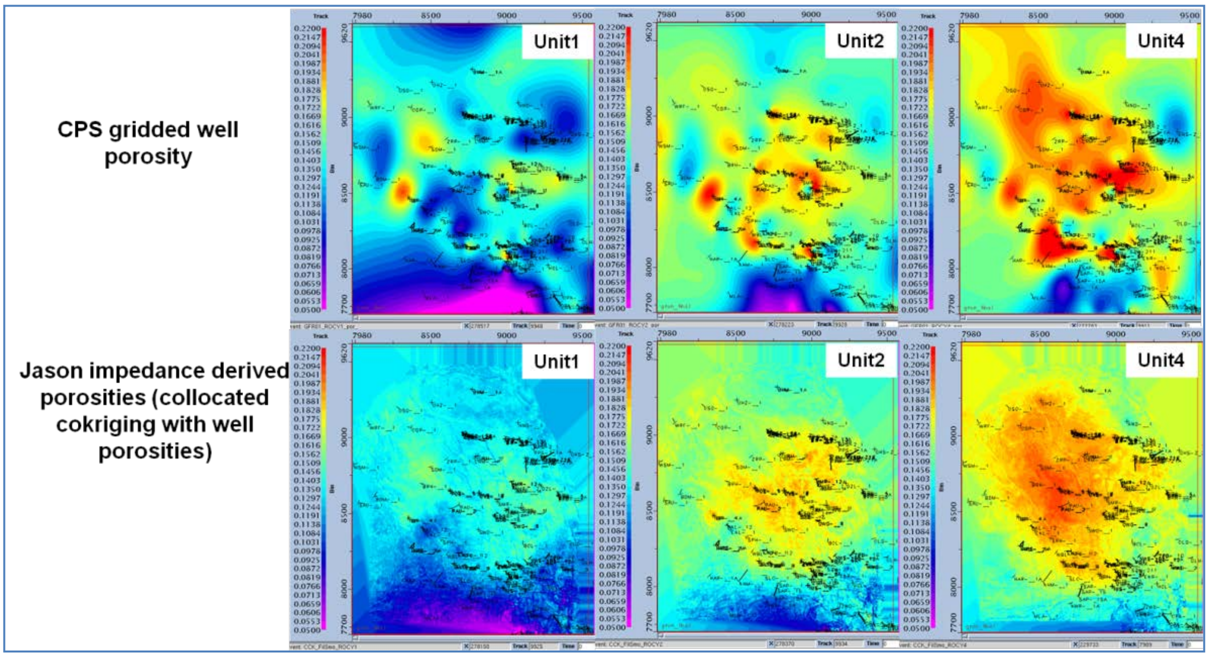


Figure 3-4 Comparison between acoustic impedance logs and acoustic impedance from the inversion

3.2.2 PROMISE INVERSION

Promise Inversion is a stochastic inversion of acoustic impedance and followed by co-simulation of porosity. Regarding the Promise inversion report from NAM, several aspects were reviewed by SGS:

- Promise input model: Porosity maps from Jason were used as input, together with thickness and net-to-gross maps. Secondary reservoir property parameters, interpreted horizons and fluid parameters were also introduced. Sensitivity analyses were performed in order to compare the results when the input parameters are changed. The results show that the deviation between the modeled porosities is less than 1% in five wells. This shows that the inversion is robust.

- Wavelet: The same wavelet It was used as in the Jason inversion, which is considered acceptable by SGS.

- Outputs from the inversion: The outputs were thickness, net-to-gross and porosity maps for each reservoir unit and an AI volume. The difference between the modeled porosities and the log porosities per reservoir unit (26 wells used) are less than 2% (Figure 3-6). A correlation coefficient of 0.8 between the modeled porosity from Promise and the porosity logs is shown for Unit 5 (i.e. the USS2 zone in the Upper Slochteren reservoir). The correlation coefficients of the other units cannot be corroborated from the Promise inversion report.

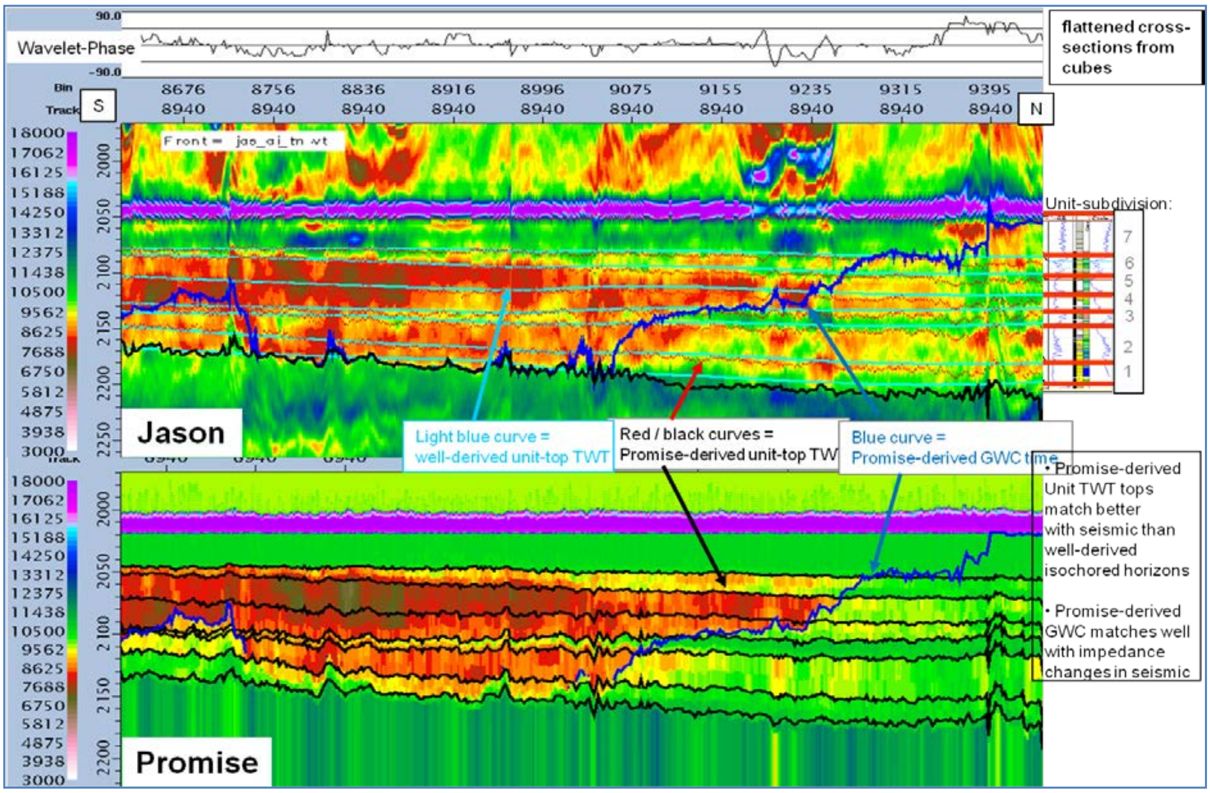


Figure 3-5 Comparison between absolute acoustic impedances - 2003

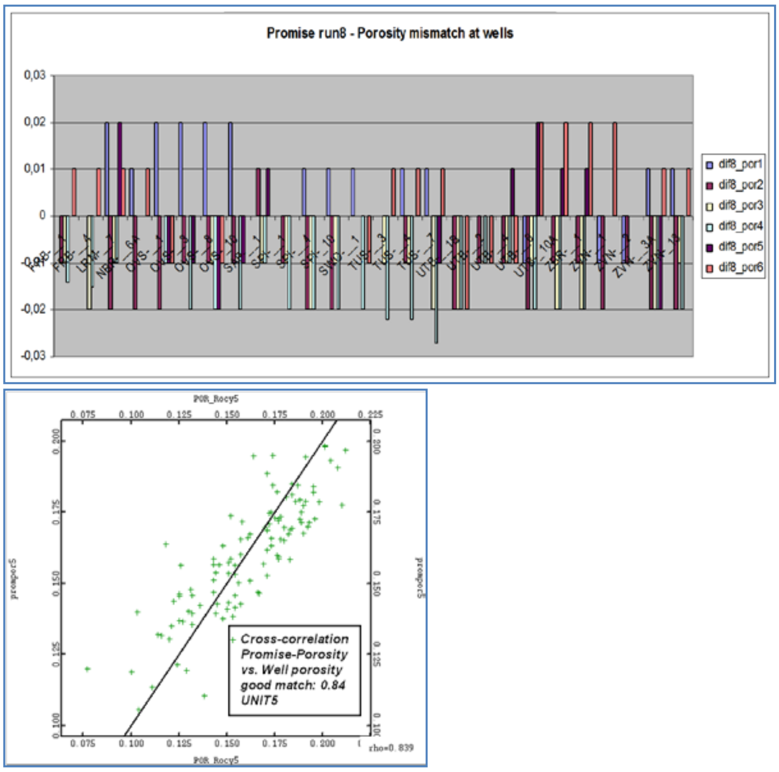


Figure 3-6 Comparison between well-log porosities and porosities estimated from stochastic inversion (average porosity per reservoir unit) – Promise report

- Improved correlation between modeled porosities and log porosities: It was described that the composite property porosity*thickness*net-to-gross has a better correlation (0.97) than the porosity alone. This correlation was improved to 0.998 using kriging with external drift (Figure 3-7). The crossplot of Unit 5 is illustrated in the Promise report, for the other units it is not substantiated.

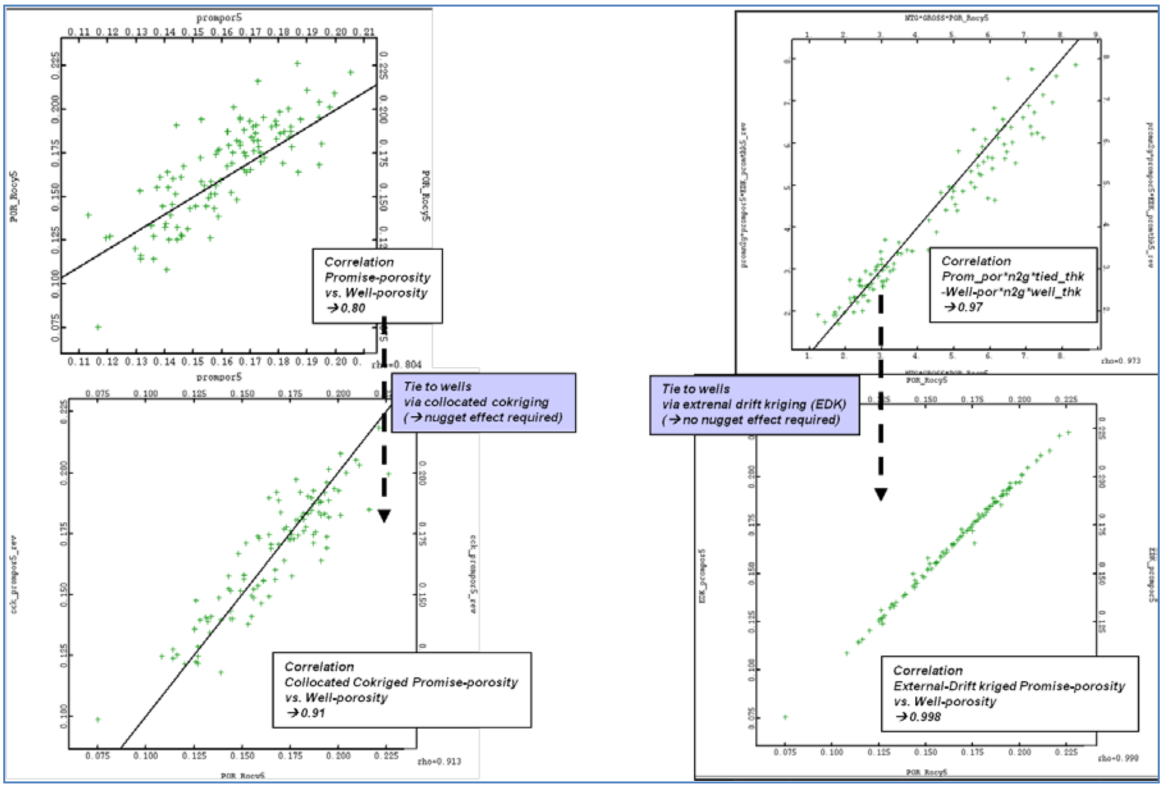
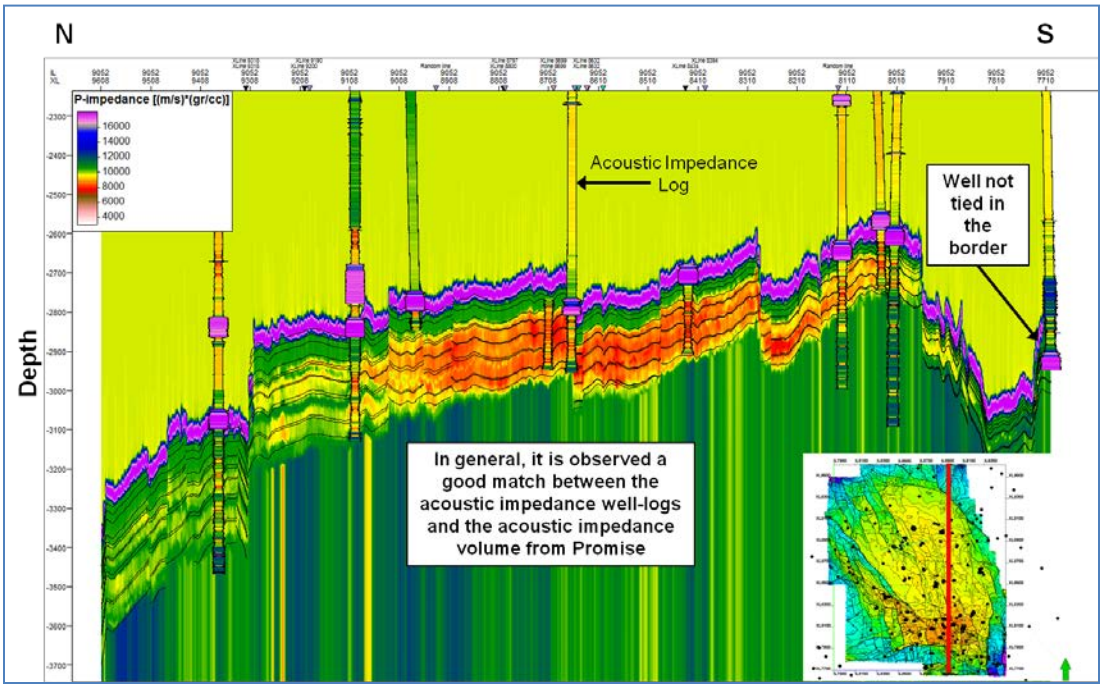


Figure 3-7 **Crossplots of porosities from well-logs versus estimated porosities using collocated cokriging. Crossplots of porosities*thickness*net to gross from well-logs versus estimated porosities*thickness*net using kriging with external drift (average porosity, Unit 5)**

3.3 DATA REVIEWED IN THE 2015 STATIC MODEL

A review by SGS was performed using the first version of the static model supplied. In the second version, similar inversion inputs were used.

- AI Volume from Promise Inversion 2003: This volume was already in depth. It was observed a good match between the AI logs and the modeled AI at well locations.



Acoustic Impedance Log

Well not tied in the border

In general, it is observed a good match between the acoustic impedance well-logs and the acoustic impedance volume from Promise

Figure 3-8 **Comparison between acoustic impedance well-logs and acoustic impedance from stochastic inversion**

- Porosity*thickness*net-to-gross maps (Promise 2003): These maps are different from the porosity maps found in Petrel.

- Porosity maps using AI from Promise: The AI volume was resampled as a coarse grid. Porosity maps were denoted as “April 24 2015”. It is observed by SGS that the AI resolution is reduced due to this resampling. Subsequently a porosity grid was estimated using a linear trend (Pseudo_POR_from_AI=-3.29616E-5 * AI_Promise_2003_clipped2 + 0.448454). These porosity maps (Figure 3-11) show a strong gas imprint, showing higher porosities in the gas zones compared to lower porosities in the water zones.

As illustrated in Figure 3-9 and Figure 3-10, there are different correlations between porosity and impedance in the gas bearing part of the reservoir compared to the water bearing part of the reservoir.

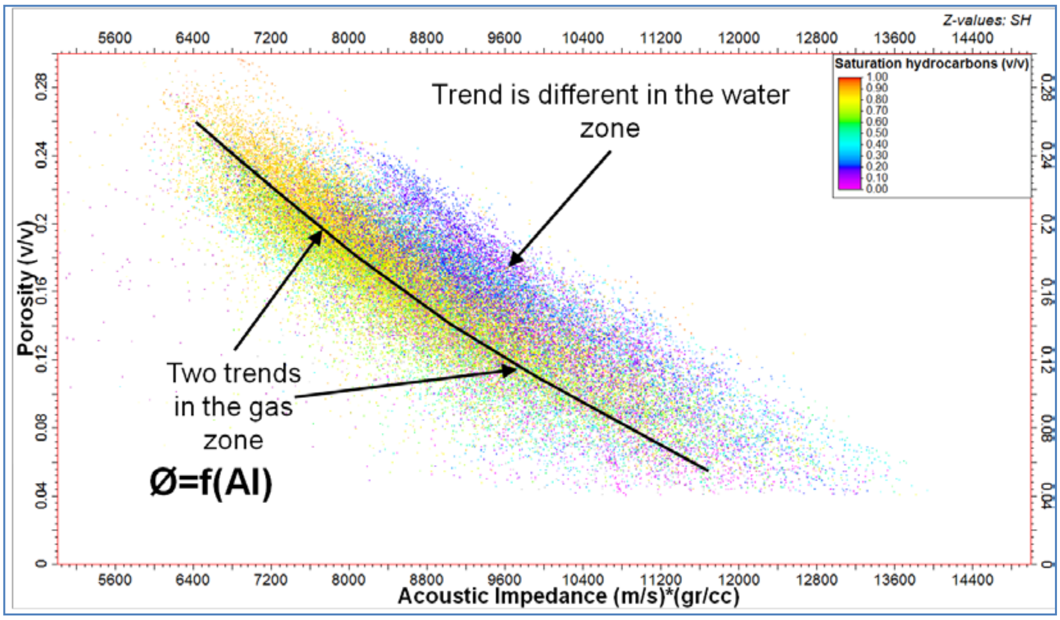
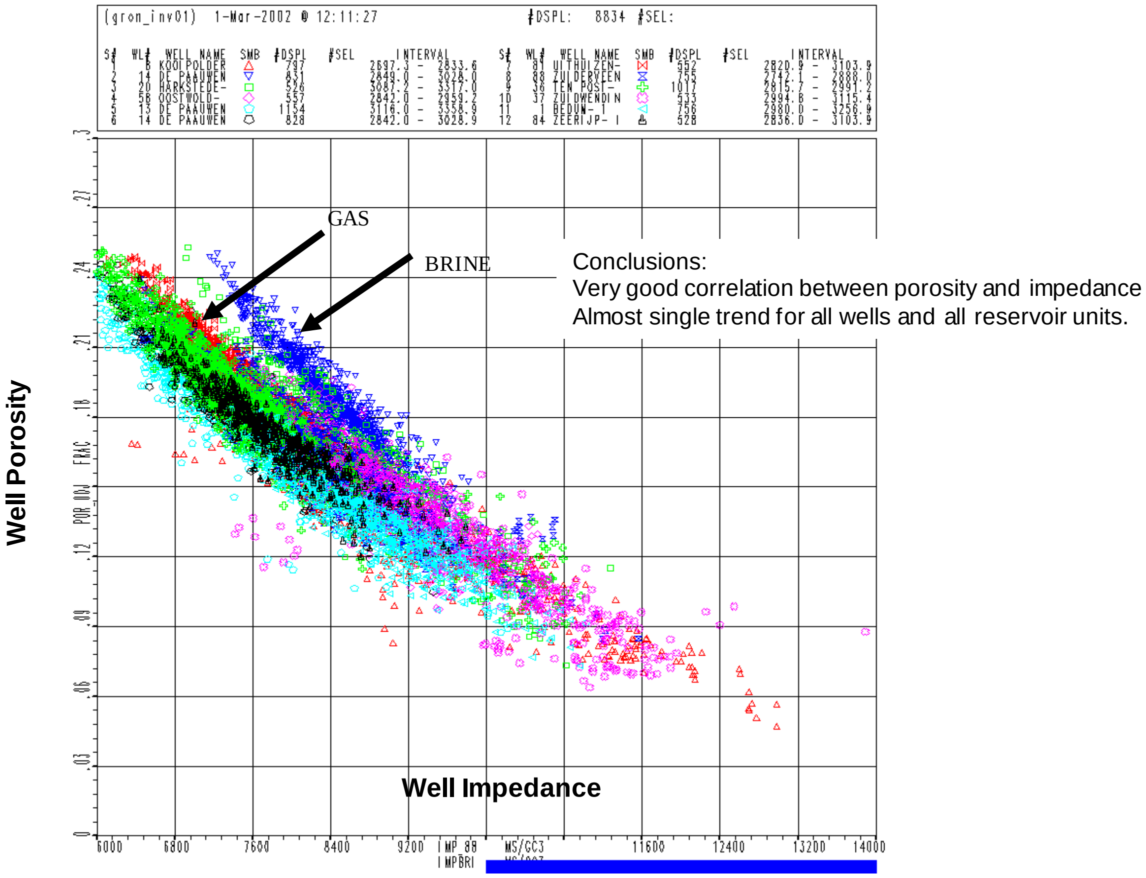


Figure 3-9 Crossplot of porosity versus acoustic impedance coloured with hydrocarbon saturation (all reservoir units are plotted)


(gron_inv01) 1-Mar-2002 @ 12:11:27 #DSPL: 8834 #SEL:

S#	WL#	WELL NAME	SMB	#DSPL	#SEL	INTERVAL	S#	WL#	WELL NAME	SMB	#DSPL	#SEL	INTERVAL
1	6	KOOIPOLDER	△	797		2697.3 - 2833.6	7	81	UITHUIZEN-	⋈	552		2820.9 - 3103.9
2	14	DE PAAUWEN	▽	831		2849.0 - 3028.0	8	88	ZUIDERVEEN	⧖	755		2742.1 - 2888.0
3	20	HARKSTEDE-	□	526		3087.2 - 3317.0	9	36	TEN POST-	✚	1017		2815.7 - 2991.2
4	56	OOSTWOLD-	◇	557		2842.0 - 2959.2	10	37	ZUIDWENDIN	✲	533		2994.6 - 3115.4
5	13	DE PAAUWEN	⬠	1154		3116.0 - 3358.9	11	1	BEDUM-1	◁	756		2980.0 - 3256.9
6	14	DE PAAUWEN	○	828		2842.0 - 3028.9	12	84	ZEERIJP-1	♙	528		2836.0 - 3103.9

Conclusions:
Very good correlation between porosity and impedance
Almost single trend for all wells and all reservoir units.

Figure 3-10 Crossplot of porosity (log) versus acoustic impedance (log) - 2003

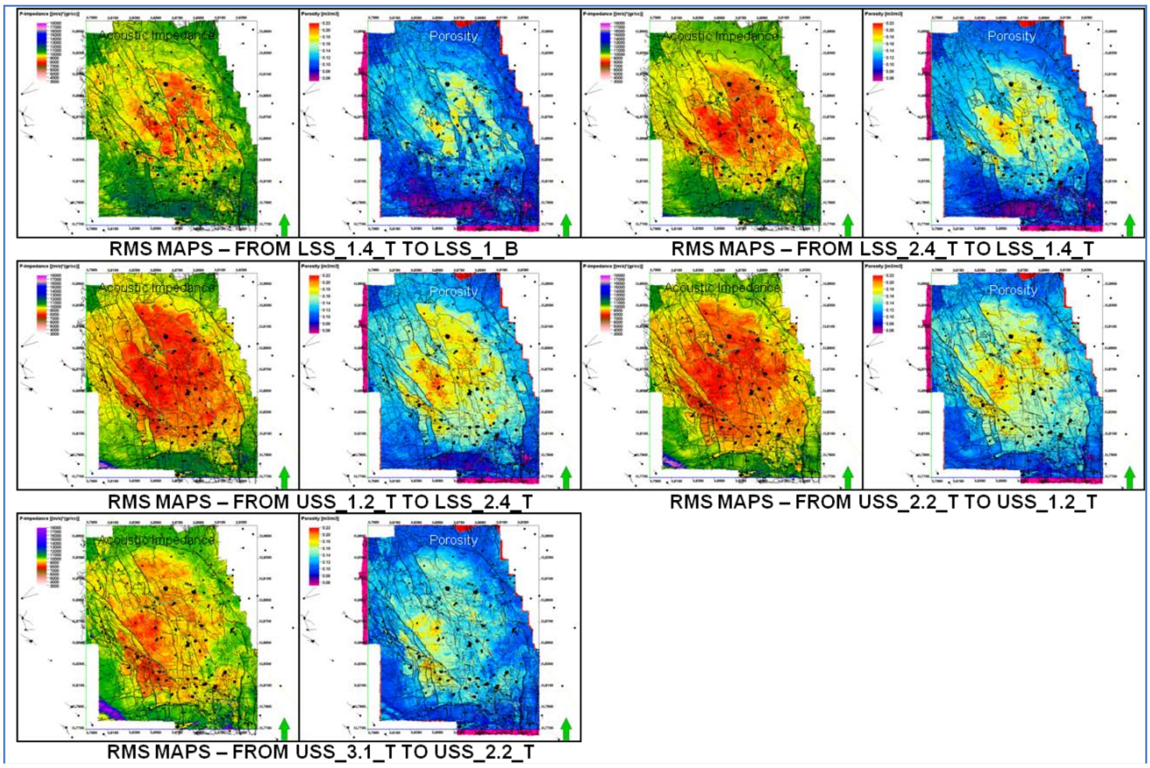
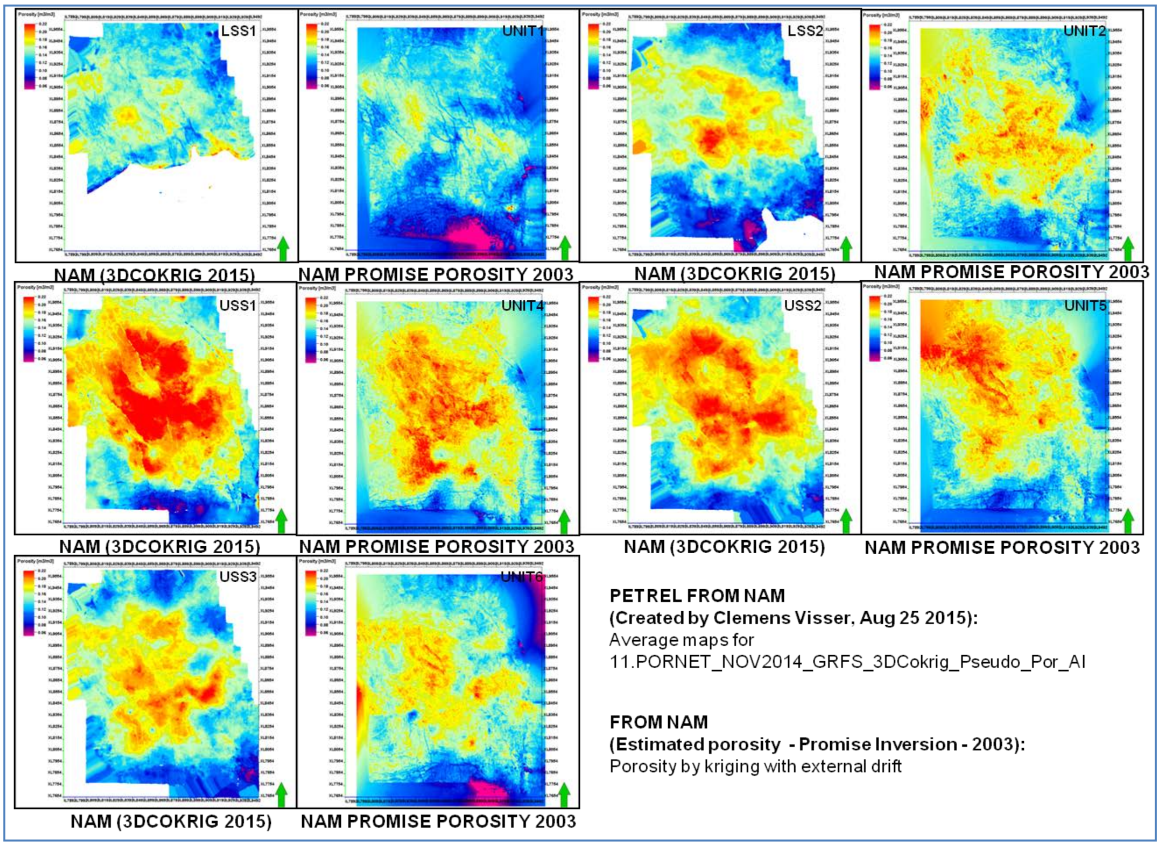


Figure 3-11 Comparison between acoustic impedance maps and porosity maps estimated using only linear gas trends

- <u>Porosity maps using 3DCokriging:</u> These maps (denoted with "August 25 2015") show more uniform porosities distributed in over gas bearing and water bearing zones compared to the maps created in 2003. Figure 3-12 illustrates this. The red colours indicate the highest porosities.



PETREL FROM NAM
(Created by Clemens Visser, Aug 25 2015):
Average maps for
11.PORNET_NOV2014_GRFS_3DCokrig_Pseudo_Por_AI

FROM NAM
(Estimated porosity - Promise Inversion - 2003):
Porosity by kriging with external drift

Figure 3-12 Comparison between porosity maps. Left pictures: 3D Cokriging 2015; right pictures: kriging with external drift 2003

Comparisons between porosity from well logs, both on the fine grid and on the coarse grid, are shown in Figure 3-13 and Figure 3-14. Overall, the porosity of the wells correspond to the porosity in the model. In the gas bearing part of the reservoir it appears to correspond better compared to the water bearing part of the reservoir.

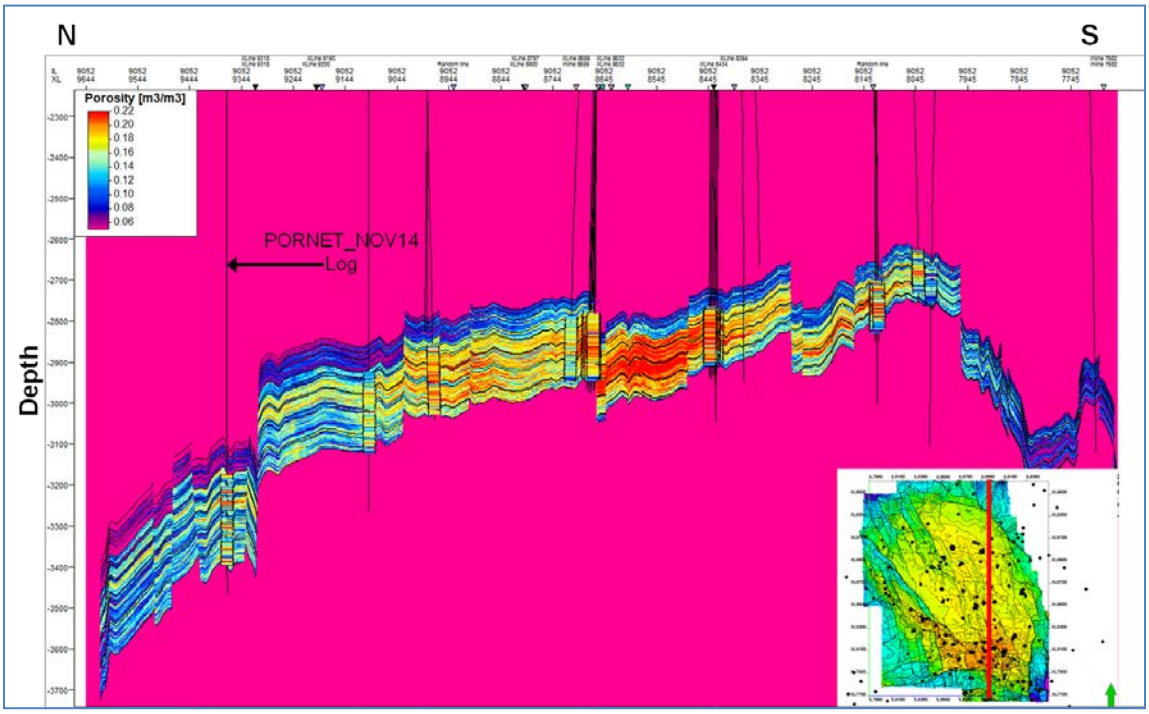


Figure 3-13 Comparison between porosity of well-logs and modeled porosity (fine grid)

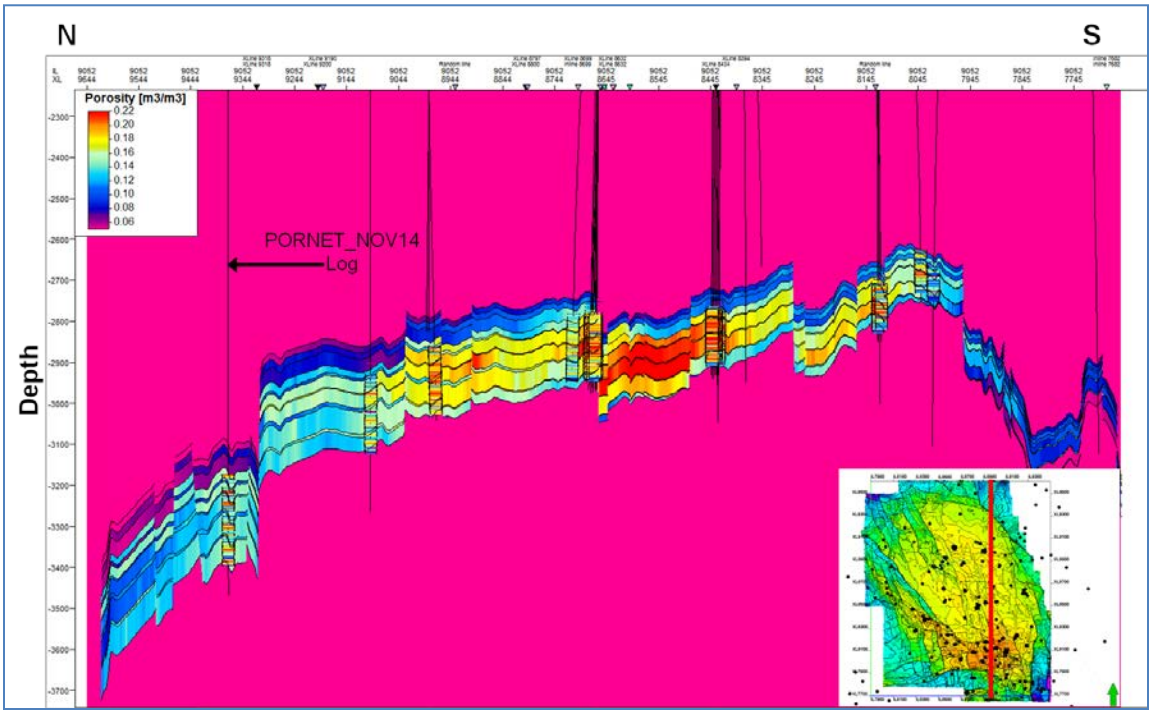


Figure 3-14 Comparison between porosity of well-logs and modeled porosity (coarse grid)

3.4 OBSERVATIONS AND CONSIDERATIONS

The CSSI-plus-collocated co-kriging approach is relatively straightforward. This method captures lateral variability but tends to smooth and average the data. The fit between inverted acoustic impedance and well log acoustic impedance is good in the reservoir units. As expected, resolution of the inverted impedance is lower than that of the well log. The kriged porosity maps incorporate heterogeneities introduced by the seismic information. However, this method does not handle the vertical scale difference among well logs, the porosity model, and the seismic does not account for the scatter between seismic-derived acoustic impedance and porosity. As a result, lateral and vertical heterogeneities in porosity are smoothed.

Stochastic inversion of acoustic impedance (=Promise) and followed by co-simulation of porosity, thickness and net-to-gross handles the scaling issue much better than as described in the paragraph above (seismic = poor vertical resolution, well data = poor lateral resolution). Models generated through stochastic inversion are consistent with well information, honour the seismic data, and retain the geostatistical properties of each parameter at the scale of the model

It is important to note that the trend of acoustic impedance versus porosity in the gas bearing part of the Groningen field reservoir is different to the trend in the water bearing part of the reservoir. In order to corroborate this, a crossplot of porosity logs versus acoustic impedance logs coloured with hydrocarbon saturation can be built (Figure 3-9) using several wells at the reservoir interval. In this crossplot it is observed by SGS that the gas zone has two linear trends and the water zone has one linear trend. When these different trends would be taken into consideration in the determination of porosity, the strong gas imprint observed in the porosity maps may disappear, thus correcting the porosities in the water zones.

3.5 DETAILED CONCLUSIONS & RECOMMENDATIONS

Perform detailed analysis of core and rock physics diagnostics to the well-log data to identify relationships between seismic response and various reservoir parameters, and the derivation of an acoustic impedance – porosity trend.

Porosity distribution in the water bearing part of the reservoir needs more attention in future inversion and porosity modelling. Porosity distribution in the water bearing part of the reservoir has not been clearly validated during earlier studies in absence of clear comparison of well porosity logs to the model below the FWL.

For reservoir modelling, the porosity maps should be used, not the acoustic impedance maps, in view of the clear gas imprint.

4 PETROPHYSICS

4.1 ITEMS REVIEWED

No new petrophysical analysis on wells has been performed by NAM since the 2012 modelling. Three new wells were drilled, which is a very low number compared to the more than 300 wells already available. SGS has not reviewed in detail the three new well log interpretations.

The aspects reviewed by SGS on petrophysics are changes to the modelling as indicated by NAM:

- NTG cutoffs
- Permeability model
- Saturation height functions

These modelling elements are independent from each other and have been reviewed separately. NAM provided only documents to support the changes, and a static Petrel model.

The well data used in the evaluations had been provided separately by NAM in 2013 and it was also partially included in the 2015 static Petrel model. The evaluations were carried out by SGS using Techlog and Interactive Petrophysics (IP) software.

No feed-back loop with dynamic modelling has been performed.

4.2 NTG DETERMINATION

4.2.1 ANALYSIS

The net-to-gross determination for the Groningen field is described in by NAM in [2] and [3]. It was based on core data from eight wells. Four rock types were defined from the core analysis and the gamma ray log was normalized. Through this method, a Vclay cut-off value of 0.41 was established for the Slochteren formation (ROSL) and of 0.435 for the Ten Boer formation (ROCLT). This Vclay cut-off was used for the NTG determination.

In a more recent study (2014, [3]) NAM reported to have a quality check performed on more than twenty wells. NAM concluded slightly lower values for the Vclay cut-off (= normalized gamma ray cut-off). This time the cut-off for the NTG was 0.38 for the Slochteren and 0.51 for the Ten Boer. No detailed information was provided by NAM on the method employed for neither this particular study nor which wells were involved.

SGS performed a statistical sensitivity analysis on Vclay cut-off for the Slochteren using the EHC for the present model and found it is consistent with 0.41 as shown in Figure 4-1.

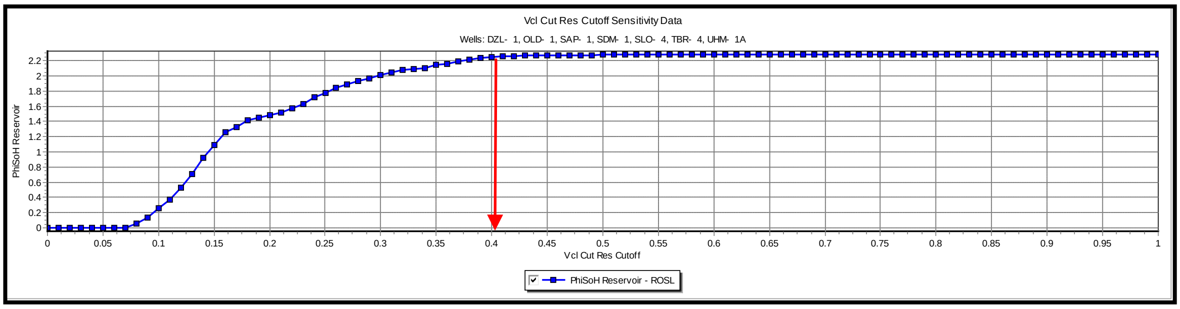


Figure 4-1 **Sensitivity analysis for Slochteren formation Vclay cut-off vs. EHC**

NAM reported [3] to have performed an additional quality check using 350 wells with petrophysical facies in Petrel. Cut-off values resulting were 0.42 for the Slochteren and 0.435 for the Ten Boer respectively.

NAM's conclusion appeared to be to continue using the original cut-off values, but this is not explicitly documented.

4.2.2 OBSERVATIONS

From the cored wells location map over the field, Figure 4-2, it is indicated how the cored Slochteren reservoir (used for NTG determination) is represented at the field level: the eight cored wells are not evenly distributed and several of them are close to the flanks. Table 4-1 and Figure 4-3 show that the statistics will be biased to a few wells with long cored sections and this amplifies the issue of uneven geographical distribution of cored wells. The central part of the field, containing most of the GIIP, is not representatively captured in the data availability. More emphasis is put, due to the use of all available data without weighting factors, on the northern and southern sectors and the flanks. While reservoir properties are better in the central part of the field, a higher NTG scenario for the main reservoir is possible if more weight is put on the central area of the Groningen field.

It has to be highlighted that while applying the cut-offs, no distinction was made by NAM between:

- Layered shale (this is expected to be the main component in view of sedimentology)
- Dispersed shale.

The 2014 work on NTG could not be properly quality checked as no documentation was available. Analysis by SGS showed that while differences are very small, the properties established for the 2014 work would give a lower NTG than the 2012 model.

The additional analyses by NAM give results of Vclay cut-off within the uncertainty range as investigated by SGS in 2013 (ref. [1], section 8.2.1).

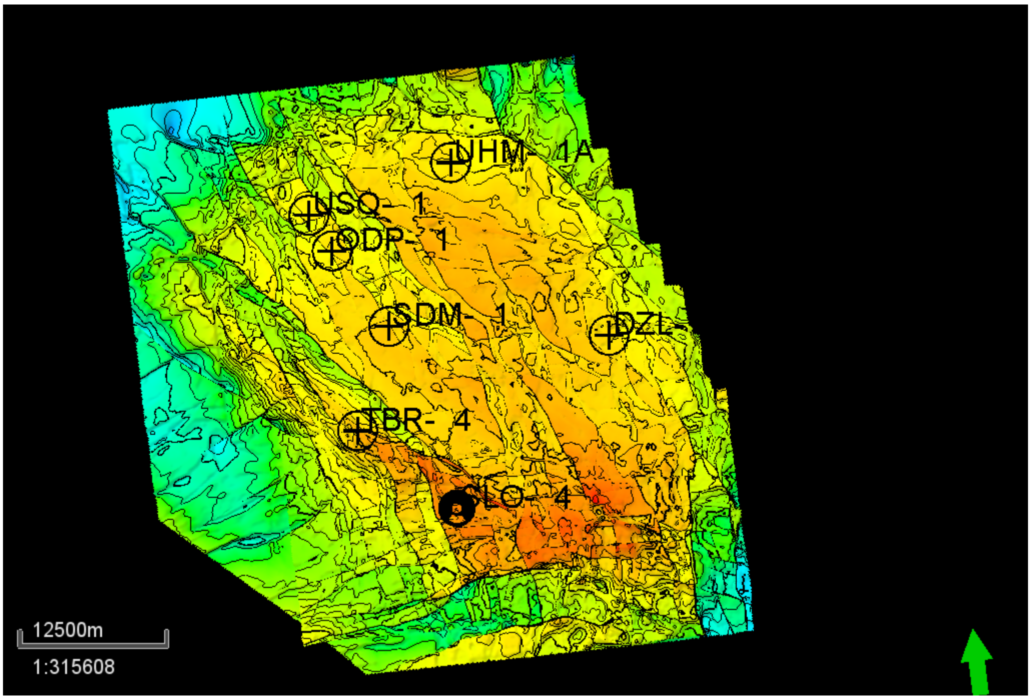


Figure 4-2 **Location of the cored wells used for NTG determination**

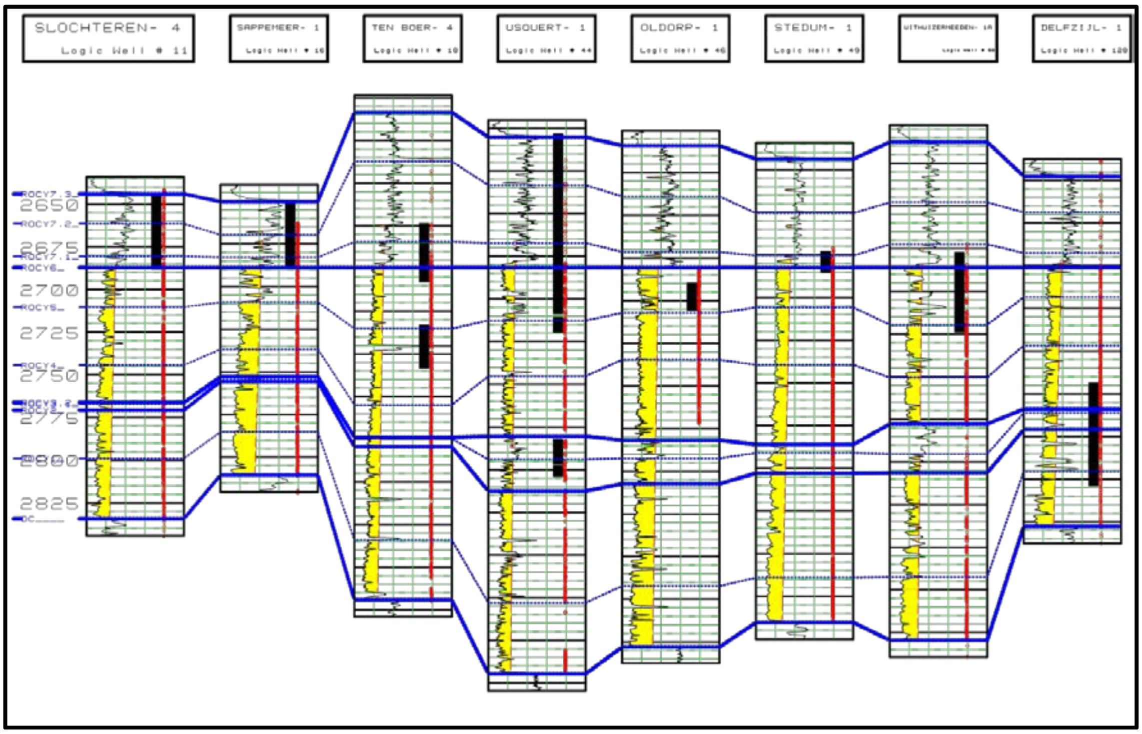


Figure 4-3 **Cored sections used for 2014 / 2015 NTG study by NAM, indicated by black flags**

Table 4-1 **Statistics of the cored wells used for NTG determination (ROSL)**

Well	Length cored interval	weight %	Location
SLO-4	1.2	0.4	
TBR-4	59.2	19.6	West flank
USQ-1	122.6	40.6	North-West flank
ODP-1	18	6.0	
SDM-1	3.2	1.1	
UHM-1A	38	12.6	North flank
DZL-1	60	19.9	East flank
Total	302.2		

4.2.3 DETAILED CONCLUSIONS AND RECOMMENDATIONS

SGS supports the (previous) Vclay cut-offs for NTG determination, 0.41 for the Slochteren formation and 0.435 for the Ten Boer formation. Overall the approach taken by NAM is considered adequate, in view of the data limitations.

As in the 2012 model, the eight cored wells used for the NTG determination are not evenly distributed across the field. A higher NTG for the main reservoir could be possible if the central area would be better represented / weighted in data and data analysis.

The NTG cut-offs applied by NAM in the static modelling should be more clearly documented.

4.3 PERMEABILITY MODELLING

4.3.1 ANALYSIS AND OBSERVATIONS

The porosity-permeability relationship was updated by NAM, as part of the 2015 modelling update, for the Sand facies, with different relationships above and below the FWL, and with different relationships for porosity above and below 15%, and including a depth trend, ref. [4]. Three new porosity-permeability transforms are introduced in 2015 for the Sand facies. The porosity-permeability transforms were not changed for Shale and Conglomerate facies.

The recommendations from SGS in 2013 (ref. [1], section 8.2) have been taken into account for 2015 NAM model.

Documentation about functions used is ambiguous; only the “Python script” in the Petrel model reveals what has been applied.

The new permeability model shows improvement to the 2012 model (based on comparison to the permeability from core by SGS) and overall changes are not large; see Figure 4-4 and Figure 4-5. Also the statistics comparison in Table 4-2 between core permeability and the two models shows that the 2015 model has a closer match to core values.

Table 4-2 Statistics comparison for 19 cored gas wells between 2012, 2015 models and core permeability

Permeability Model	Mode	Median	Arithmetic mean	Geometric mean	Variance	St. Dev.
Core Permeability	109.9	73.4	182.6	49.0	95332	309
PERMNET 2012	85.7	55.8	160.1	40.2	110064	332
PERMNET 2015	NA	66.3	169.1	45.6	92779	305

The 2015 Petrel static model contains two permeability curves named PERMNET 2015 (Final Permeability including scatter correction for log-normal distribution), and PERMNET_NOV14.

PERMNET_NOV14 is after poro-perm transform on the wells using a Python script but before applying “random scatter” – equivalent to curve PERMHNET in 2012 (naming of PERMNET_NOV14 is confusing), see Figure 4-6 and Figure 4-7.

A “random scatter” was applied resulting in a property PERMNET in Petrel.

The Petrel curve PERMNET was used for upscaling to the dynamic model:

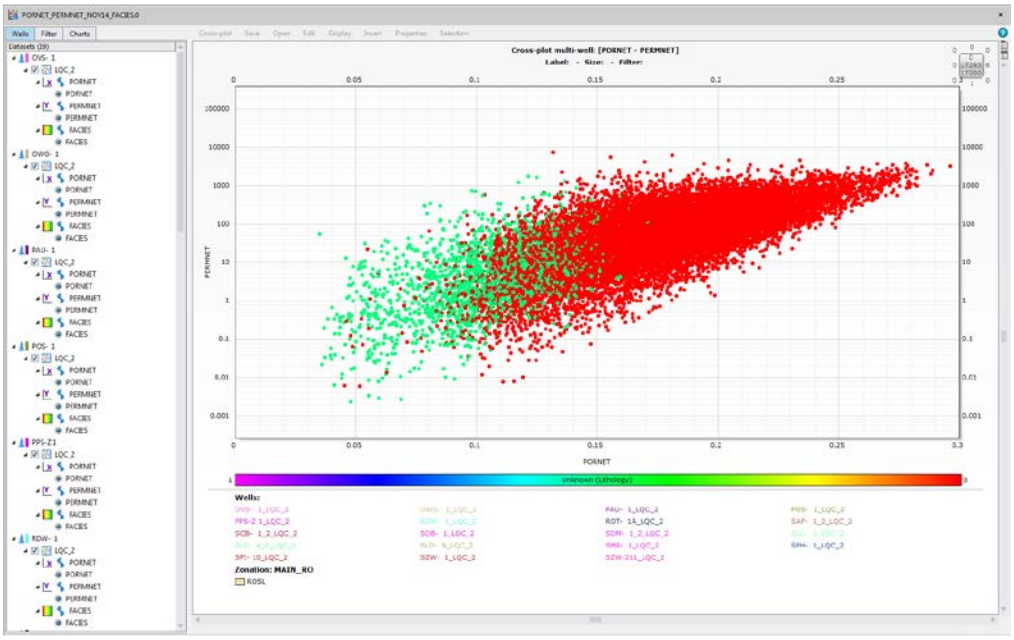


Figure 4-4 PORNET vs. PERMNET 2012

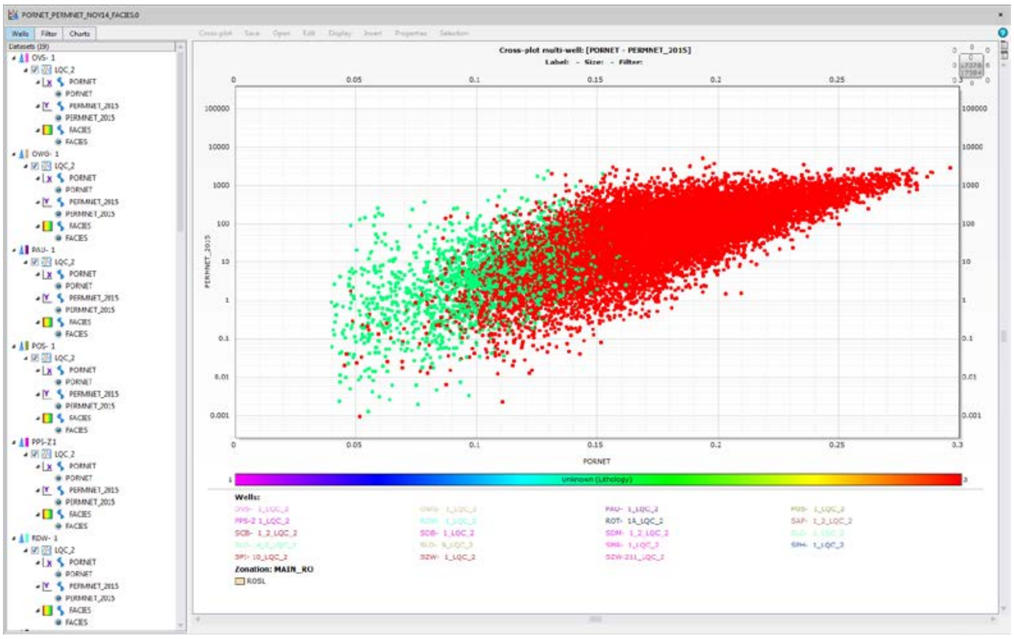


Figure 4-5 PORNET vs. PERMNET 2015

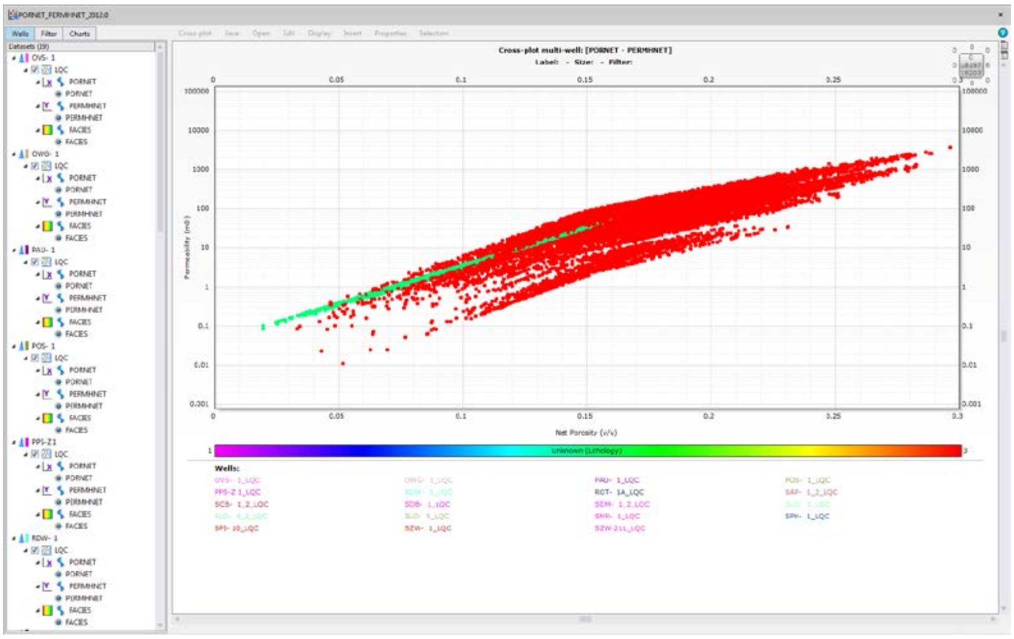


Figure 4-6 PORNET vs. PERMHNET 2012

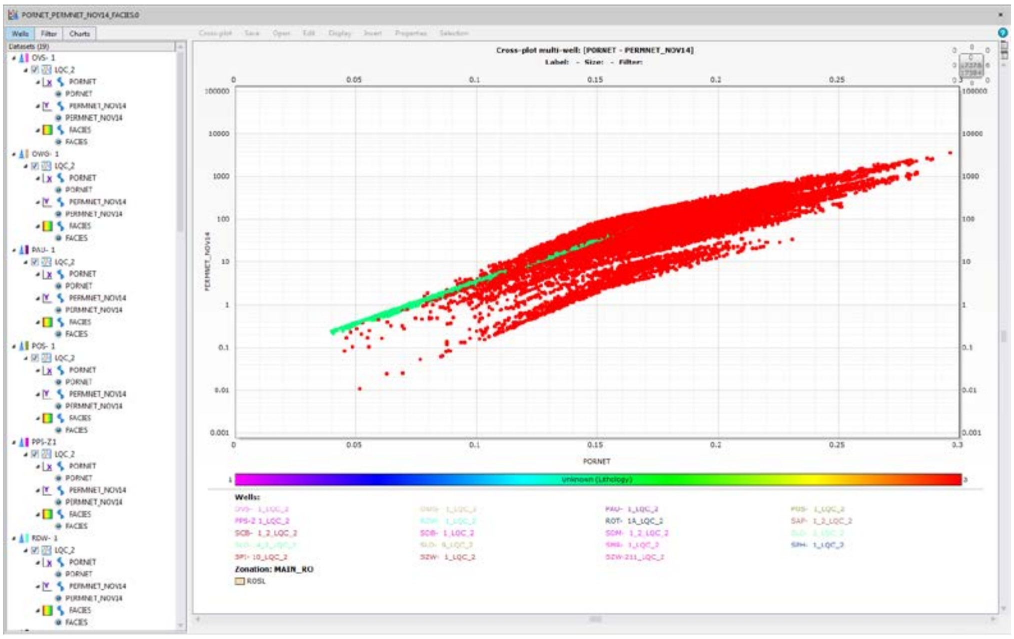


Figure 4-7 PORNET vs. PERMNET NOV2014

It is observed from visual inspection of the porosity-permeability crossplot (Figure 4-5) that there is a very wide range of permeability values for each porosity; this is not expected from the geology and puts doubt by SGS on the “random scatter” method applied:

- for 15% porosity, permeability ranges from ~0.5 mD to ~1000 mD
- for 20% porosity, permeability ranges from 10 mD to ~ 2000 mD

Applying the random scatter better captures the uncertainty range on the input data, but its relevance after upscaling to the dynamic model is questionable:

- the scatter observed in core data may be partially related to facies changes, to regional changes, to additional permeability-depth trends, etcetera
- applying the scatter to the model implicitly assumes there is no other relationship between porosity and permeability than in the functions applied
- applying the scatter might result in overestimation of heterogeneity
- due to large cell size in the dynamic model it is questionable if applying random scatter has any effect on the permeability in the coarse scale grid – this has not been investigated by SGS.

It is further observed by SGS that the PERMNET in the 2015 model shows more scatter than the PERMNET in the 2012 model: Figure 4-8.

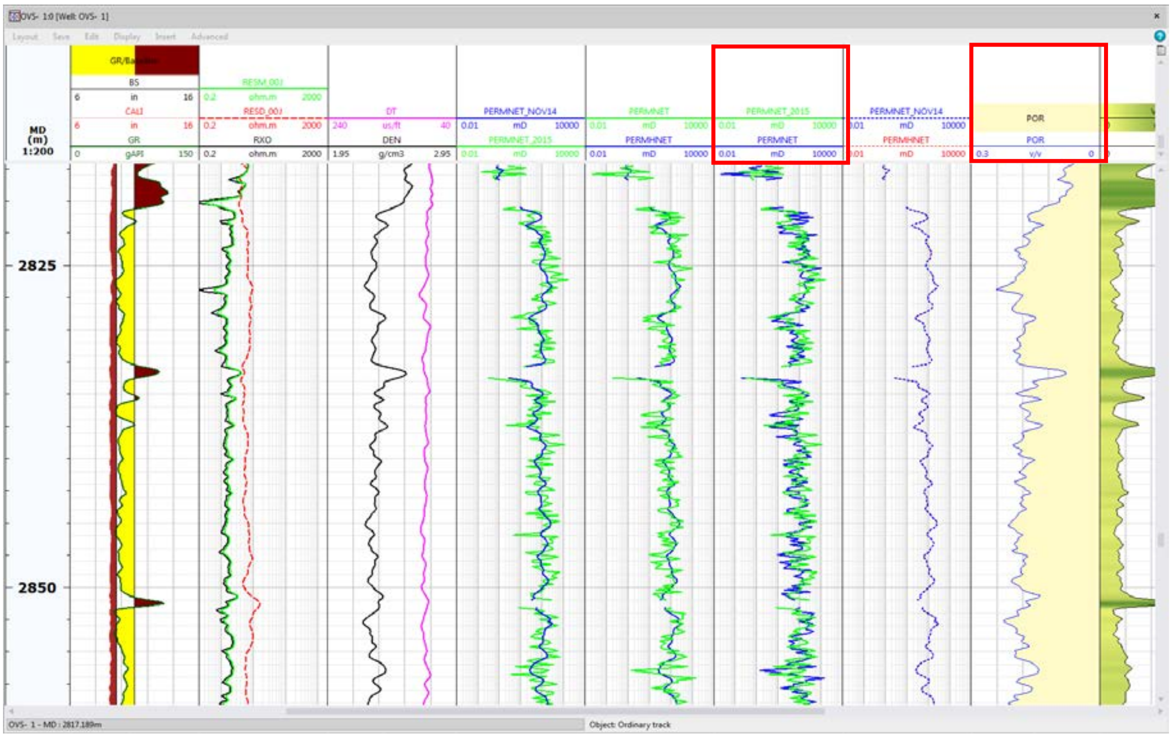


Figure 4-8 **PERMNET of 2015 (green) is compared with the PERMNET of 2012 (blue), showing that PERMNET 2015 is more irregular and less following porosity (example well OVS-1)**

4.3.2 DETAILED CONCLUSIONS AND RECOMMENDATIONS

The 2015 permeability model shows improvement over the 2012 model, and the update is in line with recommendations from SGS in 2013.

The 2015 permeability model should be more clearly documented.

Application of random scatter on permeability for population of the static model is a questionable method.

4.4 SATURATION HEIGHT MODELLING

4.4.1 ANALYSIS AND OBSERVATIONS

The saturation height function (SHF) was updated by NAM, as part of the 2015 modelling update, ref. [5]. The new model for the SHF is the result of converting the original Lambda function to a Brooks-Corey function to ensure the consistency between the SHF and Swirr. In the previously used Lambda function the Swirr goes towards 0 as the HAFWL increases to infinity and therefore it could not be used without Swirr conditioning. The Brooks-Corey function is conditioned for the Swirr, this function better represents rock physics.

NAM compared the functions to capillary pressure measurements, but has not used this data in a quantitative analysis.

The recommendations from SGS in 2013 (ref. [1], section 9) have been taken into account for 2015 NAM model. Limitations on data availability, as discussed in the 2013 review, remain.

Several plots were generated by SGS to quality check if the updated water saturation modelling is a reasonable match to the data (e.g. logs).

4.4.1.1 *Saturation Height Functions*

The 2015 functions show a minor increase in hydrocarbon saturation compared to the 2012 functions, Figure 4-9, but there is no major difference between the functions, visually they are very similar.

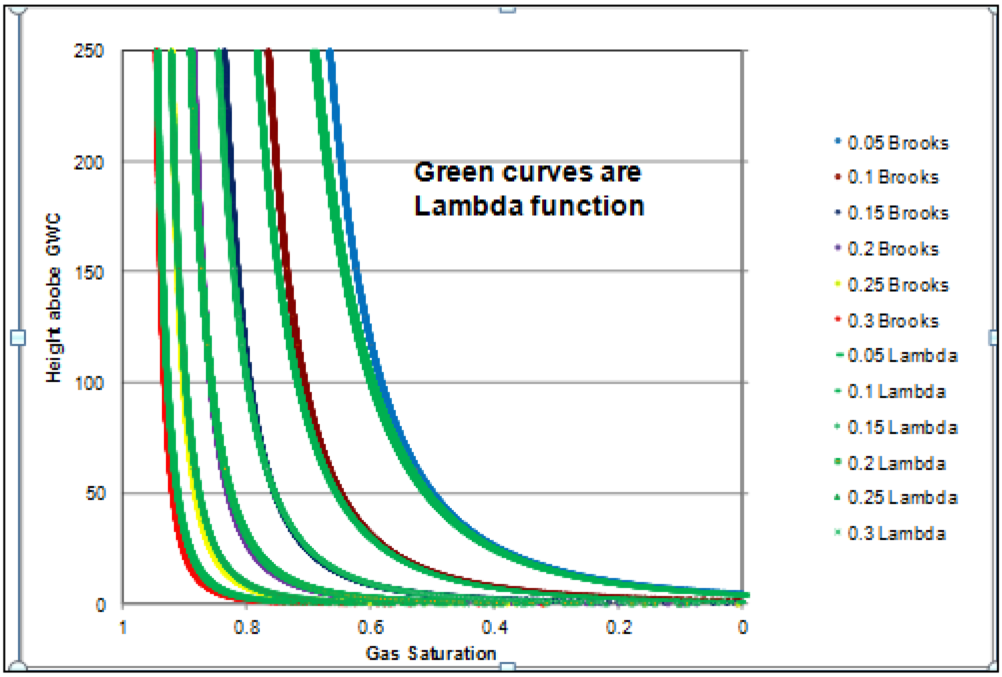
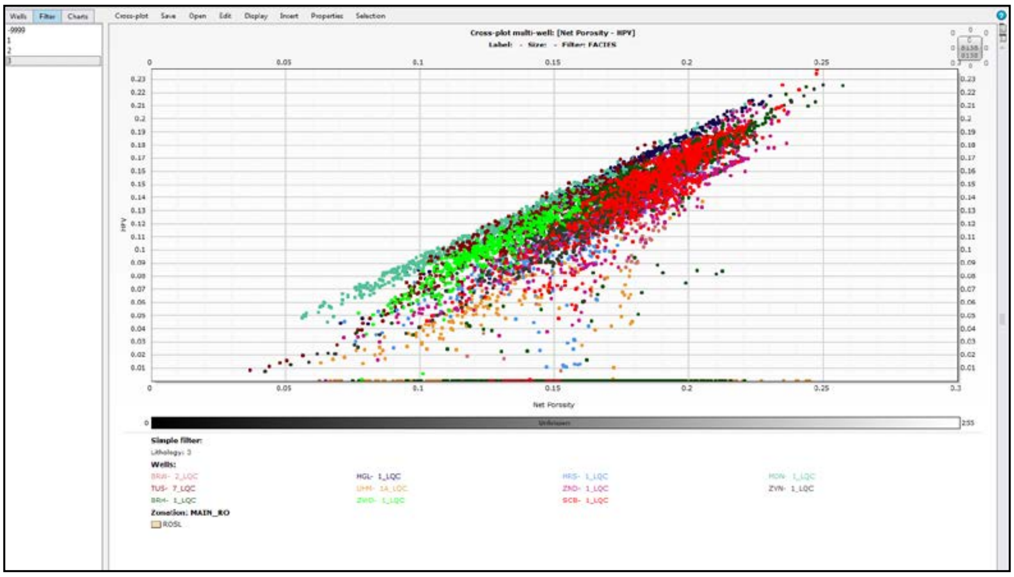


Figure 4-9 Comparison between Brooks-Corey and Lambda saturation height functions

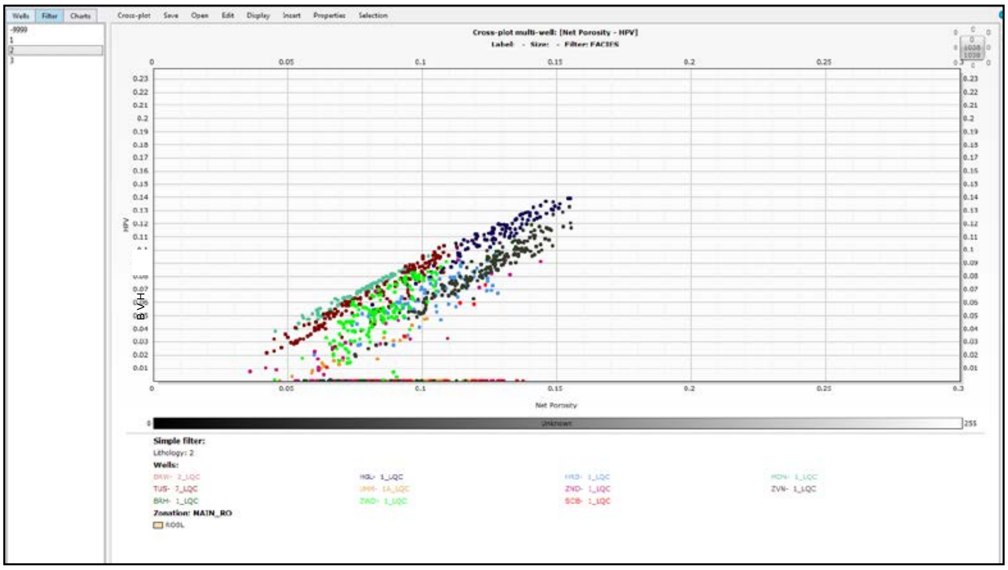
4.4.1.2 *Porosity vs. BVH Plot*

This plot was used by SGS to check the rock quality dependency based on the facies log (shale, sand and conglomerate). Porosity vs. BVH were plotted for different facies in ROSL reservoir. Figure 4-10, Figure 4-11, Figure 4-12 and Figure 4-13 show multiple trends between 11 wells and within the well, indicating different rock quality, even for one facies. Maximum porosity for facies 2 (conglomerate) is about 15%, except for ZWD-1 and UHM-1 where the maximum porosity is about 10%. Porosity range for sand (facies 3) is 5-25%, while the range for conglomerate is 5-15%.



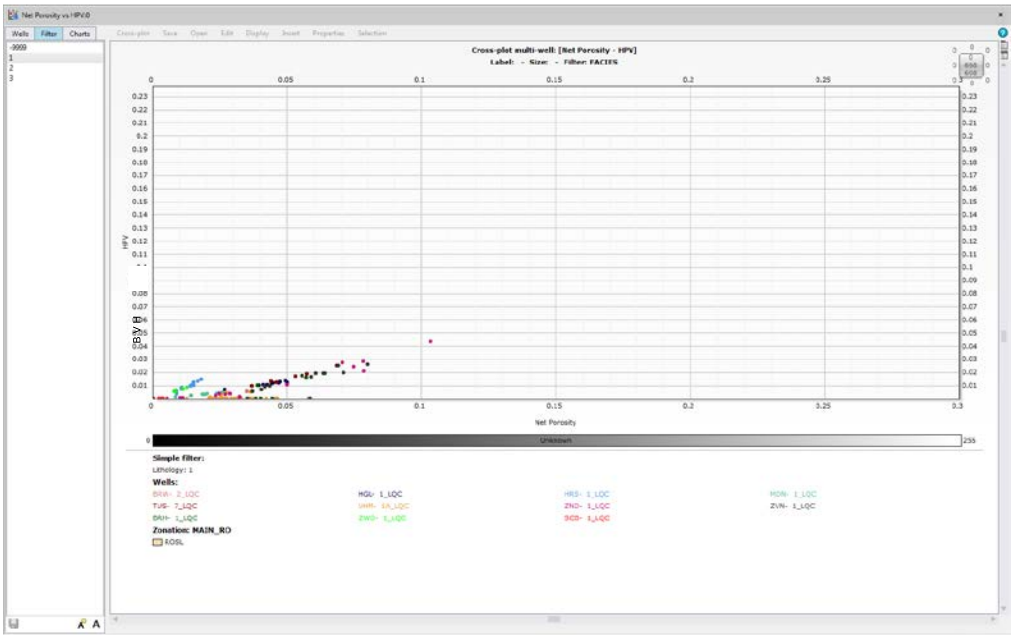
Simple filter:
Lithology: 3
Wells:
BRW- 2_LQC
TUS- 7_LQC
BRH- 1_LQC
HGL- 1_LQC
UHM- 1A_LQC
ZWD- 1_LQC
HRS- 1_LQC
ZND- 1_LQC
SCB- 1_LQC
MON- 1_LQC
ZVN- 1_LQC
Zonation: MAIN_RO
ROSL

Figure 4-10 PHI vs. BVH for Facies 3 Sand



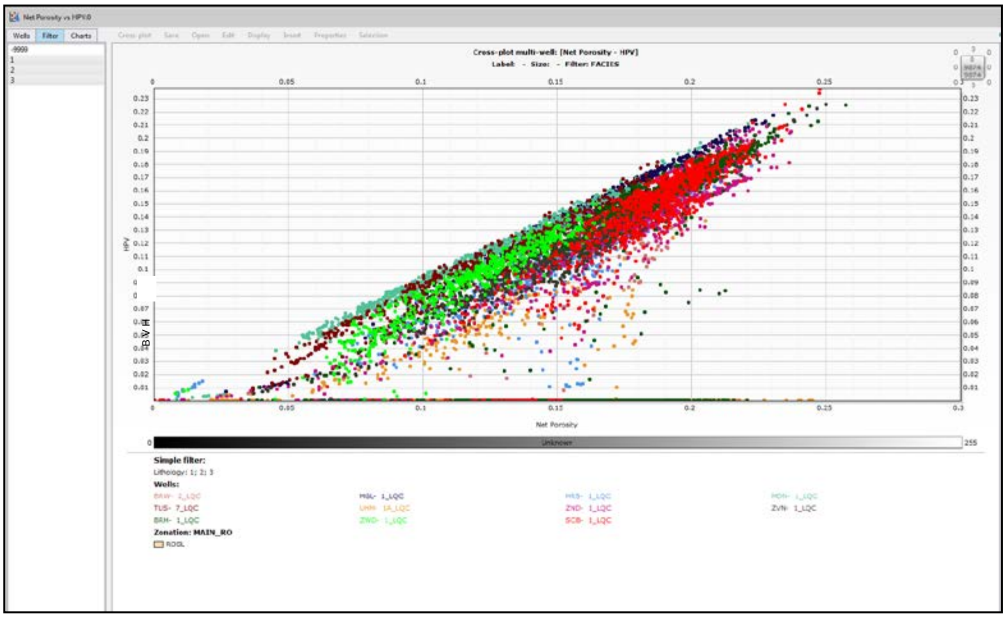
Simple filter:
Lithology: 2
Wells:
BRW- 2_LQC
TUS- 7_LQC
BRH- 1_LQC
HGL- 1_LQC
UHM- 1A_LQC
ZWD- 1_LQC
HRD- 1_LQC
ZND- 1_LQC
SCB- 1_LQC
MON- 1_LQC
ZVN- 1_LQC
Zonation: MAIN_RO
ROSL

Figure 4-11 PHI vs. BVH for Facies 2 Conglomerate.



Simple filter:
Lithology: 1
Zonation: MAIN_RO

Figure 4-12 PHI vs. BVH for Facies1 Shale.



Simple filter:
Lithology: 1; 2; 3
Zonation: MAIN_RO

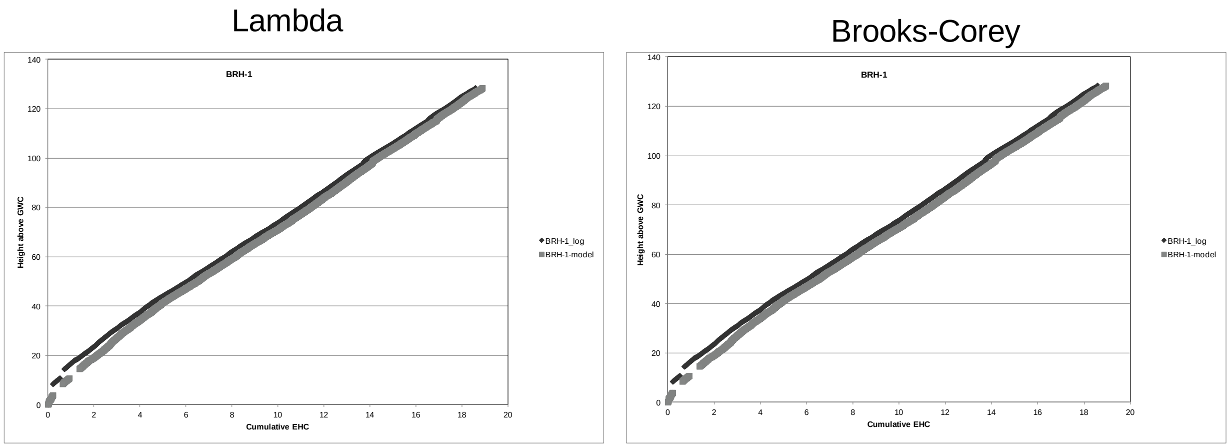
Figure 4-13 PHI vs. BVH for All facies.

4.4.1.3 Cumulative EHC_model vs. EHC_log plot

This plot was used by SGS to check the height dependency and volume bias. A comparison was made between the 2015 and 2012 model for the 11 wells used to build the SHF, see Figure 4-14 for one of the wells. These plots show the cumulative EHC calculated from the porosity log and SHF (“model”) and the EHC of the CPI log, as a function of height above the FWL.

Most of the wells have a very good match between cumulative EHC_model vs. EHC_log, except for wells UHM-1A and ZWD-1, which have a low porosity (<10%) for conglomerate, see Figure 4-11. For these two wells, both Lambda and Brooks-Corey functions have a similar deviation.

The difference between 2012 and 2015 SHF is not significant, as seen from these plots.


Lambda

Brooks-Corey

Figure 4-14 **Comparison between cumulative EHC for Left: Lambda and Right: Brooks-Corey saturation height functions, and compared to interpreted well logs (example well BRH-1)**

4.4.2 DETAILED CONCLUSIONS AND RECOMMENDATIONS

SGS supports the current saturation-height functions used, so the change from a Lambda function to a Brooks-Corey function.

The effect on GIIP will be minor.

5 STATIC MODEL

5.1 ITEMS REVIEWED

The review is based on the Petrel project file for the Groningen field static model from NAM "2015_GFR_2ndPass2SGS.pet", also denoted as the "2015 2nd pass model" and further referred to in this report as "2015 static model". This model has been used as the input for the dynamic model used for the Winningsplan 2016.

Items reviewed in the 2015 static model include:

- Trend maps used in property modelling
- The implementation of CPI logs in property modelling
- The use of well tops in the construction of structural model
- Gas Initially In Place

The permeability distribution has not been reviewed from the static modelling point of view. It is addressed in the dynamic modelling section of this report (see chapter 6).

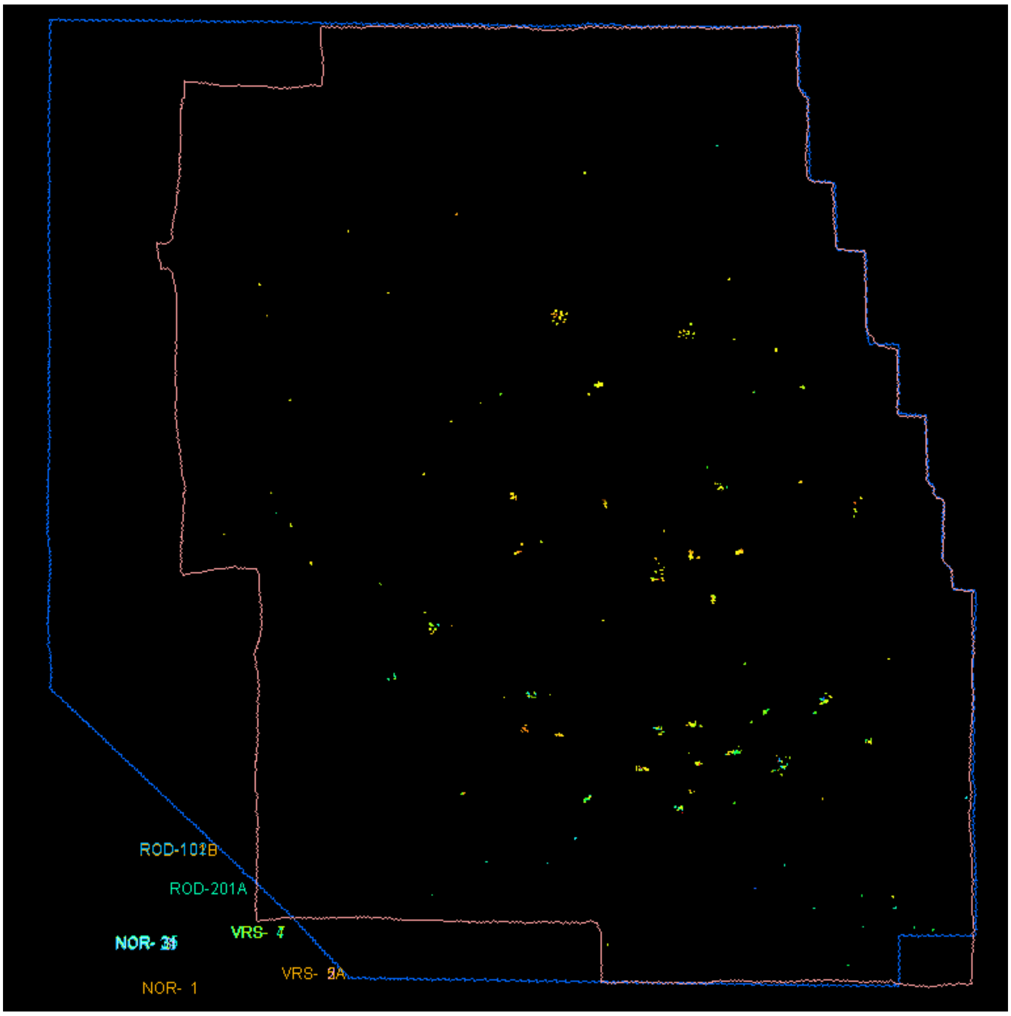


Figure 5-1 **Map showing the comparison between 2015 static model boundary (blue) and 2012 model boundary (red). Wells are indicated by dots. Additional wells in 2015 model are indicated by well names.**

5.2 GENERAL COMPARISON WITH 2012 STATIC MODEL

5.2.1 3D GRID ARCHITECTURE

In the 2015 static model, the extent of the area coverage has been increased to cover also the aquifer and adjacent fields. The extension is mainly towards the W and NW of the field (Figure 5-1). Several faults in the extended area have been added accordingly.

In Figure 5-1, the additional wells in the 2015 model are indicated by well names. It is noted that no wells are added to the W and NW of the field.

The grid construction with pillar gridding has been improved when comparing to the first pass 2015 and 2012 models. These improvements are the result of two main modifications:

- The rotation angle has been changed from 30.6 to 16.5 degrees
- The number of faults has been reduced from 708 to 627

A visual inspection has been performed on the mid pillar gridding (Figure 5-2). The number of irregular small cells has been reduced and that improves the regularity of the mesh near faults. A general improvement of regularity of the overall grid skeleton is observed.

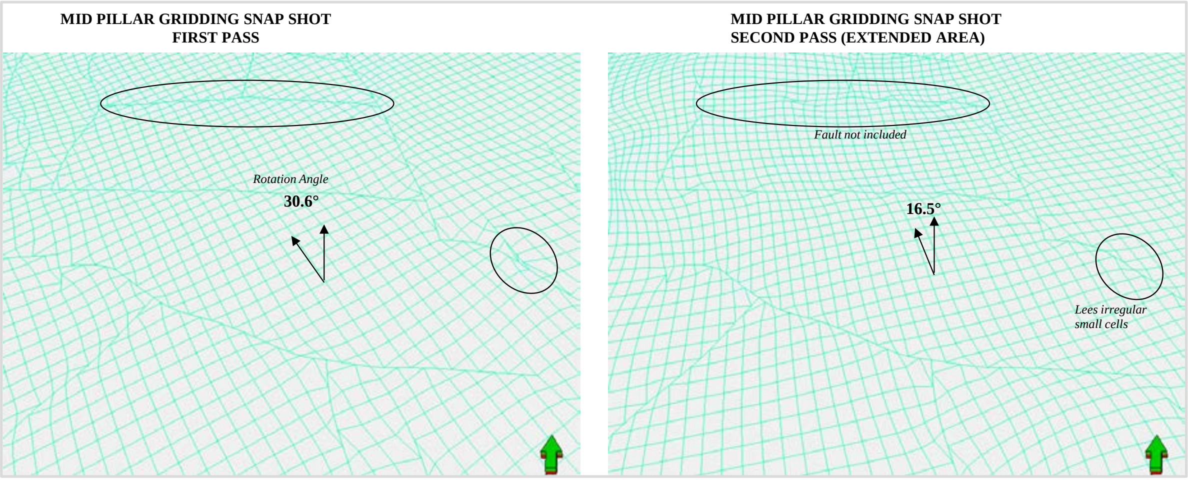


Figure 5-2 **Left: 2012 configuration of pillar gridding. Right: 2015 model configuration of pillar gridding with reduced number of faults and change of rotation angle**

5.2.2 PROPERTY MODELLING

There are several differences related to the property modelling between 2012 and 2015 static models. In porosity modelling, the 2012 model used the existing 3D property on NTG as the collocated co-kriging with a low correlation. Differently in the 2015 model, 2D trend maps were used to guide the overall distribution with a relatively strong correlation coefficient, based on acoustic impedance (chapter 3).

As for the Vclay model, the 2012 model was built with no trend maps at all. The 2015 model used trend maps with a strong correlation coefficient (see section 5.4.4).

In the NTG model, in the 2012 model a simple approach was implemented through the property calculator solely based on the Vclay cutoff. In the 2015 model, the NTG model was built with Vclay model as collocated co-kriging with strong correlation (see section 5.4.4).

5.2.3 VOLUMETRIC COMPARISON

In terms of gas initially in place volumes, the 2015 static model has less GIIP compared to the 2012 static model. As shown in Table 5-1, in the current static model the overall GIIP is 2871 x 10^9 Nm^3, while the 2012 model is reported to have 2927 x 10^9 Nm^3. It is noted that the GIIP is for the full model, not only for the Groningen field. A further discussion on the Groningen field GIIP in the dynamic model is provided in section 6.3.5. Overall the changes are not considered major by SGS.

The reason for these changes could be related to various aspects in the static model. The impact of new top structure maps in the overall model is shown in the changes in the GRV values, increased up to 8% from the 2012 model, likely due to an increased extent of the static model in 2015 (see also Table 2-1). The 2015 model has lower average NTG, and lower average porosity and higher average water saturation compared to the 2012 model. Such differences contribute to the decrease in the overall GIIP of the 2015 model. It is noted that for the history match of the 2015 dynamic model, the GIIP has been increased to a total GIIP close to the 2012 static model GIIP.

Due to the different model areas between 2015 and 2012, and due to different segmentation between 2012 and 2015 models, a more detailed reconciliation is tentative and has not been performed by SGS. NAM has not supplied documentation of the differences to SGS.

Table 5-1 Volumetric comparison between 2012 and 2015 static models (full model, not only Groningen field). The volumetric unit is 10^6 Nm^3. Tables in the right show the average value of properties, back-calculated from the volumetric results

2012 Model (10^6 Nm^3)

Zones	GRV	Net.Vol	Pore.Vol	HCPV	GIIP
TBS.3	11961	790	61	43	9979
TBS.2	13303	1275	126	93	21349
TBS.1	23388	3784	414	309	71572
USS.3.res	17071	16183	2677	2188	508807
USS.2.het	2700	2079	303	239	55312
USS.2.res	26207	25150	4428	3649	850431
USS.1..het	1708	1617	284	231	53859
USS.1..res	24052	23786	4325	3511	819143
LSS.2..het	2440	2035	284	211	49249
LSS.2..res	16308	15689	2464	1847	430762
LSS.1.het	421	378	57	38	8718
LSS.1.res	2383	2332	332	208	47915
TOTAL	**141942**	95098	15755	12567	**2927096**

Average Properties

NTG	PHI	SW
0.066	0.077	0.295
0.096	0.099	0.262
0.162	0.109	0.254
0.948	0.165	0.183
0.770	0.146	0.211
0.960	0.176	0.176
0.947	0.176	0.187
0.989	0.182	0.188
0.834	0.140	0.257
0.962	0.157	0.250
0.898	0.151	0.333
0.979	0.142	0.373
0.670	**0.166**	**0.202**

2015 2nd pass Model (10^6 Nm^3)

Zones	GRV	Net.Vol	Pore.Vol	HCPV	GIIP
TBS.3	13942	773	49	25	5848
TBS.2	15213	1222	101	62	14471
TBS.1	24007	4170	398	248	57867
USS.3.res	18756	17157	2753	2085	485860
USS.2.het	3124	2452	362	266	61976
USS.2.res	28796	27366	4629	3571	831962
USS.1..het	1973	1794	307	234	54550
USS.1..res	25366	24775	4421	3459	805923
LSS.2..het	2610	2202	325	240	55854
LSS.2..res	17244	16312	2524	1869	435455
LSS.1.het	460	401	65	46	10615
LSS.1.res	2385	2314	343	219	51060
TOTAL	**153876**	100938	16277	12324	**2871441**

Average Properties

NTG	PHI	SW
0.055	0.063	0.490
0.080	0.083	0.386
0.174	0.095	0.377
0.915	0.160	0.243
0.785	0.148	0.265
0.950	0.169	0.229
0.909	0.171	0.238
0.977	0.178	0.218
0.844	0.148	0.262
0.946	0.155	0.260
0.872	0.162	0.292
0.970	0.148	0.362
0.656	**0.161**	**0.243**

5.3 THE USE OF 2D TREND IN POROSITY MODEL

For the porosity modelling in the 2015 model, NAM has implemented the probabilistic maps based on acoustic impedance (AI) generated from Shell proprietary Promise software, as further discussed in chapter 3. These maps, however, generally have a strong hydrocarbon imprint. As can be observed from Figure 5-3 and Figure 5-4, the distribution of the overall porosity trend generally coincides with the fluid contacts. Additionally SGS observed that the AI-based trend maps have a rather low correlation with porosity logs at some wells used in the model. This is especially true for some wells located close to the gas-water contact. In the other areas, the lower correlation may be caused by potentially anomalous porosity values (section 5.4.3). To investigate these observations further, SGS established alternative porosity trend maps (also presented in Figure 5-3 and Figure 5-4). These alternative 2D porosity trend maps were generated for each reservoir unit using only well information after filtering out the wells discussed in section 5.4.3.

From comparing these maps it is observed that, from a volumetric point of view, the use of AI based trend maps may impact the Groningen model in several ways;

- at the flank areas, the AI trend maps will clearly underestimate the porosity values
- in the crestal area, porosity may be overestimated.
- bull's eyes pattern will be produced in porosity distribution.

SGS recommendation from this analysis is that regional well data trends could be used more in further modelling by NAM.

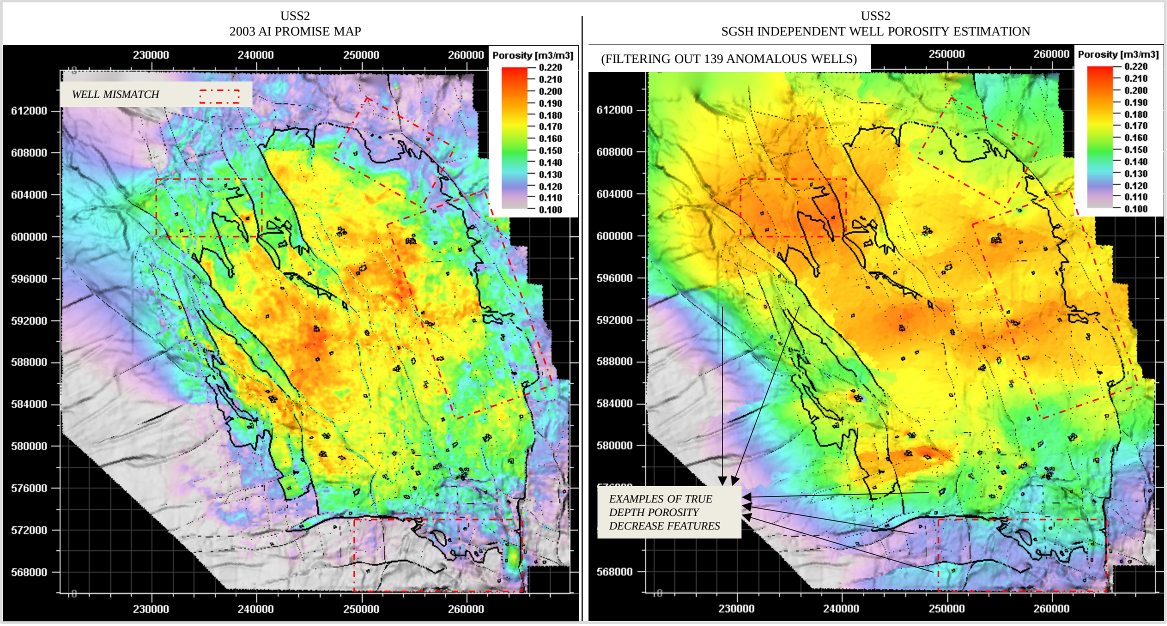


Figure 5-3 **USS2 zone porosity map. Left: 2003 AI Promise. Right: SGS alternative porosity trend based on well data**

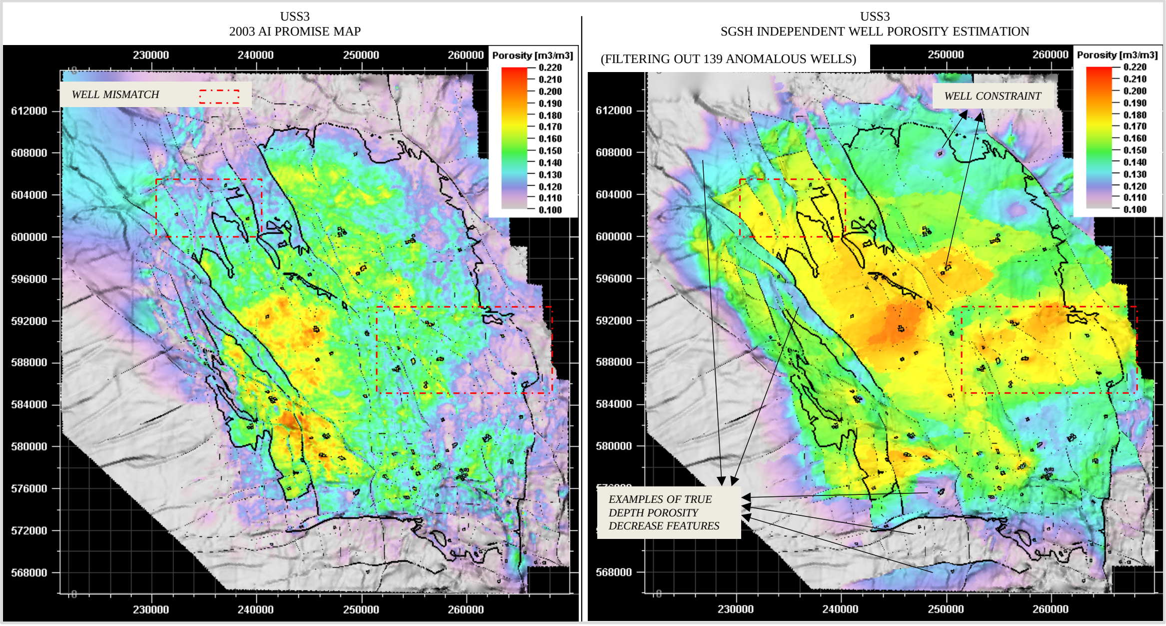
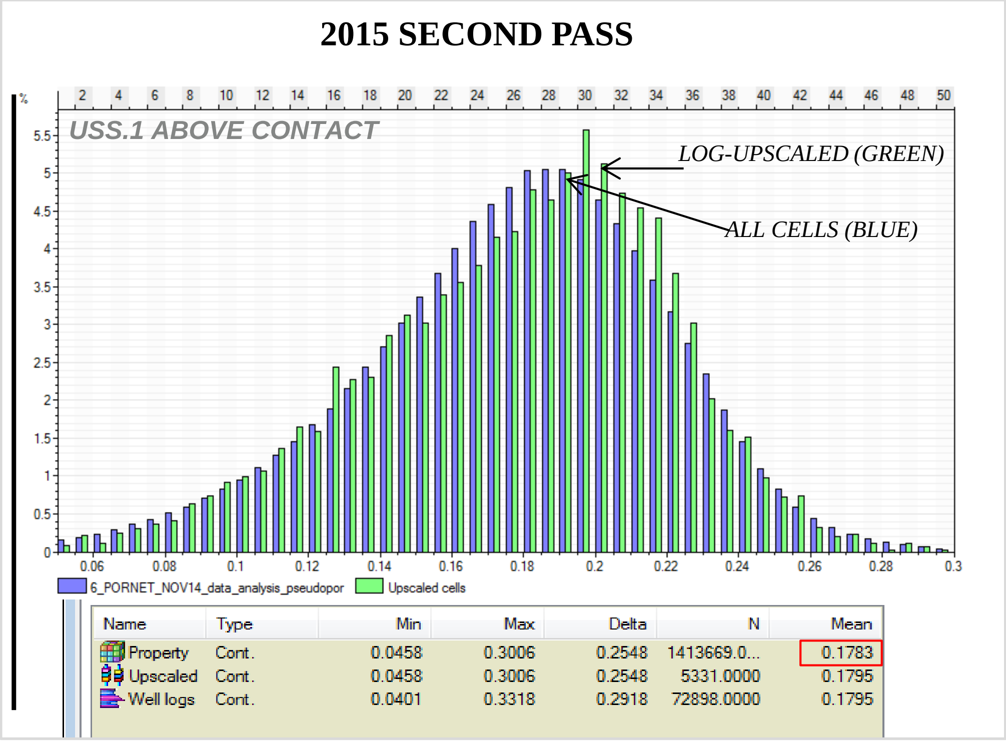


Figure 5-4 USS3 zone porosity map. Left: 2003 AI Promise. Right: SGSH alternative porosity trend based on well data

5.4 PROPERTY MODELLING: POROSITY, VCLAY AND NTG

In general, the property models contained in the 2015 static model have well constrained statistical input. For instance (Figure 5-5), the overall distribution of the porosity values in the model is comparable with the values from the interpreted input well logs and upscaled cells. However, there are several aspects that could be further evaluated, especially related to property modelling parameters, well data evaluation and trend maps construction.



Name	Type	Min	Max	Delta	N	Mean
Property	Cont.	0.0458	0.3006	0.2548	1413669.0...	0.1783
Upscaled	Cont.	0.0458	0.3006	0.2548	5331.0000	0.1795
Well logs	Cont.	0.0401	0.3318	0.2918	72898.0000	0.1795

Figure 5-5 **Histogram of porosity values from the input logs, upscaled and modeled in the 2015 model**

5.4.1 POROSITY MODEL

As mentioned earlier in section 5.3, AI trend maps have been used in the porosity modelling. These have low correlation with the porosity log at some wells. Typically such wells are located close to the fluid contacts in the model (see further the discussion in chapter 3).

5.4.2 EXTENDED AREA

As shown in Figure 5-1, only a limited amount of wells outside the Groningen field was used for modelling reservoir properties in the extended area of the Petrel model. No wells to the West and North-West of the Groningen field, outside the extended area, were used. However, regional information shows that many wells are present in a wider region, and.

5.4.3 WELL DATA ANALYSIS

During the review of the 2015 property model, SGS noted a relatively high level of heterogeneity on reservoir properties at short distances, i.e. on porosity between wells in the same cluster. Such heterogeneity is not expected from the regional geology. SGS performed an analysis on consistency of the interpreted logs and on well log data quality. SGS concluded that the root cause is issues related to density log measurements. It is observed that most wells were logged in the 1960’s and 1970’s with less good quality logging tools than available currently, and that different logging companies with different logging tools may result in different interpretations of porosity.

The issue is not new to the 2015 model. It is noticed that there is no industry standard method on how to use potentially conflicting well data. The issue is outside the main review conclusions of SGS, it is presented in this report for further consideration by NAM.

5.4.4 VCLAY MODEL AND NTG MODEL

In terms of Vclay distribution, NAM has implemented trend maps via data analysis (Figure 5-6). There are several observations by SGS related to these maps:

- The Vclay trend maps used in the 2015 model are generally very smooth, mainly to reflect the geological concept in Vclay distribution. This will lead to a low correlation between the trend maps and the Vclay value at some wells.
- The correlation factor with trend maps used in modelling the Vclay is very high at 0.8.
- Variogram used in the Vclay and NTG generally do not reflect the well data (Figure 5-7).
- In modelling the NTG, the Vclay model was used as the 3D trend with a strong, as considered by SGS, correlation factor (0.8).

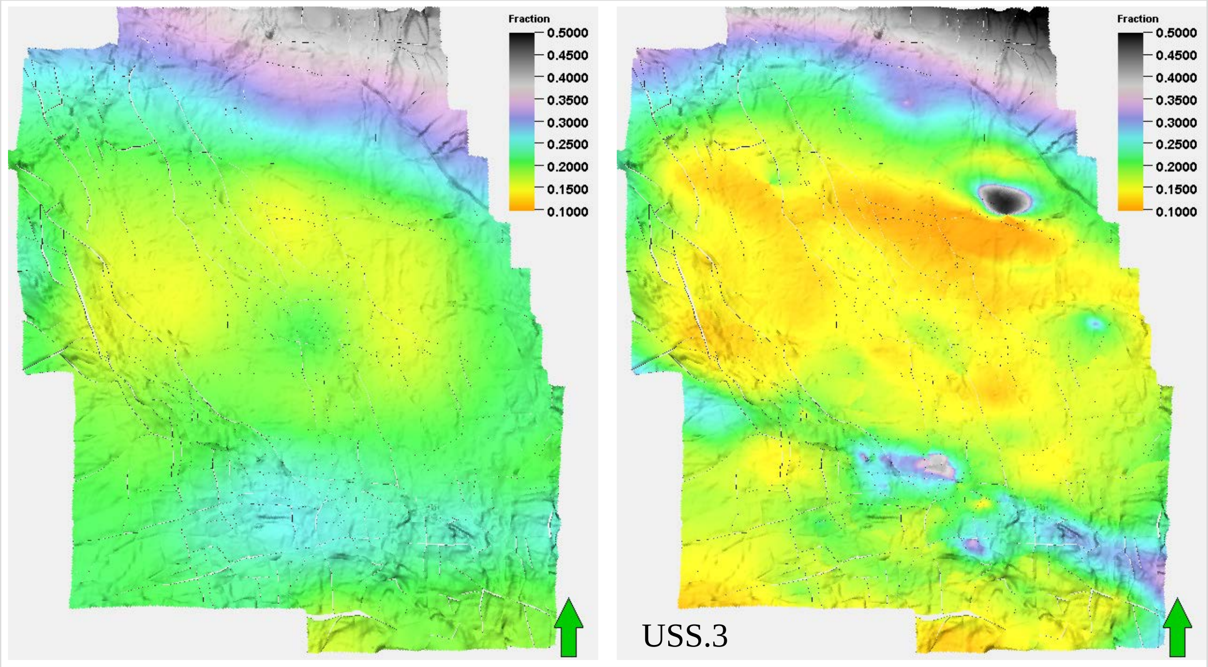


Figure 5-6 **Analysis of Vclay trend mapping. Left: example of trend map used in the USS3 reservoir unit to distribute the Vclay in the 2015 static model. Right: an alternative approach by SGS in constructing the trend map from well data**

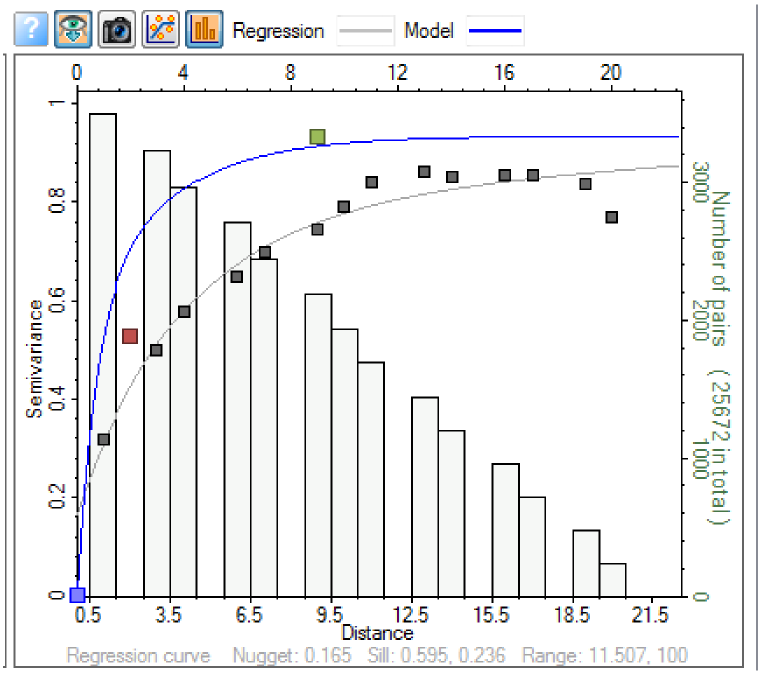


Figure 5-7 **Variogram modelling for Vclay in USS.3 res zone. Note the discrepancy between the model (blue line) and the data (square dots with grey line)**

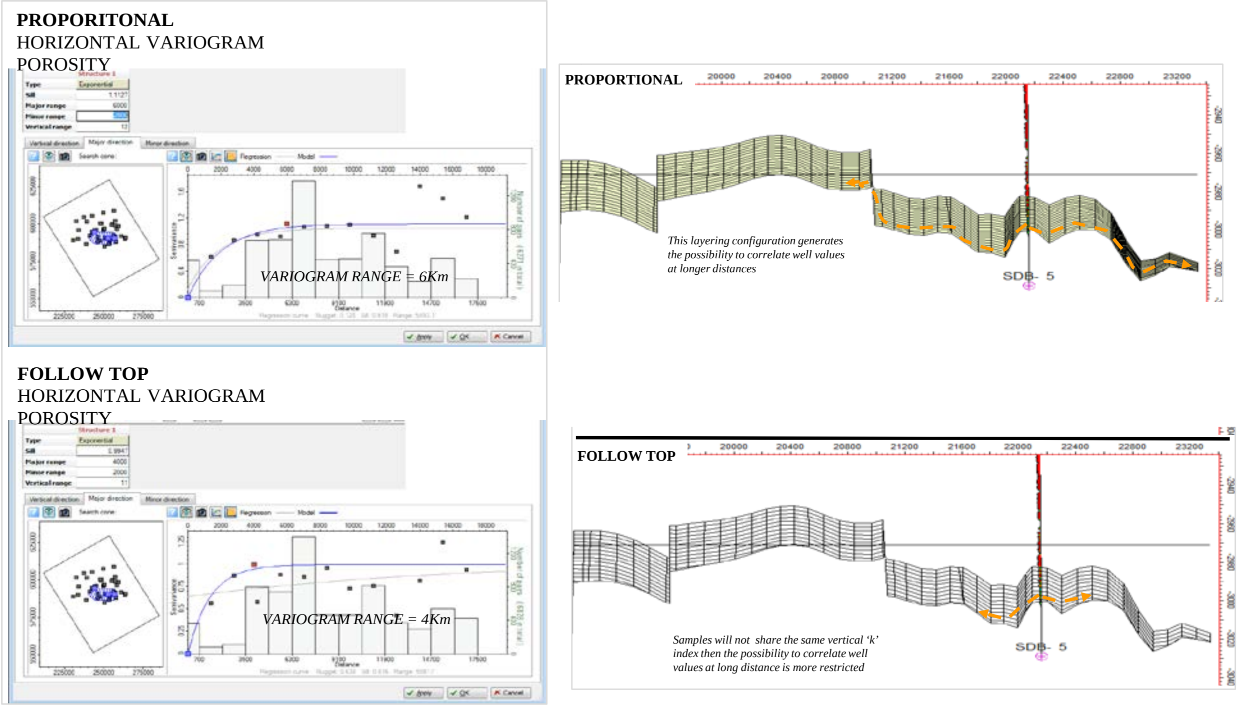
5.5 MODEL ARCHITECTURE AND LAYERING

The Rotliegend reservoir is onlapping on the underlying Carboniferous reservoir in the South of the Groningen field. An issue with the grid architecture was highlighted in a 2013 review of the static model by TNO-AGE / SodM.

In the 2015 model, for the Lower Slochteren reservoir, the grid architecture was updated. The LSS.1 is constructed with an updated layering scheme: proportional layering with thickness cut-off. This zone contains only 1.8% of total GIIP and only 7% of the grid cells of this zone are above the gas water contact. Geometrical differences between 2012 and 2015 layering configurations will only occur in the most southern part of the field, the 'wedge area' where the onlap takes place.

An impact of layering scheme is apparent especially when calculating the variogram of the porosity data (Figure 5-8). In the case of lateral variogram, proportional layering will have a tendency to generate a longer variogram compared to "follow top" layering. In the vertical variogram proportional layering exhibits a rather poor depth trend whilst "follow top" layering shows a more clear depth trend. This is expected due to the nature of the on-lapping truncation.

A simple volumetric calculation was performed by SGS to investigate the impact from the layering scheme in the model. In general, in different segments of the Groningen field, the pore volume could be reduced by up to 0.5% when using proportional layering as opposed to "follow top" (Table 5-2).



PROPORITONAL
HORIZONTAL VARIOGRAM
POROSITY

Structure 1
Type: Exponential
Sill: 1.1127
Major range: 6000
Vertical range: 13

VARIOGRAM RANGE = 6Km

FOLLOW TOP
HORIZONTAL VARIOGRAM
POROSITY

Structure 1
Type: Exponential
Sill: 0.9947
Major range: 4000
Minor range: 2000
Vertical range: 11

VARIOGRAM RANGE = 4Km

PROPORTIONAL

This layering configuration generates the possibility to correlate well values at longer distances

FOLLOW TOP

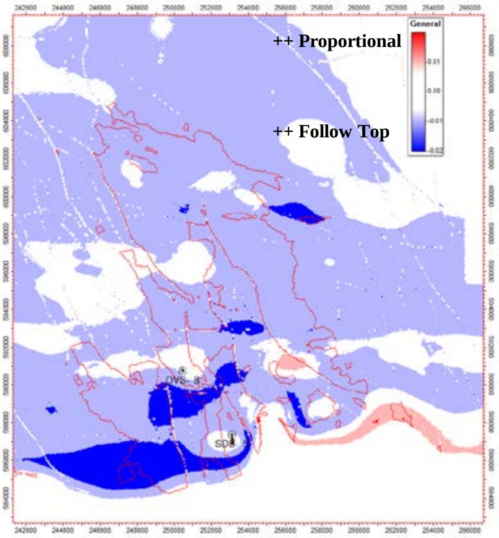
Samples will not share the same vertical 'k' index then the possibility to correlate well values at long distance is more restricted

Figure 5-8 **Sensitivity analysis for different layering styles, especially for the impact on variogram model. Note the differences in variogram ranges**

Table 5-2 Pore volume comparison of different layering styles applied in the 2015 Petrel model

Same NTG	**SENSITIVITY A**		
	FOLLOW TOP	**DIFF(%)**	**PROPORTIONAL**
Case	Pore volume[*10^6 rm3]		Pore volume[*10^6 rm3]
TOTAL	**323.05**	**-0.5**	**321.43**
Segments			
't Zandt-Bierum	190.57	1.1	192.74
Amsweer	1.38	4.3	1.44
Borgsweer	0.09	11.1	0.1
De Paauwen	41.17	-5.3	39
Delfzijl	2.47	1.6	2.51
Eemskanaal	0.25	-4.0	0.24
Eemskanaal West	7.05	-7.1	6.55
Farmsum	45.05	-2.9	43.74
Overschildt	15.23	0.7	15.33
Siddeburen-Oudeweg	10.43	-1.3	10.29
Ten Boer Pop-Up	0.82	-2.4	0.8
Ten Post	6.64	2.1	6.78
Zeerijp	1.84	2.7	1.89

DIFFERENCE MAP



5.6 DETAILED CONCLUSIONS AND RECOMMENDATIONS

Property Model:

- Implement the porosity cube from the inversion for the porosity model construction.
- Alternatively, consider to construct 2D trend maps from well data for sensitivity analysis purposes. This is applicable for both porosity and Vclay model.
- For further consideration by NAM: perform analysis to identify wells with anomalous logs and potentially exclude them in the property modelling.
- In modelling the NTG, the correlation coefficient with Vclay should be adjusted according to well data.
- Property distribution in extended area could use wells outside the Groningen field, these wells could be used for a rough calibration of reservoir properties, and allowing interpolation instead of extrapolation.

3D Grid construction and structural model:

- Updates to the grid orientation in the 2015 model is supported by SGS.
- Follow-top layering type is considered more appropriate in modelling the Rotliegend reservoir zones of the Groningen field. However, proportional layering is considered acceptable by SGS.

Volumetric evaluation:

- There is a noticeable reduction in the gas volumes in the Groningen field from 2012 to 2015 static models, albeit within the uncertainty range of 5% as defined by NAM. The dynamic model of the Groningen field therefore required non-negligible GBV multipliers.
- More justification and reconciliation by NAM of the difference in gas volumes and pore volumes between static and dynamic models is desirable in future modelling.

6 DYNAMIC MODEL

6.1 ITEMS REVIEWED

NAM has provided SGS with documentation explaining their (computer assisted) history matching methodology, which employs Shell proprietary software, reference [6] and [7] and section 10.7.

NAM provided to SGS for review a single history matched dynamic model (HM) and a single forecast scenario for the Groningen gas field identified as "GRO_2015_ED_v34_v9_noforecast" and "FM_2P_27Bcm". The history matched dynamic model is also denoted by NAM as "version 2.5".

The history match scenario includes production data up to December 2015. The forecast scenario is developed as a "restart file" based on the reviewed HM model. It covers the time period of January 2016 until December 2035.

As it was communicated by NAM, the dynamic model was based on the static model by NAM as provided to SGS as part of the current review, and on the dynamic model as it was used for the Winningsplan 2013 (GFR2012). Items of the dynamic model that had changed (from the static model during HM or from the 2012 model) are listed in section 6.3. Items that have been specifically reviewed by SGS are:

- Fault seal multipliers
- Analytical aquifers
- Gross bulk volume (GBV) multipliers
- Permeability multipliers
- Relative permeability
- Capillary pressure
- Fluid properties (gas and water)
- Gas initially in place
- Pressure match quality
- Water production match quality
- Water movement match quality
- Forecast

Other items have not been reviewed again in 2015, as these have been reviewed by SGS in 2013, amongst others:

- Gas composition and properties
- Upscaling and dynamic model initialisation

The MoReS deck reviewed by SGS did not include the historical tubing head pressures for producing wells. For that reason the review of quality of the well deliverability was not performed by SGS in the current review.

NAM is using proprietary software to achieve the history match. In addition to reservoir data, as has been provided to SGS, NAM has also used subsidence data to steer the history match, which has not been provided to SGS. The review by SGS both entails the aspects mentioned above, and the resulting history match and forecast. SGS has not reviewed the intermediate work steps of NAM. This particularly is relevant for the review of the production forecast: the surface network model element of the production forecast models has not been reviewed in detail, nor have models and "surface data" been supplied by NAM, only the methods and supporting documentation have been reviewed by SGS.

At the time of the review, no formally documented audit trail by NAM of automatic and manual history match adjustments were available. An informal audit trail of history match adjustments was however provided in the files of the MoReS deck. In this SGS report, overview tables extracted from the MoReS deck are presented.

While SGS has also reviewed an earlier history matched version of the dynamic model, this report covers the review of the “dynamic model version 2.5” (see above in this section) only.

6.2 HISTORY MATCH METHODOLOGY

A new computer assisted history matching (CAHM) approach was used in the HM process, as described by NAM (ref. [6], [7]). A summary of the method as applied and documented by NAM is provided in this paragraph. SGS has not reviewed the intermediate steps as applied and described by NAM, but is supportive of the approach taken.

NAM chose as main ranking parameters for the quality of the match: static bottom hole pressure, gas water contact (PNL and RFT) and subsidence. Measured data were weighted by quality per well and “binned” by time. To come up to the reference model, a manual tuning along with the CAHM approach was used. The best matched model was identified by performing a “space filling exercise” (1st and 2nd cycles). The best model candidates were identifies using a “3 axes plot”. In the 1st cycle of the spacing filling exercise the following parameters were set as variable parameters: fault seal factors, analytical aquifer length, permeability multipliers, GBV multipliers. The best models with the lowest global RMS (root mean square) values were chosen and analyzed. A narrower range of the variables was given for the 2nd cycle of the space filling in order to achieve a better match [14]. Further “manual match improvements” were performed by NAM to arrive at the selected history match model.

No sensitivity analysis of the selected history matched dynamic model (denoted by NAM as version 2.5) was provided by NAM. SGS did not perform a complete sensitivity exercise. The only parameter tested was analytical aquifer length in order to evaluate the impact of the attached aquifers to the history match in the Groningen area. Both NAM and SGS realise that a single history match model is by definition “a non-unique solution” within the inherent range of uncertainty. With so many parameters that can be changed, many different model realisations may provide a good history match.

The dynamic model has some limitations, for instance, the grid size. The size of a cell in XY directions is approximately 450x450 m. The dynamic model was upscaled up to 30 vertical layers, therefore the reservoir property distribution in the dynamic model is more homogeneous than in the static model. A further discussion has been provided in [1]. While the static model can be considered to be relatively coarse, the dynamic model is much coarser. As a result, in the dynamic model the wells of a cluster are located close to each other. They can penetrate the same grid cell or cells next to each other.

6.3 HISTORY MATCH PARAMETERS

The history match parameters used in the dynamic model are reviewed in this section of the report, including analysis of the parameter ranges employed and impact to the field gas in place calculation and the reservoir description.

The following parameters were adjusted by NAM during the history matching, compared to the static model and the 2012 dynamic model, in the matching of the current dynamic model:

- Fault seal multipliers
- GBV multipliers
- Permeability multipliers
- Analytical aquifer
- Relative permeability parameters: residual gas saturation intercept and slope, end points for gas and water, Corey exponents for gas and water
- Salinity tuning factor

- Lowest porosity value for saturation functions bins
- FWLs
- Skin factors
- Aquifer water viscosity
- Gas and water density
- Subsidence parameters: Poisson ration, measurement uncertainty, and rock compressibility multiplier

The most critical parameters for the history match have been reviewed by SGS. It is noted that the subsidence was not reviewed, neither with respect to data, with respect to modelling, and with respect to matching; reference is made to chapter 1 for the scope of the current SGS review.

The tubing head pressures have not been reviewed by SGS. For the forecasting method applied by NAM, these are not critical to the forecast of the reservoir pressure prediction (section 6.5.1). It is described by NAM how the THPs in the model were matched to data, and this method is overall supported by SGS. The THP was matched in a different method than in 2012, following a recommendation by SGS.

6.3.1 FAULT MODEL

6.3.1.1 Observations

The dynamic model contains more than 630 faults. More than 130 faults were modified during the history match. During the HM six reservoir engineering faults were implemented into the dynamic model in order to extend existing faults and performing the HM.

The overview of the fault seal multipliers is presented in Table 12-1 in Appendix B. The fault seal multipliers vary from 0 (a fault is totally closed) up to 1 (a fault is totally opened). In Table 12-1 the faults are divided by groups. The title of each group indicates the reason for that division as specified by NAM (mainly geographical area). All comments are taken from the MoReS deck.

6.3.1.2 Detailed Conclusions and Recommendations

The fault seal multipliers are a single realisation and therefore a non-unique solution, see also section 6.3.2.2. The effect of individual fault seal multipliers on the match is not transparent and has not been reviewed in detail by SGS.

More sensitivity analysis by NAM to the effect of fault seal parameters, especially in combination with aquifer parameters, is recommended.

6.3.2 ANALYTICAL AQUIFERS

6.3.2.1 Observations

Nine analytical aquifers are implemented in the dynamic model.

The analytical aquifers are created using a build-in MoReS function which identifies the cells at the edge of the model and attaches analytical aquifers with the required direction with respect to compartments.

The type of the analytical aquifers is finite linear.

The only parameters set are aquifer length and water viscosity (0.57 cP for all aquifers), no water viscosity multipliers were implemented.

Other parameters were set as “default”, which means that reservoir properties like porosity and permeability will be calculated from the adjacent model grid cells by the software. Also the model “transmissibility” will be calculated by the software from the grid cell model. An overview of the analytical aquifer information is presented in Table 6-1.

Table 6-1 Aquifer parameters

#	Aquifer name	Compartment	Type	Length, m
1	AnnerveenVeendam	Aquifer_AnnerveenVeendam	finite linear	1500
2	Lauwersee1	Aquifer_Lauwersee1	finite linear	6000
3	Lauwersee2	Aquifer_Lauwersee2	finite linear	1000
4	Lauwersee3	Aquifer_Lauwersee3	finite linear	1000
5	Lauwersee4	Aquifer_Lauwersee4	finite linear	3000
6	Moewensteert	Aquifer_Moewensteert	finite linear	35000
7	Rodewolt	Aquifer_Rodewolt	finite linear	10000
8	Rysum	Aquifer_Rysum	finite linear	5000
9	Usquert	Aquifer_Usquert	finite linear	1000

Figure 6-1 shows the aquifer compartments (black circles) and the lines where the aquifers are attached along the grid (yellow and green solid lines). Each aquifer is defined by a number of cells at the edge of a compartment, a length of an aquifer, the geometrical properties and porosity, permeability and compressibility of the cells which an aquifer attached to.

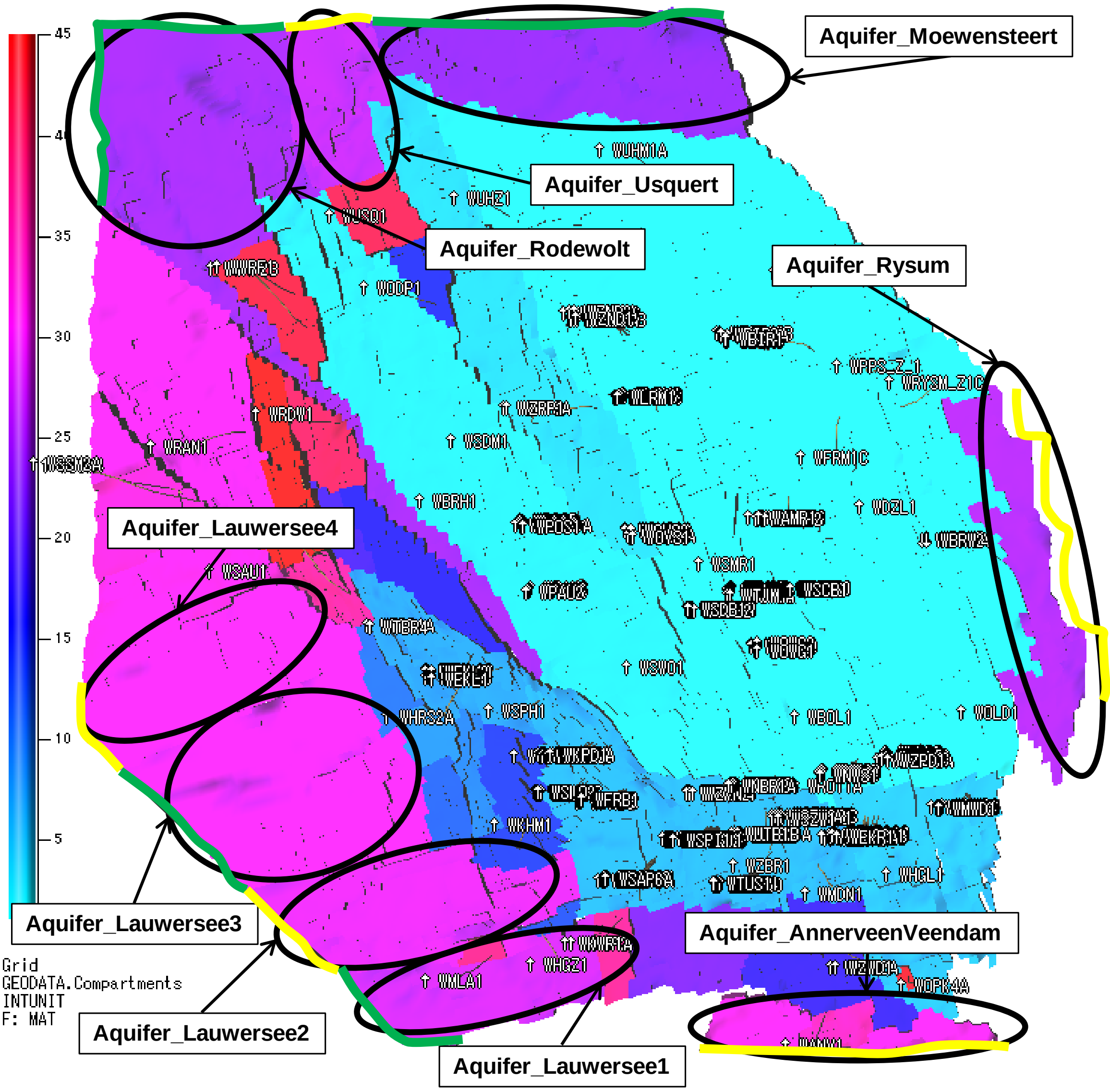


Figure 6-1 **Top view of "Compartments property" with indicated analytical aquifer compartments and attaching lines (green and yellow solid lines)**

Visual inspection by SGS of the water movement in the model (by using cross sections from the dynamic model output) indicated that the water influx into the Groningen field is limited relative to the size of the field whilst local water movement occurs as already indicated in the 2012 model review [1]. Only in the peripheral areas of the field and close to the original gas water contact, notable water influx has been predicted by the model.

6.3.2.2 Detailed Conclusions and Recommendations

SGS has performed a sensitivity analysis during the current review where the aquifer length parameter was set to zero. The sensitivity simulation result showed that the predicted pressure for the Groningen area was only slightly changed. This will be related to the fault seal multipliers, section 6.3.1, which are applied to "counter-act" the pressure support and water ingress from external aquifers. A considerable level of non-uniqueness for aquifer parameters would be present.

SGS recommends to further investigate the impact of the analytical aquifers on the history match by excluding the analytical aquifers and/or by changing the length of the aquifers. The combination with fault seal parameters should be included in such analysis.

6.3.3 RESERVOIR PROPERTY MODEL

6.3.3.1 Items reviewed

The following items of the reservoir properties in the dynamic model were reviewed:

- Gross Bulk Volume multipliers (impacting gas initially in place)
- Permeability multipliers

6.3.3.2 Observations

6.3.3.2.1 GBV multipliers

The GBV multipliers are implemented for the global and local matching for Groningen and the adjacent fields. Comments are taken from the provided MoReS deck. The multipliers are summarised in Table 6-2.

Table 6-2 GBV multipliers

Multiplier name	Value	Compartment	GIIP, 1e+9 m^3	Comments
SlochterenGBVMult	1.05	UpperSlochteren	-	Global matching - upper and lower Slochteren To SGS: multipliers needed for the energy. No match is possible without these multipliers. Discussions took place with Geologists at the time.
		LowerSlochteren	-	
LocalGBVMultHarkstedeBlock	1.17	Gron_Harkstede	11.9	Local matching - Harkstede/EKL-13 block
LocalGBVMultTBR4EKLArea	1.01	Gron_Eemskanaal	104.1	Local matching - SW-periphery blocks near the Ten Boer wells
		Gron_Ellerhuizen	-	
		Gron_HarkstedeNorthWest	2.4	
		Gron_TenBoerNorth	26	
LocalNEGBVMult	0.96	Groningen_NE	969.7	Local matching - Central
LocalOPK4GBVMult	1.55	Field_ZuidwendingEast	0.9	Local matching - Zuidwending East (OPK4)
LocalBDMFieldGBVMult	0.85	Field_Bedum	11.3	Local matching - BDMbkill 6403 field
		Field_BedumSouth	2.2	
LocalKWRGBVMult	0.3	Field_KielWindeweer	0.7	Local matching - Kiel Windeweer field
LocalFeerwerdGBVMult	0.39	Field_Feerwerd	0.8	Local matching - Feerwerd Field _ssm
LocalWarffumGBVMult	0.99	Field_Warffum	12.3	Local matching - Warffum field
LocalAnnerveenGBV	0.5	Field_AnnerveenVeendam	1.8	Local matching - Annerveen

A multiplier of 1.05 was implemented for the global matching of Upper and Lower Slochteren. However, in North-Eastern region the GBV multiplier of 0.96 was applied. Therefore the effective GBV multiplier in the North-Eastern area is about 1.00.

Locally GBV was increased by 17% in the area of Harkstede/ELK-13.

In the adjacent fields the multipliers vary from 0.3 to 1.55 (see Table 6-2).

The compartments and locally multiplied GBV areas of the dynamic model are shown in Figure 6-2. White circles are used for the Groningen compartments, black circles for the compartments of the adjacent fields.

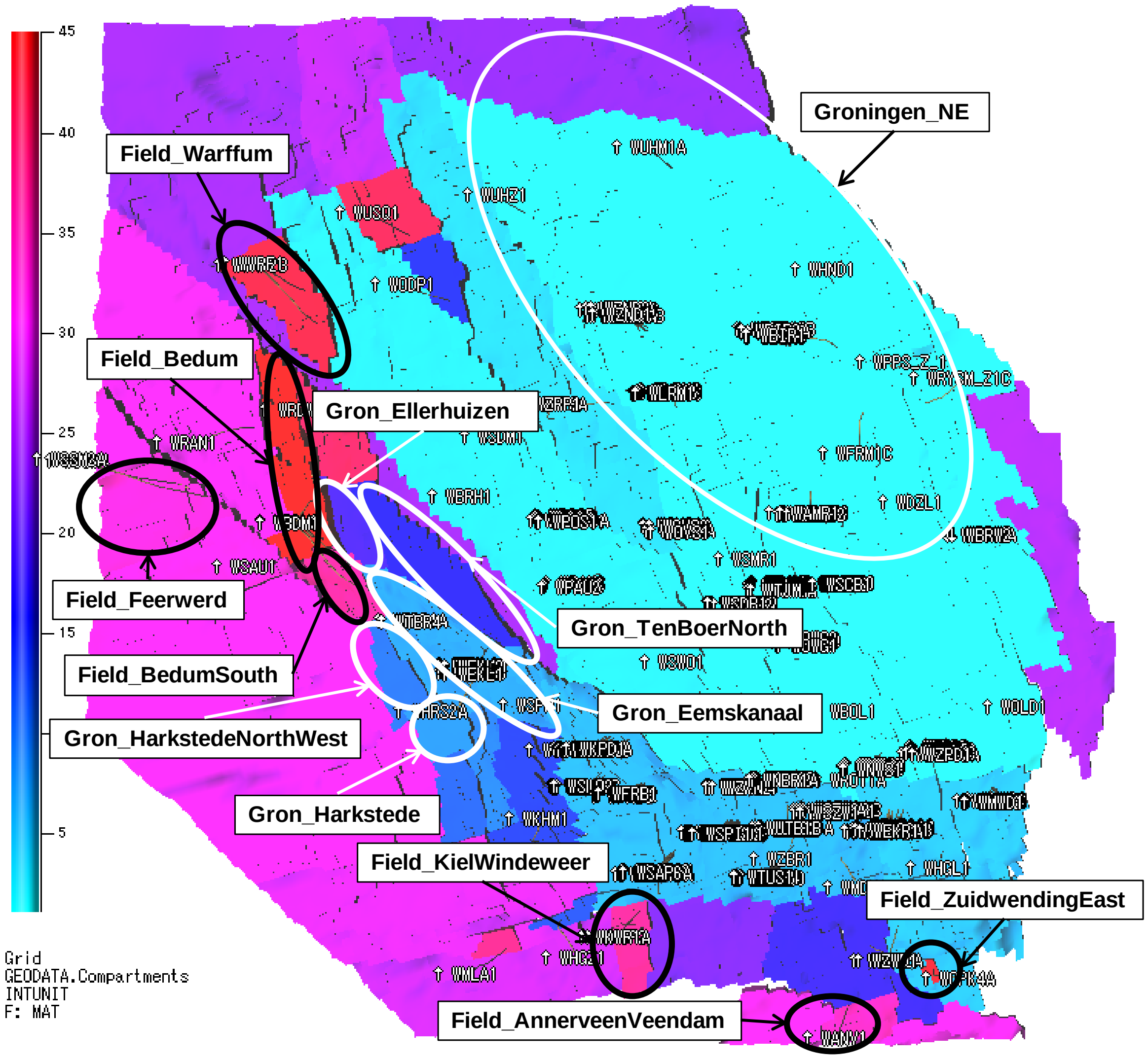


Figure 6-2 **Top view of “Compartments property” with indicated locally multiplied GBV areas**

6.3.3.2.2 Permeability multipliers

Horizontal and vertical permeability multipliers are summarised in Table 6-3. The comments are taken from the dynamic model deck as supplied by NAM.

Table 6-3 **Permeability multipliers**

Multiplier name	Value	Compartment	GIIP, 1e+9 m^3	Comments
TenBoerlog_k_h_Mult	0.032	TopTenBoer_gt12m	-	Global matching - log horizontal permeability Ten Boer
		BotTenBoer_gt30m	-	
TenBoerlog_k_v_Mult	0.032	TenBoer	-	Global matching - log vertical permeability Ten Boer
RSLUlog_k_h_Mult	0.89	UpperSlochteren	-	Global matching - log horizontal permeability UpperSlochteren
Het_SLUlog_k_v_Mult	0.01	heterolitics_ROSLU2	-	Global matching - log vertical permeability heterolitics Lower Slochteren
		heterolitics_ROSLU1	-	
Amelandlog_k_v_Mult	0.0025	ameland	-	Global matching - log vertical permeability Ameland
Het_SLLlog_k_v_Mult	0.01	heterolitcs_ROSLL	-	Global matching - log vertical permeability heterolitics Lower Slochteren
Central_k_h_Mult	2.51	Groningen_Central	206.5	Local matching Central To SGS: multiplier based on the early time pressure match improvement. No connection with the Salt Mine in the overburden.
KWRLog_k_Mult	0.32	Field_KielWindeweer	0.7	Local matching permeability multiplier ODP
Feerwerd_k_Mult	0.012	Field_Feerwerd	0.8	Local matching permeability multiplier in Feerwerd (SSM wells)

Permeabilities in X and Y directions are equal to each other.

The top view of “Compartments property” in the MoReS model with indicated compartments and locally multiplied permeability areas is shown in Figure 6-3. The compartments of Groningen and the adjacent fields (also called peripheral fields) are highlighted with white and black color circles respectively.

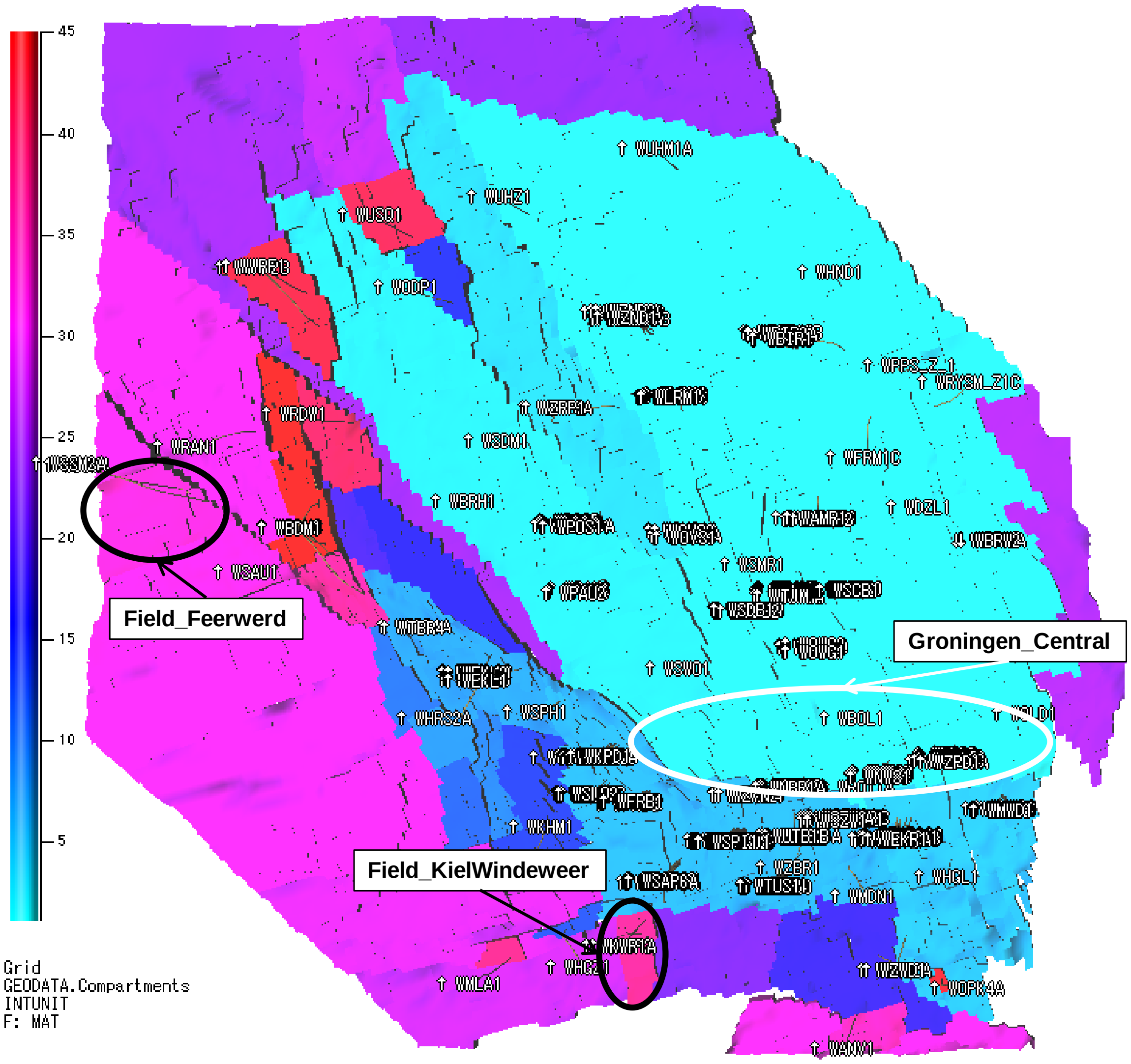


Figure 6-3 **Top view of “Compartments property” with indicated locally multiplied permeability areas**

6.3.3.3 Detailed Conclusions and Recommendations

The global GBV multiplier of 1.05 for Upper and Lower Slochteren is relatively large, especially when considering the minor changes applied to the petrophysical parameters as described in section 4. The GBV multiplier has only impact on GIIP, not on other parameters like permeability. Further discussion on the GIIP is provided in section 6.3.5.2.

The horizontal permeability multiplier to the Upper Slochteren reservoir of 0.89 is considered by SGS to be a minor adjustment which is justifiable and it indicates a good fit of the overall porosity-permeability relationship.

The vertical permeability multipliers appear to be large, but SGS considers them justifiable in view of the coarse grid. SGS has not performed nor observed sensitivity analysis on these parameters.

The local horizontal permeability multiplier for the “Central” region of 2.51 is not negligible. NAM appears to have investigated this, based on the comments in the MoReS deck.

6.3.3.4 RELATIVE PERMEABILITY AND CAPILLARY PRESSURE

6.3.3.5 Observations

6.3.3.5.1 Relative Permeability

Gas-water relative permeability is generated based on the porosity bins (min 0.06, max 0.27, step 0.01). Totally 22 sets of relative permeability curves are presented in the dynamic model.

Initial water saturation range of 0.075-0.23 is narrower compared to the 2012 model. Irreducible water saturation equals to critical water saturation. krg@Swc is 0.86 that is 0.04 less compared to the 2012 dynamic functions. Sgr was not changed and equals to 0.26. Corey exponent for water is 3 in both studies. Gas Corey exponent was changed slightly from 1.5 to 1.7 in the current study. Gas and water end points, residual gas saturation, Corey exponents for gas and water are set the same for all porosity classes. The relative permeability parameters for the 2012 and current models are summarised in Table 6-4.

Table 6-4 Comparison table for relative permeability parameters

Parameter	v2.5 (WP2016)	2012 model
Swirr=Swc	0.075-0.23	0.064-0.27
krg@Swc	0.86	0.9
krw@Srg	0.13	0.1
Srg	0.26	0.26
Nw	3	3
Ng	1.7	1.5

In Figure 6-4 the relative permeability sets for two porosity unit classes of 6 pu and 27 pu are presented to illustrate the comparison. It is observed that the differences are small between the functions used in 2012 and in 2015.

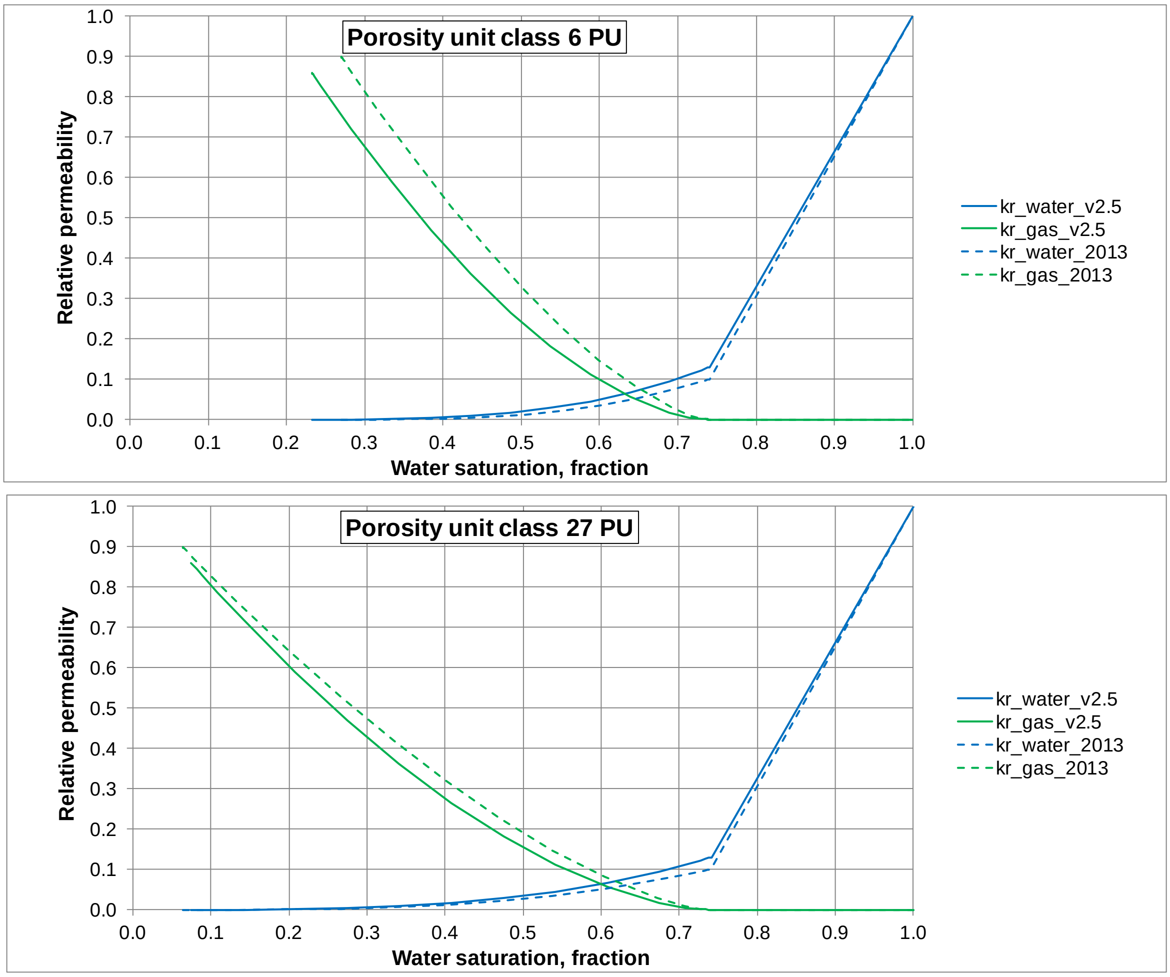


Figure 6-4 Sets of relative permeability curves for porosity unit classes of 6 pu and 27 pu used in the 2012 and current models

Residual gas saturation in the dynamic model was obtained based on the following equation:

$$S_{gr} = 0.0035 * (0.3 - \varphi) + 0.26$$

where φ is fractional porosity.

As a result, after initialisation the residual gas saturation equals to approximately 0.26 for each cell. However, according to the information provided by NAM [12], the residual gas saturation should vary from 0.26 up to 0.35 for porosity of 30 pu and 4 pu respectively (Base case).

The issue originates from mixing up fractional porosity with porosity units. The equation mentioned in the report [12] contains φ in porosity units, while fractional porosity is used in the dynamic model.

It is suggested to correct the function in the MoReS deck according to fractional porosity in a way presented below:

$$S_{gr} = 0.35 * (0.3 - \varphi) + 0.26$$

where φ is fractional porosity.

6.3.3.5.2 Capillary Pressure

Updates by NAM to the saturation height functions for the 2015 modelling is discussed in section 4.4 of this report. In the MoReS model, the saturation height functions are applied using capillary pressure tables.

The Brooks-Corey correlation was used to generate capillary pressure versus water saturation tables in the MoReS model. ShapeParN parameter of 2.86 was assumed that indicates pore-size distribution index (λ) of 0.35 (ShapeParN=1/ λ). The value of pore-size distribution index is related to the good quality sands [10]. The entry capillary pressure was calculated based on the correlation which includes only the porosity parameter.

In Figure 6-5 the capillary pressure sets, for two porosity unit classes of 6 pu and 27 pu, are presented as examples (graphs made by SGS).

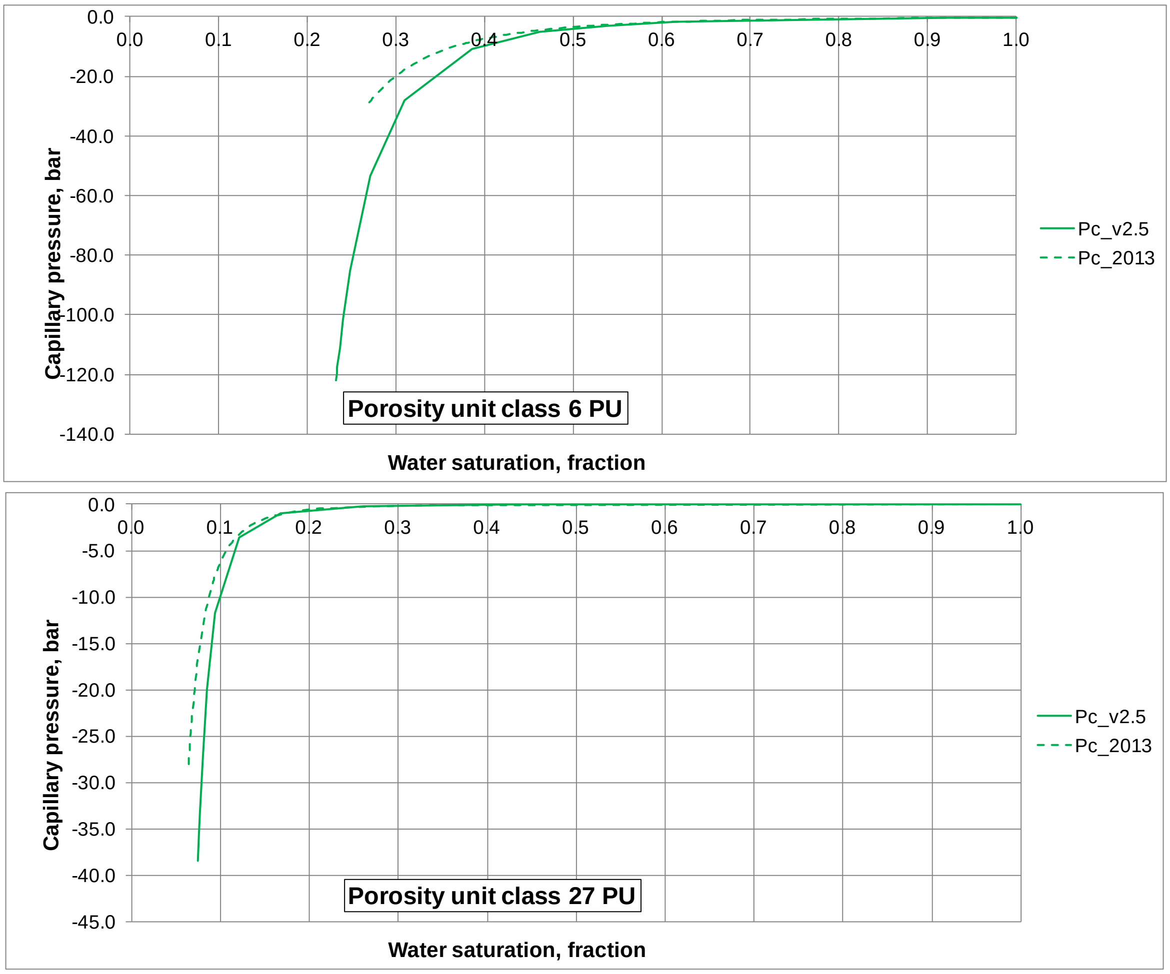


Figure 6-5 Sets of capillary pressure curves in the model for porosity classes of 6 pu and 27 pu used in the 2012 and current models

Negative capillary pressures indicate the water capillary pressures are used for a water-wet rock system [11].

6.3.3.6 Detailed Conclusions and Recommendations

SGS recommends correcting the function implemented for calculations of residual gas saturation in dynamic model with respect to fractional porosity used in the model. Probably this change will not have a significant impact to simulated results due to weak water encroachment into the reservoir. The material balance exercise performed in the 2013 SGS review showed that there was no meaningful field-wide pressure support from water influx, whilst local water movement may occur.

6.3.4 GAS AND WATER PROPERTIES

6.3.4.1 Observations

6.3.4.1.1 Gas Properties

Different to the 2012 dynamic model (a dry gas table), in the current dynamic model the PVT table was specified as a wet gas table and includes the following parameters: formation volume factors and viscosities for both dry and wet gases, and water gas ratio.

Wet gas formation volume factor includes water dissolved in gas phase.

Water gas ratio was calculated using McKetta-Wehe correlation.

Gas viscosities for dry and wet gases were obtained using Lee, Gonzales and Eakin correlation (LGE). This correlation was created based on data from 8 dry gases [1]. The description of the data set used to evaluate gas viscosities correlation is presented in [1], Table 2-4. Groningen data are within these ranges. However, in the dynamic model wet gas viscosity was calculated using formation volume factor for dry gas. Correction to wet gas instead of dry gas formation volume factor is suggested to be performed.

The formula for wet gas formation volume factor calculations includes the total volume parameter. Total volume comprises gas phase, and dissolved condensate and water phase. By virtue of the fact that the only tuning parameter was salinity tuning factor, which effects to the water salinity, and as a result to water-gas ratio, it can be concluded that liquid (condensate and water) contained in gas phase was modified by changing only water content. Condensate content was calculated with respect to liquid correction table and was not modified during the match. The match was achieved by using salinity tuning factor of 0.55. As a result, the water salinity in McKetta-Wehe equation was reduced up to 154,000 ppm, weight basis [mg/kg].

6.3.4.1.2 Water properties

The water salinity used for water density calculations in the dynamic model equals to 329,000 ppm, volume basis [mg/l] or 280,000 ppm, weight basis [mg/kg]. This value was obtained at the following conditions: 100 ^{o}C and 346.8 bar, and water density of 1176 kg/m^{3} as indicated in the MoReS deck.

The information from the report provided by NAM [13] supports the implemented value of water salinity of 329,000 ppm, volume basis [mg/l].

6.3.4.2 Detailed Conclusions and Recommendations

An inconsistency of applied water salinity values was observed in the dynamic model. The McKetta-Wehe correlation contains the water salinity of 154,000 ppm, volume basis [mg/l], whereas, in contrast, the correlation for water density calculations includes water salinity of 329,000 ppm, volume basis [mg/l]. It is noted that in petrophysical analyses again different values are applied by NAM. SGS observes that measured formation water data is scarce and not fully consistent.

Clear documentation on considerations for using different formation water parameters in different parts of the modelling is recommended by SGS.

6.3.5 GAS INITIALLY IN PLACE

6.3.5.1 Observations

GIIP per each compartment and total GIIP are presented in Table 6-5 including Clusters, Observation, Land and Injection wells per compartment (for discussion of this terminology see section 6.4.2.1). The GIIP values were obtained from the initialization section of the MoReS file “GRO_2015_ED_v34_v9_noforecast.OUT”.

It is noted that in the MoReS model, the compartments are not exactly the same as the segments in the Petrel model (section 5.2.3)

Table 6-5 GIIP in dynamic model and subdivision of wells by compartment

Compartment	GIIP, 1e+9 m^3	Clusters	Observation wells	Injection wells	Land wells
Groningen:					
Gron_Zuidwending	16.5	-	WZWD2A	-	-
Gron_TenBoerNorth	26.0	-	-	-	-
Gron_Oldorp	5.6	-	WODP1	-	-
Gron_KolhamBlocks	47.9	-	WKHM1	-	-
Gron_Hoogezand	3.8	-	WHGZ1	-	-
Gron_HarkstedeSouth	0.1	-	-	-	-
Gron_HarkstedeNorthWest	2.4	-	-	-	-
Gron_HarkstedeEast	2.6	-	-	-	-
Gron_Harkstede	11.9	EKL13	WHRS2A	-	-
Gron_Eemskanaal	104.1	EKL	WTBR4	-	-
Groningen_SW	354.8	KPD SLO FRB SAP SP1 SP2 ZVN TUS UTB NBR SZW	WMDN1 WSPH1 WWBL1 WZBR1 WZWD2A	-	-
Groningen_SE	121.1	EKR1 EKR2 MWD	WHGL1 WZWD1	-	-
Groningen_Zeerijp	90.6	-	WZRP1 WZRP2 WZRP3A	-	-
Groningen_NW	495.4	POS PAU	WBRH1 WSDM1 WSWO1	-	-

Groningen_NE	969.7	AMR BIR LRM OVS ZND	WFRM1C WHND1 WRYSM_Z1C WPPS_Z_1 WUHZ1 WUHM1A	-	-
Groningen_E	464.6	OWG SCB SDB TJM	WBOL1 WDZL1 WSMR1	WBRW2 WBRW2A WBRW3 WBRW4 WBRW5	-
Groningen_Central	206.5	NBR NWS ZPD	WOLD1 WROT1A	-	-
Total for Groningen	2923.7	30	30	5	-
Peripheral producing fields:					
Field_Warffum	12.3	-	-	-	WWRF1 WWRF2B
Field_KielWindeweer	0.7	-	-	-	WKWR1A WKWR2
Field_Feerwerd	0.8	-	-	-	WSSM2A WSSM4
Field_ZuidwendingEast	0.9	-	WOPK4A	-	-
Field_Usquert	2.5	-	WUSQ1	-	-
Field_Rodewolt	1.8	-	WRDW1	-	-
Field_Midlaren	0.1	-	WMLA1	-	-
Field_Bedum	11.3	-	-	-	WRAN1 WBDM1 WBDM2 WBDM3
Field_BedumSouth	2.2	-	-	-	WBDM4 WBDM5
Field_AnnerveenVeendam	1.8	-	WANV1	-	-
Total for the peripheral fields	34.4	-	5	-	12
Other compartments:					
Aquifer_Feerwerd	0.0	-	-	-	WSAU1
Aquifer_SaaksumOost	0.0	-	-	-	-
Aquifer_AnnerveenVeendam	0.0	-	-	-	-
Aquifer_Bedum	1.2	-	-	-	-
Aquifer_Rysum	0.0	-	-	-	-
Aquifer_Rodewolt	1.5	-	-	-	-
Aquifer_Kielwindeweer	0.0	-	-	-	-
Aquifer_Usquert	0.0	-	-	-	-
Aquifer_Moewensteert	0.0	-	-	-	-
Aquifer_Lauwersee4	0.0	-	-	-	-
Aquifer_Lauwersee3	0.0	-	-	-	-
Aquifer_Lauwersee2	0.1	-	-	-	-

Aquifer_Lauwersee1	0.0	-	-	-	-
Model_activeBlocks	0.7	-	-	-	-
Total for other compartments	3.6	-	-	-	1
Total	2961.7	30	35	5	13

As described in section 6.3.3, several GBV multipliers were implemented to the Groningen area and the adjacent fields to obtain the pressure match.

To evaluate the impact of GBV multipliers on GIIP, SGS has performed an additional sensitivity simulation based on the dynamic model where all GBV multipliers were set to 1.000. The results are summarised in Table 6-6. Using GBV multipliers as applied by NAM, the GIIP was increased by 91.9 x 10^9 Nm^3 or 3.1% for the full dynamic model, and by 96.9 x 10^9 Nm^3 or 3.3% for the Groningen field compartments, compared to the static model. The negative numbers in Table 6-6 indicate that the GIIP without GBV multiplier is smaller than with GBV multiplier.

Table 6-6 GIIP comparison for dynamic model with and without GBV multipliers

Compartment	GIIP, 1e+9 m^3		Difference, 1e+9 m^3	Difference, %
	-	without GBV multipliers		
Groningen:				
Gron_Zuidwending	16.5	15.8	-0.7	-4.5
Gron_TenBoerNorth	26.0	24.6	-1.4	-5.5
Gron_Oldorp	5.6	5.4	-0.3	-4.5
Gron_KolhamBlocks	47.9	45.7	-2.1	-4.4
Gron_Hoogezand	3.8	3.7	-0.2	-4.3
Gron_HarkstedeSouth	0.1	0.1	0.0	-2.0
Gron_HarkstedeNorthWest	2.4	2.2	-0.1	-4.7
Gron_HarkstedeEast	2.6	2.4	-0.1	-4.1
Gron_Harkstede	11.9	9.7	-2.2	-18.2
Gron_Eemskanaal	104.1	98.4	-5.6	-5.4
Groningen_SW	354.8	338.7	-16.1	-4.5
Groningen_SE	121.1	115.5	-5.6	-4.6
Groningen_Zeerijp	90.6	86.5	-4.1	-4.6
Groningen_NW	495.4	472.9	-22.6	-4.6
Groningen_NE	969.7	964.7	-5.0	-0.5
Groningen_E	464.6	443.4	-21.3	-4.6
Groningen_Central	206.5	197.1	-9.4	-4.6
Total for Groningen	2923.7	2826.8	-96.9	-3.3
Peripheral producing fields:				
Field_Warffum	12.3	11.9	-0.4	-3.5
Field_KielWindeweer	0.7	2.2	1.5	220.4
Field_Feerwerd	0.8	2.1	1.2	145.0
Field_ZuidwendingEast	0.9	0.5	-0.3	-38.5
Field_Usquert	2.5	2.4	-0.1	-4.7
Field_Rodewolt	1.8	1.8	-0.1	-4.0
Field_Midlaren	0.1	0.1	0.0	0.0
Field_Bedum	11.3	12.7	1.4	12.4
Field_BedumSouth	2.2	2.5	0.3	12.8
Field_AnnerveenVeendam	1.8	3.5	1.7	91.1
Total for the peripheral fields	34.4	39.5	5.1	14.8

Other compartments:				
Aquifer_Feerwerd	0.0	0.0	0.0	-1.1
Aquifer_SaaksumOost	0.0	0.0	0.0	-7.3
Aquifer_AnnerveenVeendam	0.0	0.0	0.0	-7.5
Aquifer_Bedum	1.2	1.2	-0.1	-4.1
Aquifer_Rysum	0.0	0.0	0.0	-9.1
Aquifer_Rodewolt	1.5	1.5	-0.1	-4.3
Aquifer_Kielwindeweer	0.0	0.0	0.0	-7.6
Aquifer_Usquert	0.0	0.0	0.0	-13.2
Aquifer_Moewensteert	0.0	0.0	0.0	-2.4
Aquifer_Lauwersee4	0.0	0.0	0.0	-8.9
Aquifer_Lauwersee3	0.0	0.0	0.0	-4.2
Aquifer_Lauwersee2	0.1	0.1	0.0	0.0
Aquifer_Lauwersee1	0.0	0.0	0.0	-8.1
Model_activeBlocks	0.7	0.7	0.0	-4.9
Total for other compartments	3.6	3.4	-0.1	-4.2
Total	2961.7	2869.8	-91.9	-3.1
Total reservoir	2961.7	2869.8	-91.9	-3.1

6.3.5.2 Detailed Conclusions and Recommendations

As described in the 2013 report by SGS, [1] page 73, for the 2012 model NAM has established an uncertainty range on GIIP of +/- 5% around the most likely value. Therefore the difference in the gas volumes between the static and the dynamic model of the Groningen field is just within the uncertainty range. More justification and reconciliation by NAM of the difference is desirable in future modelling, see also section 5.2.3.

The dynamic model is not suitable for pressure prediction of the adjacent fields Kiel-Windeweer, Feerwerd, and Annerveen-Veendam, due to the very large GBV multipliers implemented for matching. Therefore GIIP differences between static and dynamic models are too large for the adjacent fields and additional integrated modelling would be required to make forecasts for the adjacent fields.

6.4 HISTORY MATCHING

6.4.1 ANALYSIS

The following analyses on history match quality were performed by SGS:

- Pressure match quality
- Water production match quality
- Water movement match quality

The objective of the overall model review match was, amongst others, the appropriateness of the model for preparation of production forecasts for the future reservoir pressure distribution over time in the field, based on depletion scenarios where the offtake may be variable between areas of the field. Therefore, particular emphasis was paid to the history match for each Cluster.

A similar analysis method as used in the 2013 SGS review [1] was applied for the current review. Different was that a distinction was made between Cluster wells, non-producing wells within the Groningen field and wells in adjacent fields.

The tubing head pressure match quality was not reviewed by SGS, as discussed in section 6.2.

6.4.2 OBSERVATIONS

6.4.2.1 Pressure match quality

To perform the pressure match quality analysis by SGS all wells in the dynamic model had been divided by NAM into 4 groups in the MoReS deck:

- Clusters
- Observation wells
- Land wells
- Injection wells

The Land wells are wells in the adjacent fields (also denoted as peripheral fields). The injection wells are used for injection of water. It is observed by SGS that the subdivision between Observation wells and Land wells is not entirely logical; for instance the “observation well” WMLA1 appears to be in an adjacent field. Table 6-5 shows in which compartments and adjacent fields the Observation wells and Land wells are located.

The maximum pressure mismatch (= difference between measured and simulated reservoir pressure) was evaluated by SGS for 3 separate time periods: 1956-2003, 2004-2009 and 2010-2015. The diagrams for the Clusters, Observation wells, and Land and Injections wells are presented in Figure 6-6 to Figure 6-8, Figure 6-9 to Figure 6-11, Figure 6-12 to Figure 6-14 respectively.

The color code for Clusters/Wells was set according to the following rules: green – the mismatch is < ±5 bars; yellow – the mismatch is ±5 up to ±10 bars; red – the mismatch is > ±10 bars [1]. It is highlighted that it is not possible to observe the match for every measured pressure point during the whole production history using these diagrams. The diagrams show only the maximum pressure difference between measured and simulated pressure for the particular period.

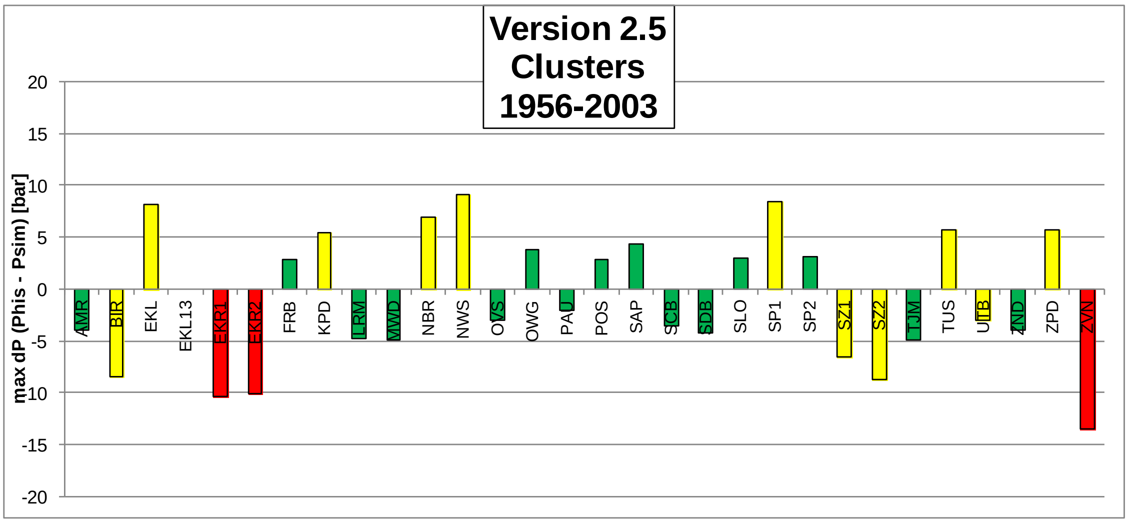


Figure 6-6 Pressure mismatch plot for Clusters (1956-2003)

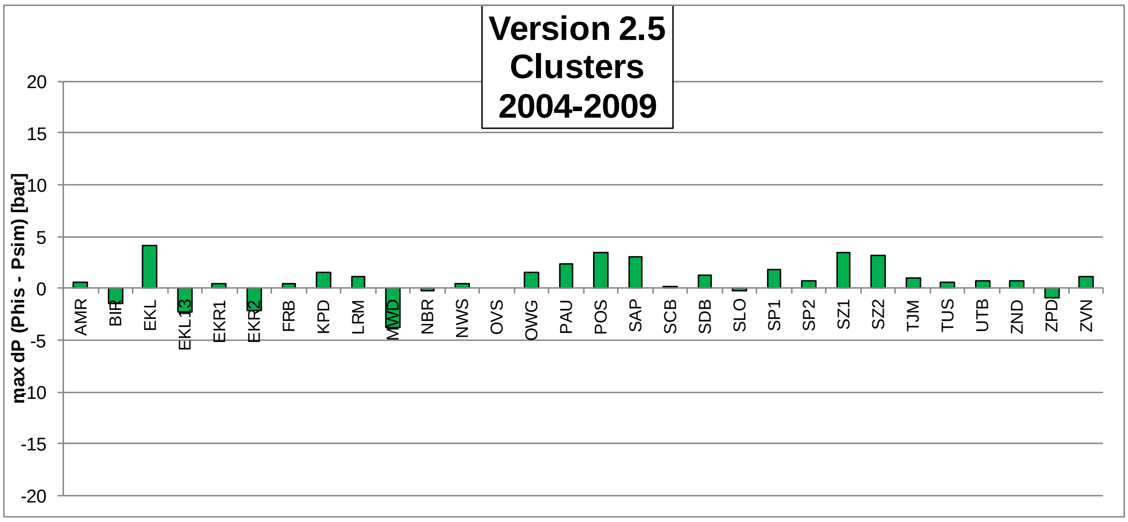


Figure 6-7 Pressure mismatch plot for Clusters (2004-2009)

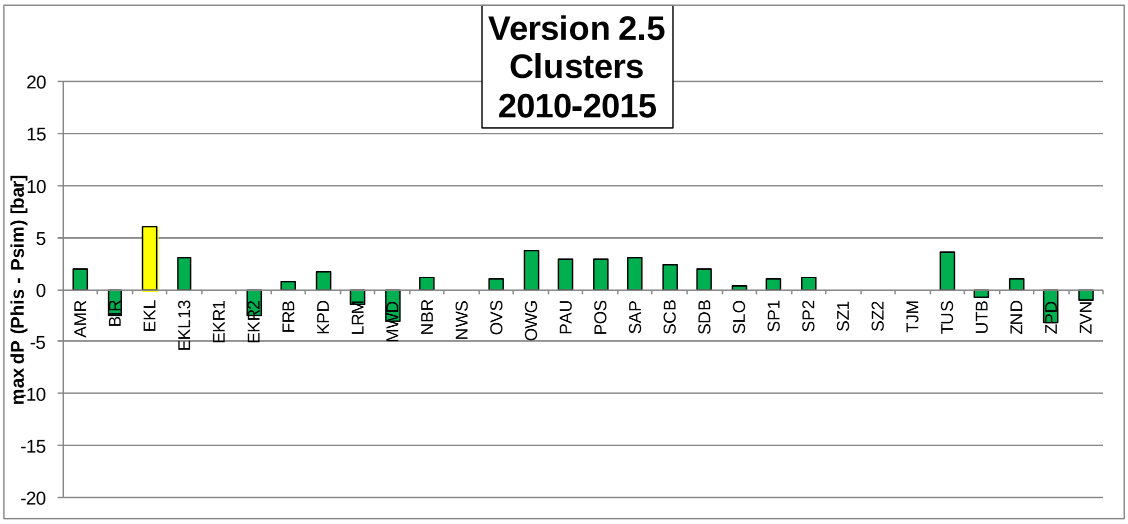


Figure 6-8 Pressure mismatch plot for Clusters (2010-2015)

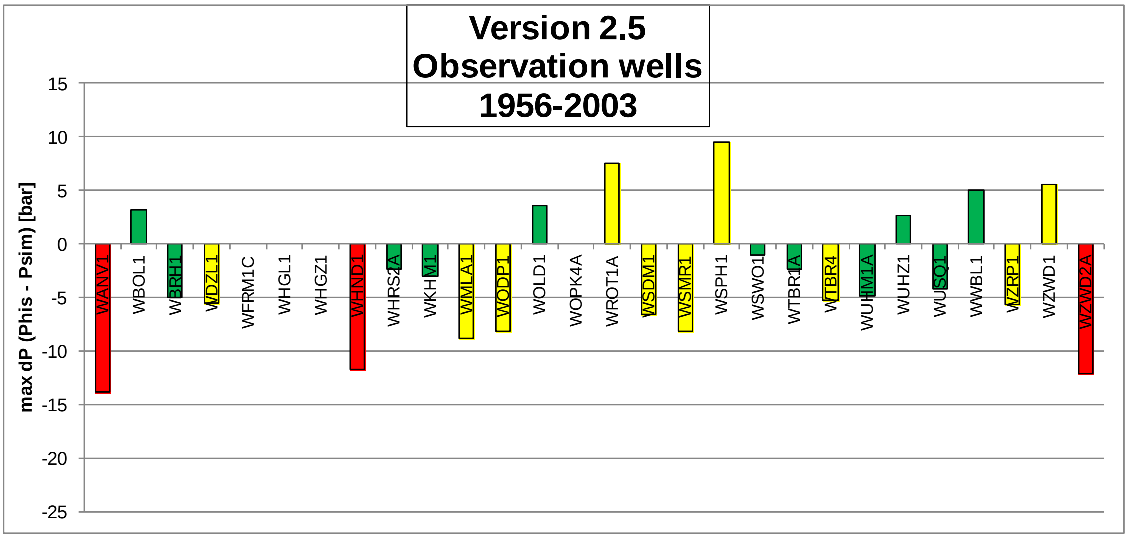


Figure 6-9 Pressure mismatch plot for Observation wells (1956-2003)

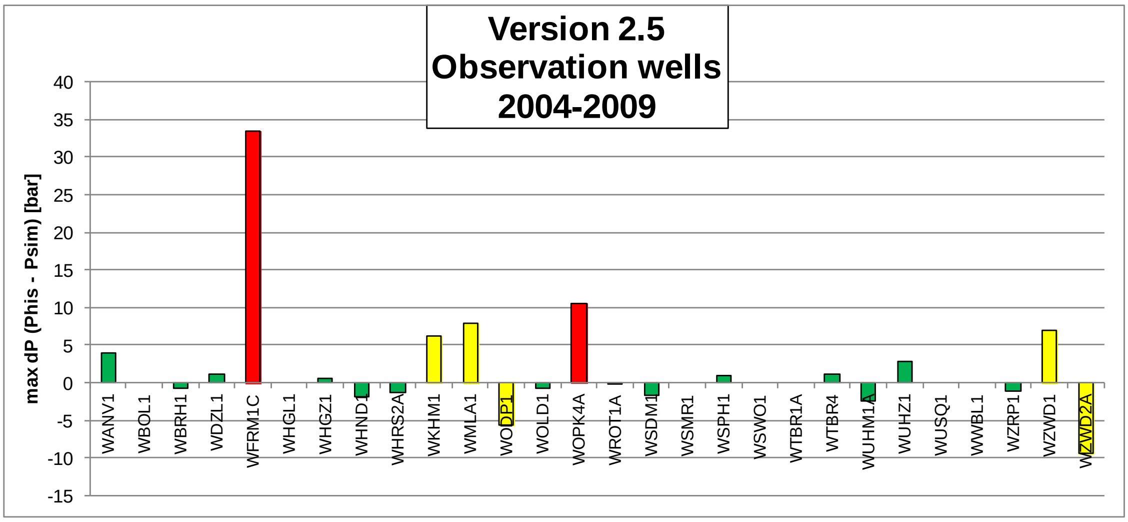


Figure 6-10 Pressure mismatch plot for Observation wells (2004-2009)

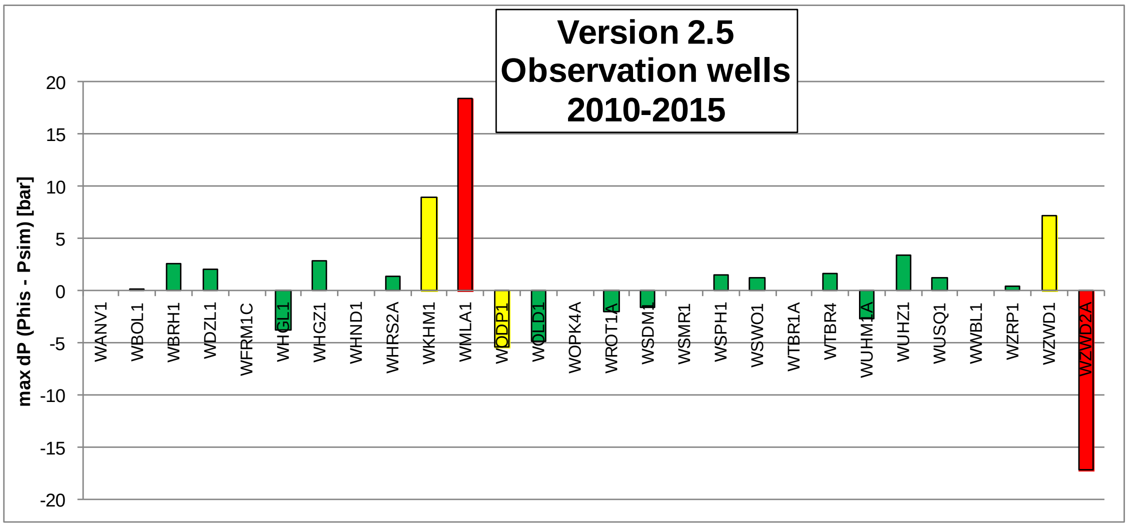


Figure 6-11 Pressure mismatch plot for Observation wells (2010-2015)

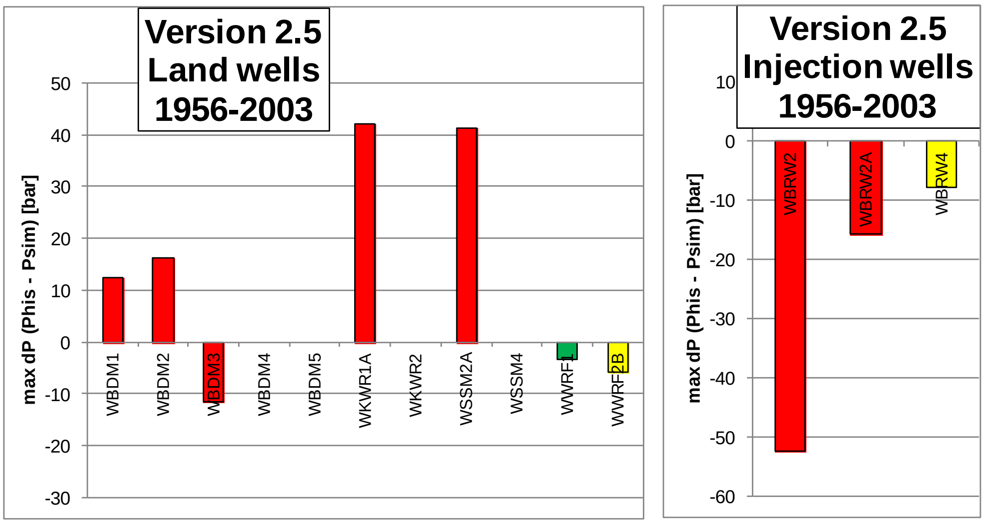


Figure 6-12 Pressure mismatch plot for Land wells and Injection wells (1956-2003)

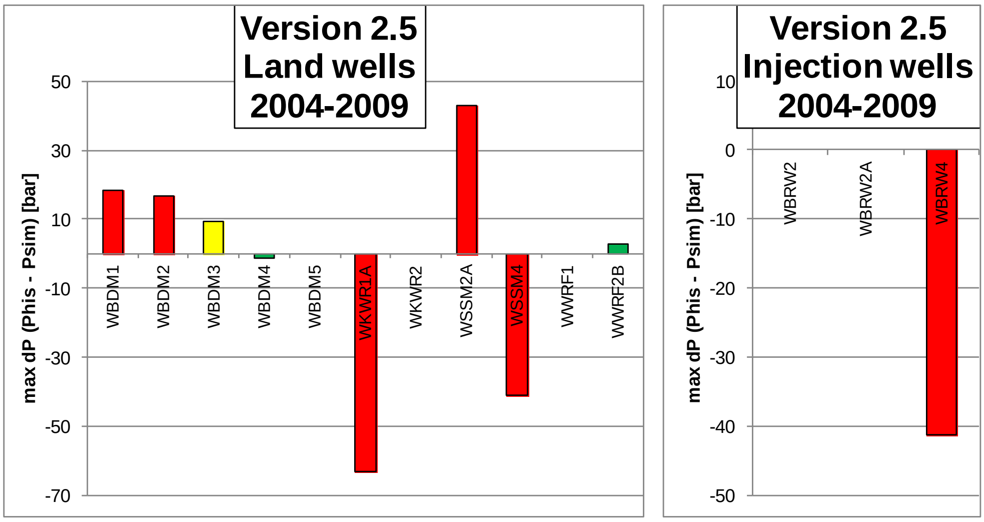


Figure 6-13 Pressure mismatch plot for Land wells and Injection wells (2004-2009)

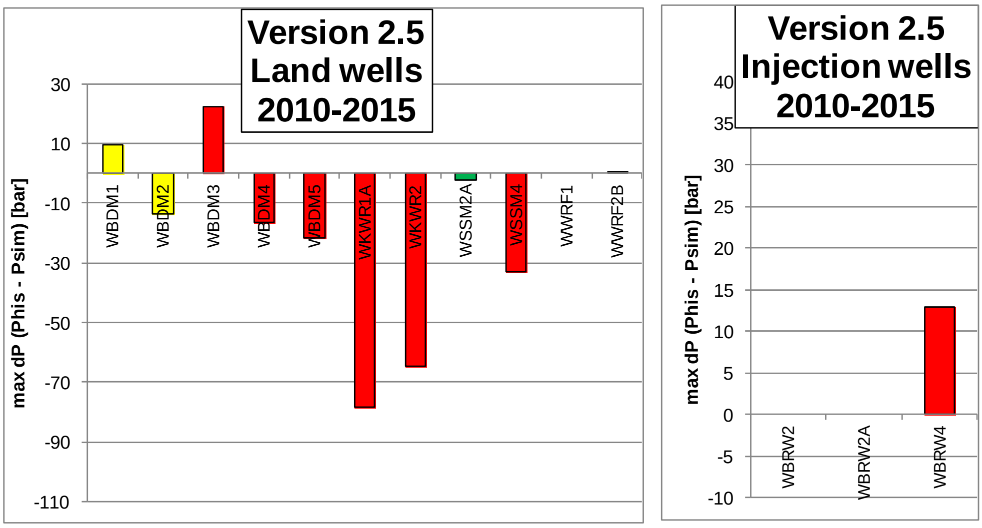


Figure 6-14 Pressure mismatch plot for Land wells and Injection wells (2010-2015)

The largest pressure mismatch for Clusters occurs in the period 1956-2003. 13 Clusters out of 30 have a maximum pressure mismatch of ±5 up to ±10 bars (10 Clusters) and >±10 bars (3 Clusters). Other Clusters show a mismatch of < ±5 bars. In period of 2004-2009 all Clusters have a mismatch of less than ±5 bars. In the period of 2010-2015 all Clusters have a mismatch of less than ±5 bar (see Figure 6-6 - Figure 6-8), except for the EKL Cluster.

The general observations from the plots for the Cluster group are:

1) during the period of 1956-2003 the maximum pressure mismatch for the majority of the Clusters is less than ±5 bars;

2) the period of 2004-2015 shows good pressure match for the Clusters.

Further analysis for the pressure match of the Clusters is provided later in this section.

Observation wells show the same behaviour as the Cluster group. The highest pressure mismatch is observed in 1956-2003. 10 wells out of 28 have a mismatch of ±5 up to ±10 bars. 3 wells have a mismatch of more than ±10 bars. 4 wells do not have measured pressure points for this period. The maximum mismatch for 11 Observation wells is < ±5 bars. The period of 2004-2009 shows that a mismatch for 5 wells is ±5 up to ±10 bars. 3 wells have a mismatch of more that ±10 bars. In 2010-2015 a maximum pressure mismatch for 3 Observation wells is ±5 up to ±10 bars and more than ±10 bars for 2 wells (see Figure 6-9 - Figure 6-11).

No trend on match quality is observed for the Land and Injection wells for the 3 periods. The majority of the wells show a pressure mismatch of more than ±10 bars (see Figure 6-12 - Figure 6-14).

Additional plots of measured pressure versus simulated pressure were created for each group for the period of 1956-2015 to further evaluate the pressure match for each measured pressure point, different from the plots above which only show the maximum pressure mismatch. The plots are presented in Figure 6-15 to Figure 6-18.

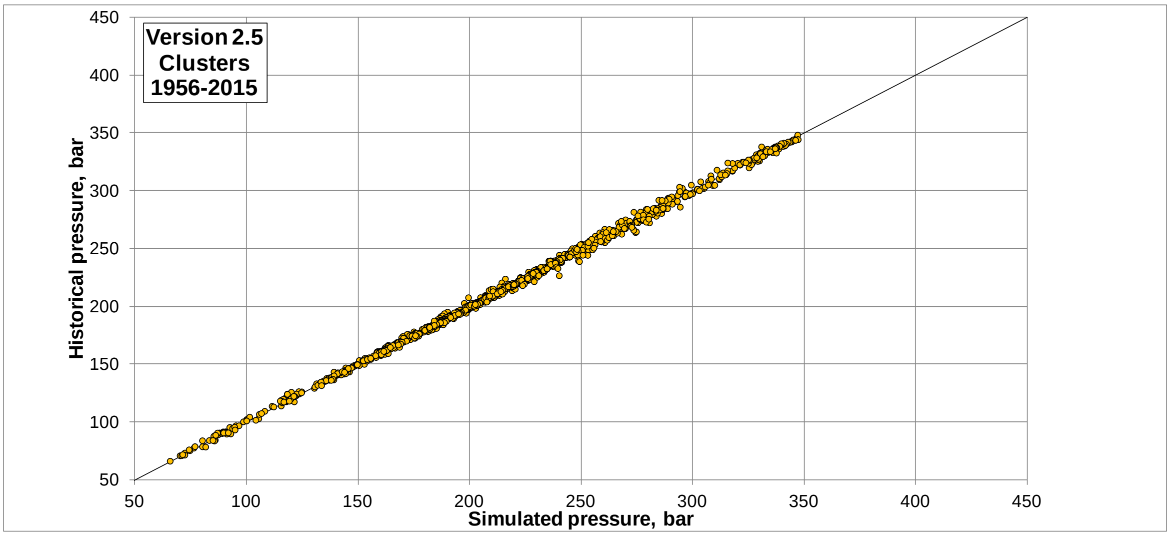


Figure 6-15 Measured vs. simulated pressures for Clusters

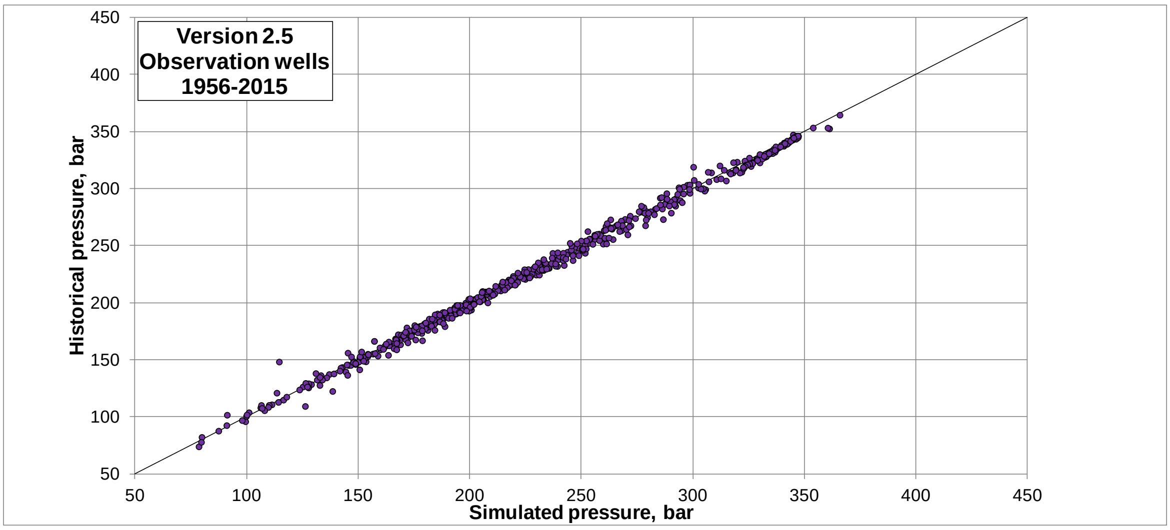


Figure 6-16 Measured vs. simulated pressures for Observation wells

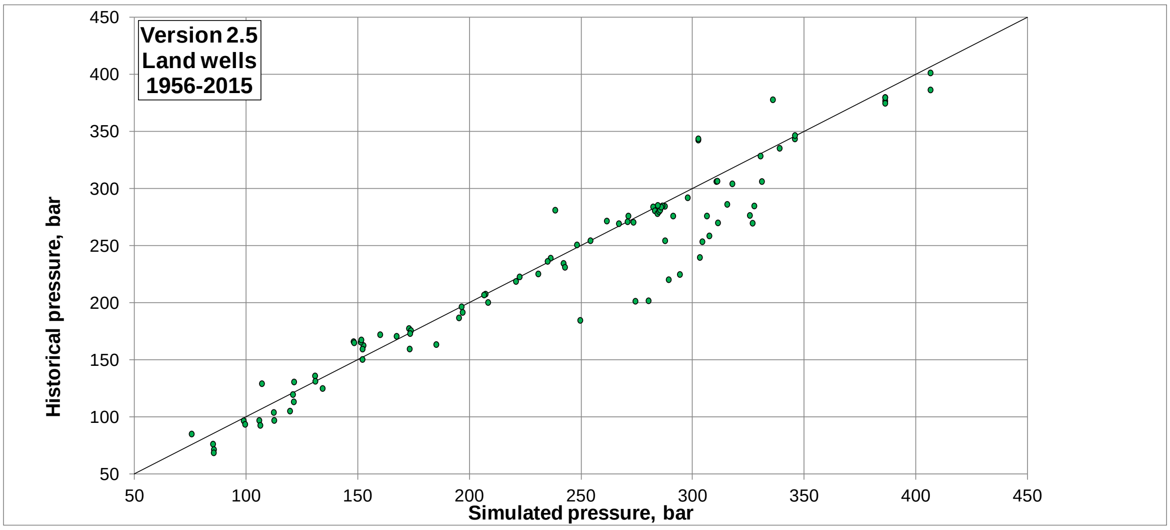


Figure 6-17 Measured vs. simulated pressures for Land wells

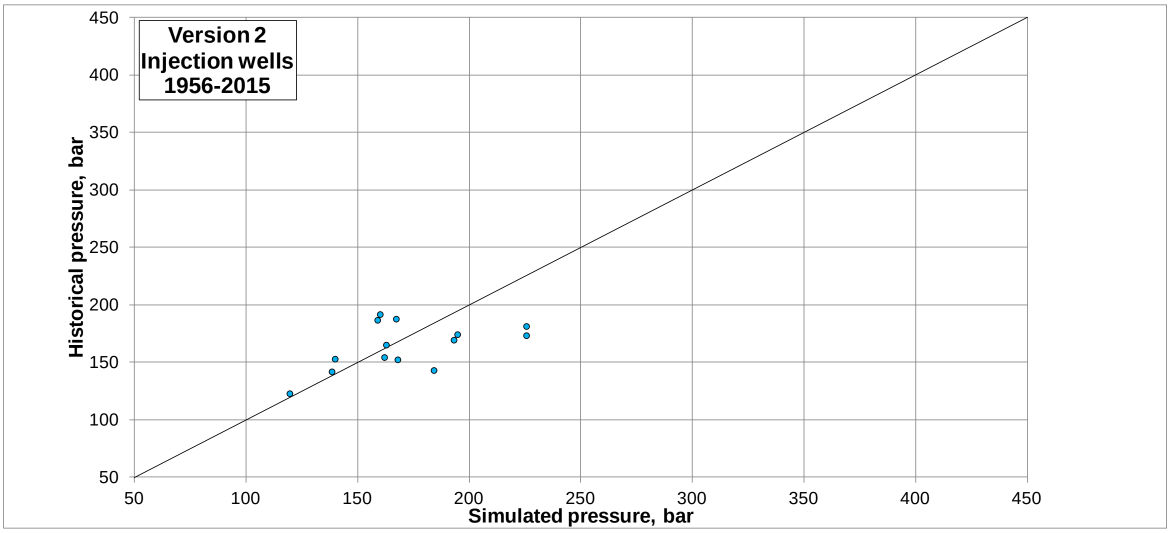


Figure 6-18 Measured vs. simulated pressures for Injection wells

The Clusters points mainly lie on the line of 45° (zero mismatch if a point falls on this line). A more detailed analysis for the Clusters was performed, splitting up these plots by time period. This demonstrates that the pressure match is improving with pressure reducing (better match since 1990) (see Figure 6-19 - Figure 6-22). The plot in Figure 6-23 focuses on the period of 2010-2015. The majority of the wells presented in the plot show the pressure match within ±3 bars except the wells of the Eemskanaal (EKL) Cluster as highlighted with red circle. A further additional pressure match analysis for Clusters is discussed later in this section (Figure 6-26).

The Observation wells points have a range around the 45° line slightly wider compared to the Clusters points (see Figure 6-16). Land and Injection wells show a less good pressure match quality. The point deviation from the line of 45° is considerable for some of these wells (see Figure 6-17 and Figure 6-18).

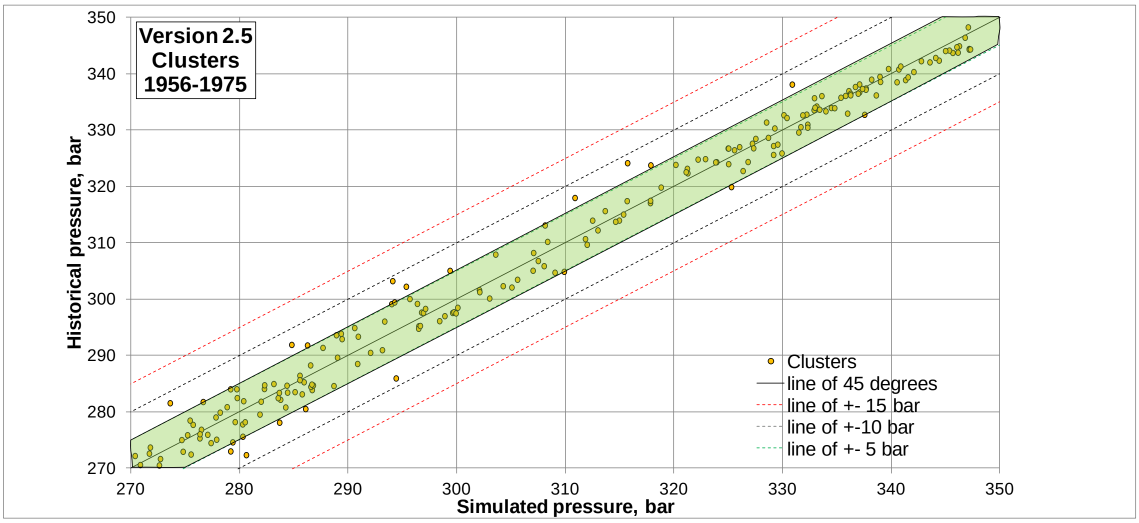


Figure 6-19 **Clusters measured vs. simulated pressure for the period of 1956-1975**

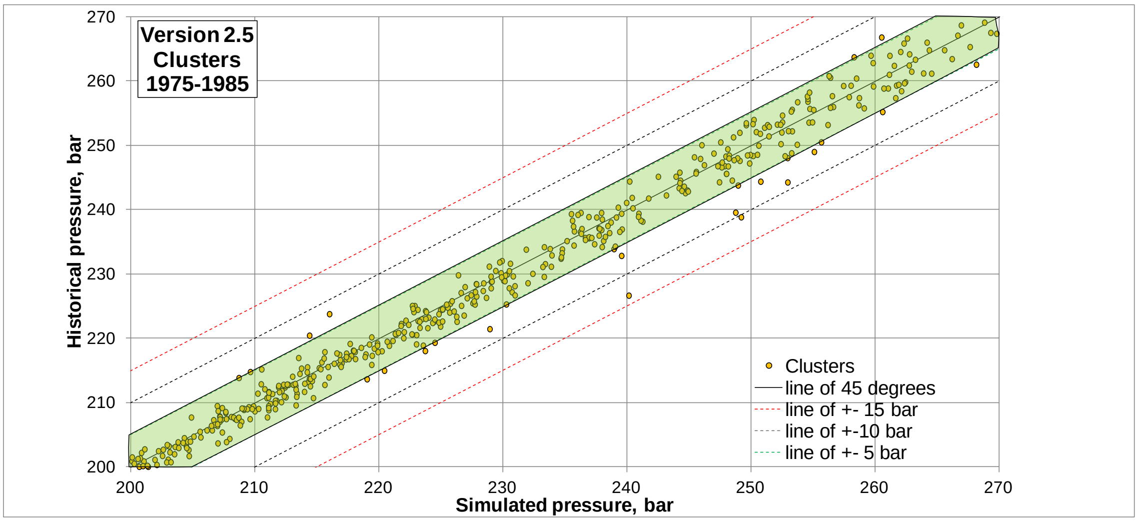


Figure 6-20 **Clusters measured vs. simulated pressure for the period of 1975-1985**

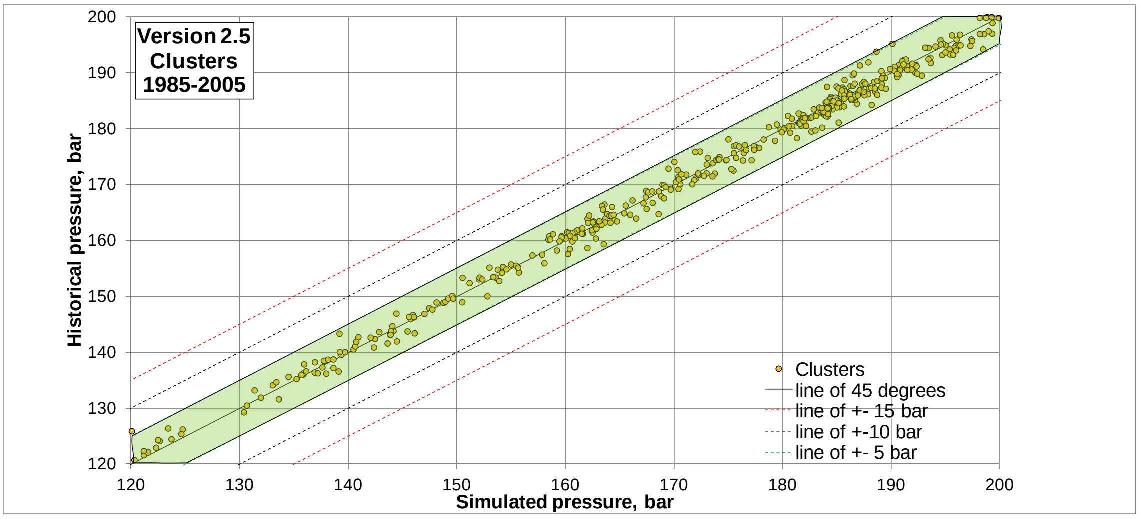


Figure 6-21 Clusters measured vs. simulated pressure for the period of 1985-2005

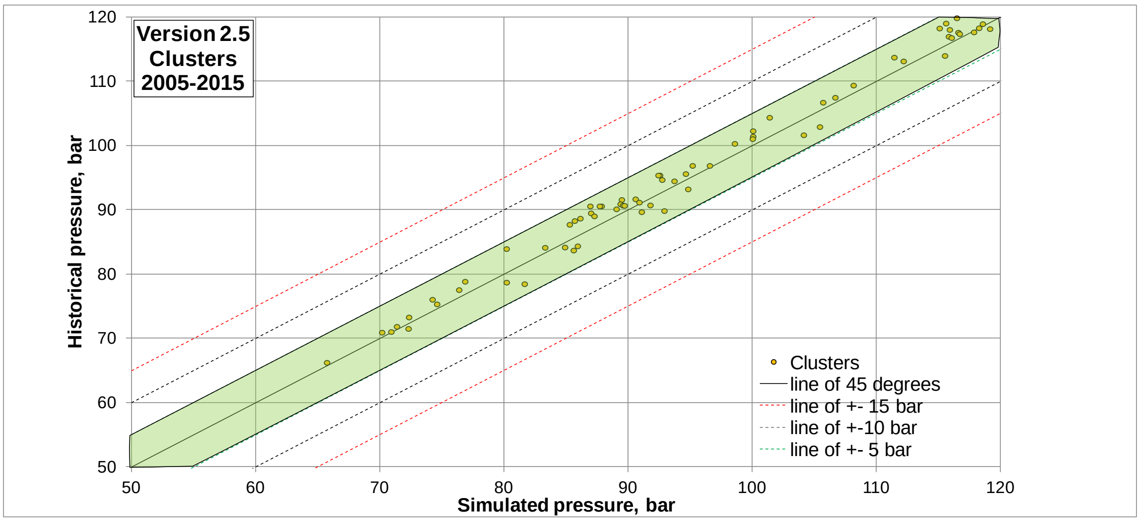


Figure 6-22 Clusters measured vs. simulated pressure for the period of 2005-2015

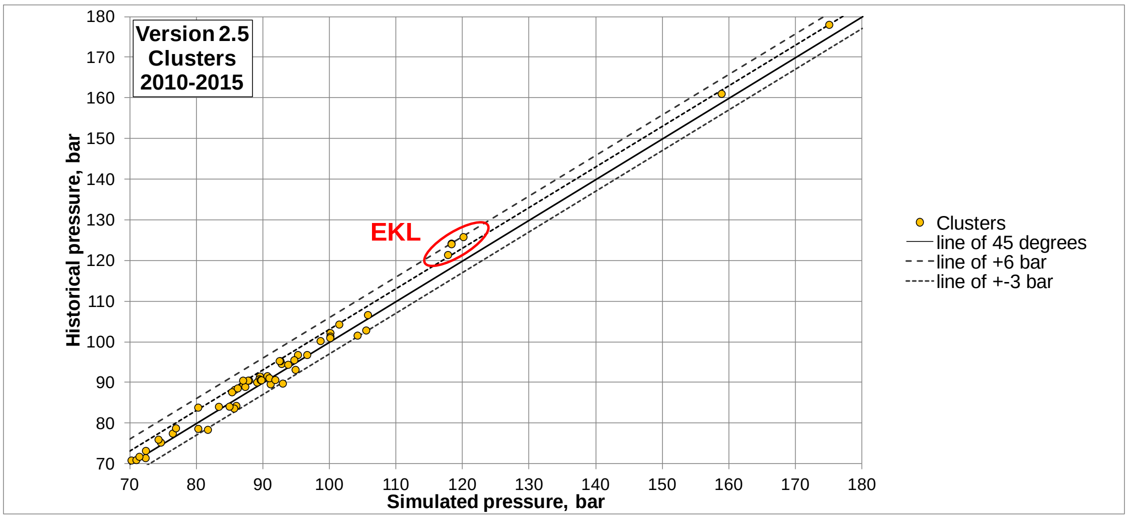


Figure 6-23 Clusters measured pressure vs. simulated pressure for the period of 2010-2015

An analysis of historical gas production volumes of the Clusters was performed, to identify the major producing clusters, and to identify any systematic trends in pressure match between different types of clusters. It was also reviewed if the recent change in production policy of the Groningen field caused a systematic mismatch.

To identify the major Clusters-producers in Groningen field the historical cumulative gas production versus time plot was created by SGS, Figure 6-24.

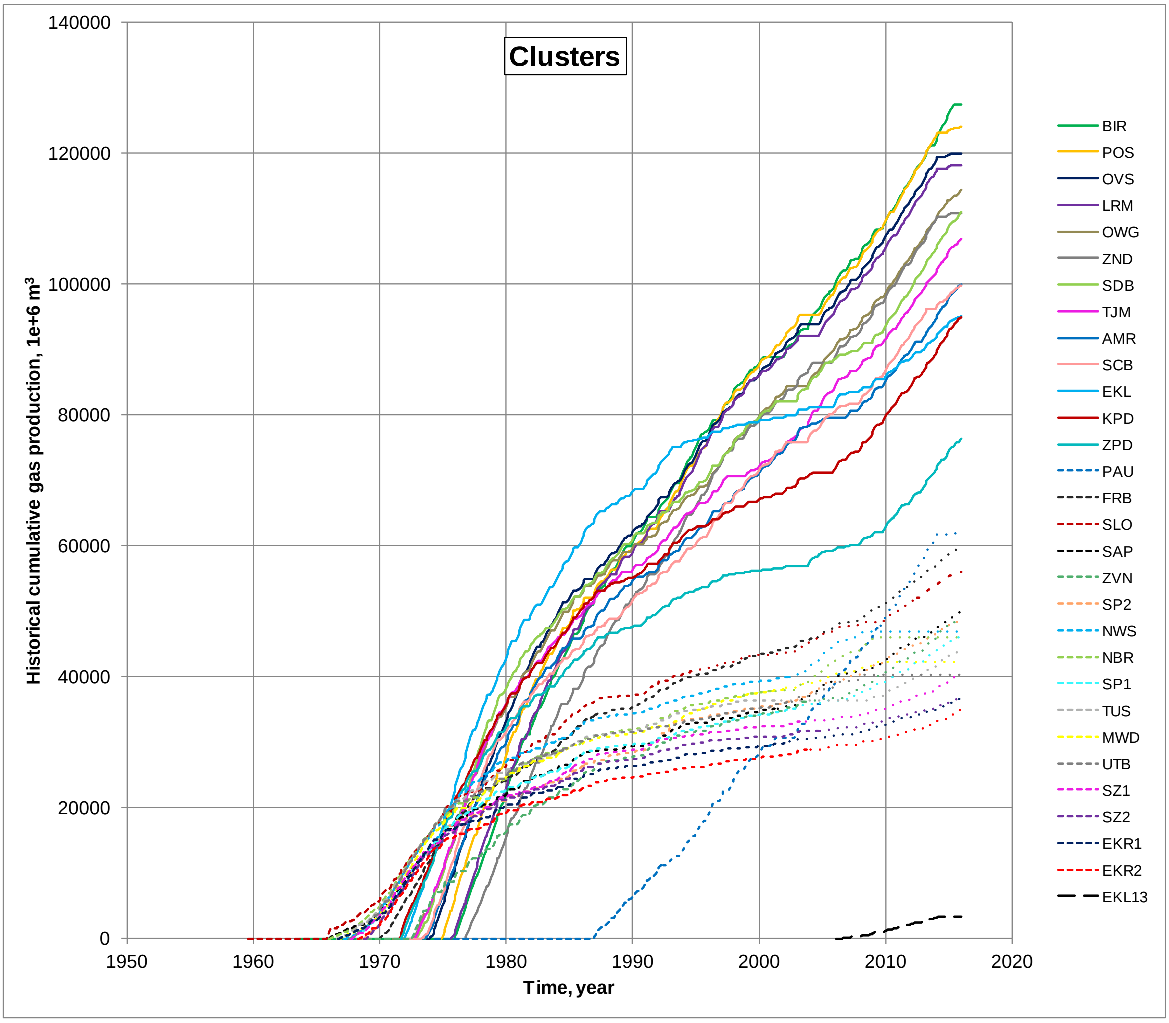


Figure 6-24 Historical cumulative gas production for Clusters (until 31 Dec. 2015)

As can be observed from Figure 6-24, the Clusters can be divided into 2 groups depending on the cumulative gas production by January 2016. Cumulative gas production for the first group of Clusters is more than 75 x 10^9 Nm^3. The second group has cumulative gas production of less than 75 x 10^9 Nm^3.

The biggest Clusters-producers in order from the biggest to the smallest ones (the 1st group) are BIR, POS, OVS, LRM, OWG, SDB, ZND, TJM, AMR, SCB, EKL, KPD and ZPD. The following Clusters are included in the second group: PAU, FRB, SLO, SAP, ZVN, SP2, NWS, NBR, SP1, TUS, MWD, SZ1, UTB, SZ2, EKR1, EKR2 and EKL13 (see Table 6-7).

It is apparent from Table 6-7 that there is a limited amount (as judged by SGS) of static pressure measurements in period 2010 to 2015 for the Clusters.

Table 6-7 Gas production (historical) and maximum pressure match mismatches for Clusters

Cluster	Cumulative gas production historical, 1e+6 m^3	Cumulative gas production historical, 1e+9 m^3	Av. monthly gas production for Jan-Dec 2015, 1e+6 m^3	Max. error Phis-Psim Years 2010-2015, bar	Year last pressure measurement	GIIP, 1e+9 m^3
Groningen_NE						
BIR	127,550	576.8	126	-2.5	2015	969.7 (33.2%)
LRM	118,207		21	-1.4	2013	
OVS	120,066		26	1.0	2010	
ZND	110,928		25	1.0	2014	
AMR	100,032		180	2.0	2012	
Groningen_NW						
POS	124,040	186.0	46	2.9	2015	495.4 (16.9%)
PAU	61,983		19	3.0	2014	
Groningen_E						
OWG	114,428	432.3	133	3.8	2015	464.6 (15.9%)
SDB	111,075		193	2.0	2015	
TJM	106,932		168	-	2009	
SCB	99,882		138	2.4	2015	
Groningen_SW						
KPD	95,031	566.2	188	1.7	2011	354.8 (12.1%)
FRB	59,697		77	0.8	2015	
SLO	56,106		60	0.3	2015	
SAP	49,955		90	3.0	2012	
ZVN	48,849		59	-1.0	2013	
SP2	48,563		65	1.1	2012	
SP1	46,085		71	1.1	2015	
TUS	44,026		68	3.6	2012	
UTB	40,334		0	-0.8	2014	
SZ1	40,675		102	-	2006	
SZ2	36,885		63	-	2006	
Groningen_Central						
ZPD	76,383	169.5	160	-3.2	2014	206.5 (7.1%)
NWS	46,994		0	-	2006	
NBR	46,122		0	1.2	2014	
Groningen_SE						
MWD	42,238	114.1	0	-3.0	2013	121.1 (4.1%)
EKR1	36,854		79	-	2005	
EKR2	34,997		88	-2.5	2014	
Gron_Eemskanaal						
EKL	95,131	95.1	95	6.0	2011	104.1 (3.6%)
Gron_Harkstede						
EKL13	3,327	3.3	0	3.1	2014	11.9 (0.4%)

Notes:

% in GIIP column indicates the GIIP fraction for a compartment out of the total GIIP for Groningen field (2923.7 1e+9 m^3)

🟧	Compartment
🟥	Pressure max error is ≥ 3.75 bars

The average monthly gas production for the period of January – December 2015 for 5 Clusters is less than 50 x 10^6 Nm^3 (LRM, OVS, ZND, POS and PAU). 5 Clusters were not producing during this period (UTB, NWS, NBR, MWD and EKL13). 20 Clusters out of 30 have the 2015 average monthly gas production of more than 50 x 10^6 Nm^3 as indicated in Table 6-7.

The Clusters with both cumulative gas production less than 75 x 10^9 Nm^3 and 2015 average monthly gas production less than 50 x 10^6 Nm^3 are: PAU, UTB, NWS, NBR, MWD and EKL13.

From the Table 6-7, no systematic trends in pressure mismatch between different types of clusters (different with respect to gas production) were observed by SGS.

A further pressure match analysis was performed by SGS. The reservoir pressure by December 2015 equals to 70-80 bars (see Figure 6-25). Therefore 5% of the current reservoir pressure equals 3.75 bar. Only the producing EKL Cluster has a maximum pressure mismatch of 6.0 bars for the period of 2010-2015 that is more than 5%.

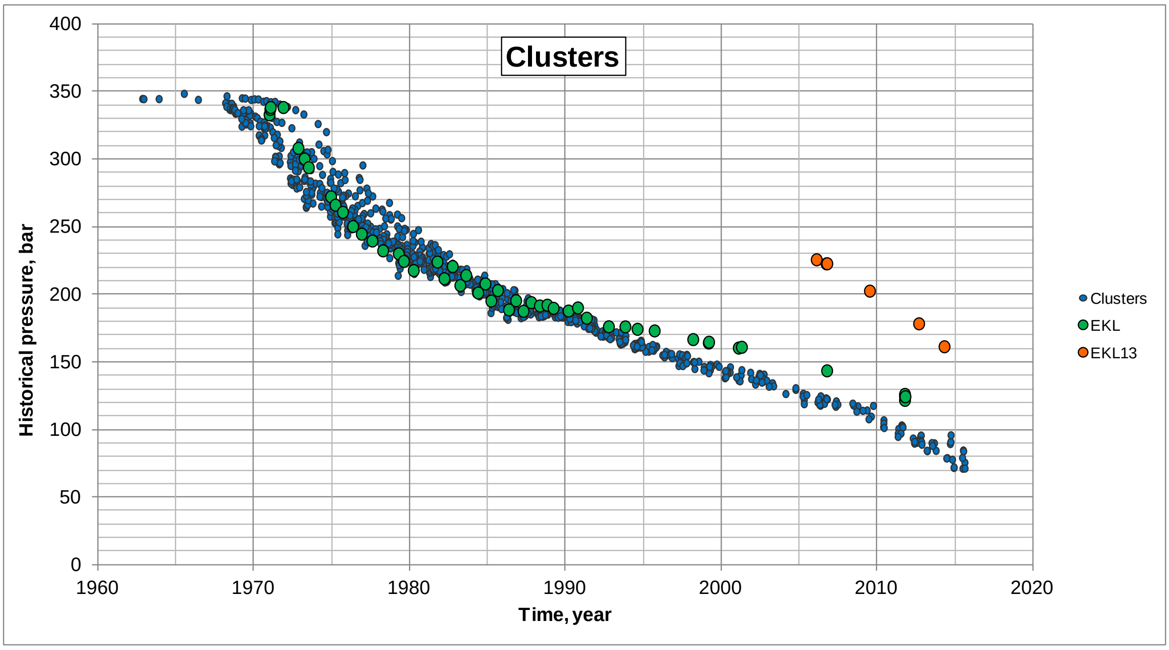


Figure 6-25 Measured pressures for Clusters

The pressure mismatch plot for all measured pressure points for Clusters, now plotted against time, is shown in Figure 6-26. It can be concluded that the pressure match quality for the Clusters was improved compared to the 2012 model (see [1], pages 115 to 117), in the 2015 model there is no significant trend of pressure mismatch against time.

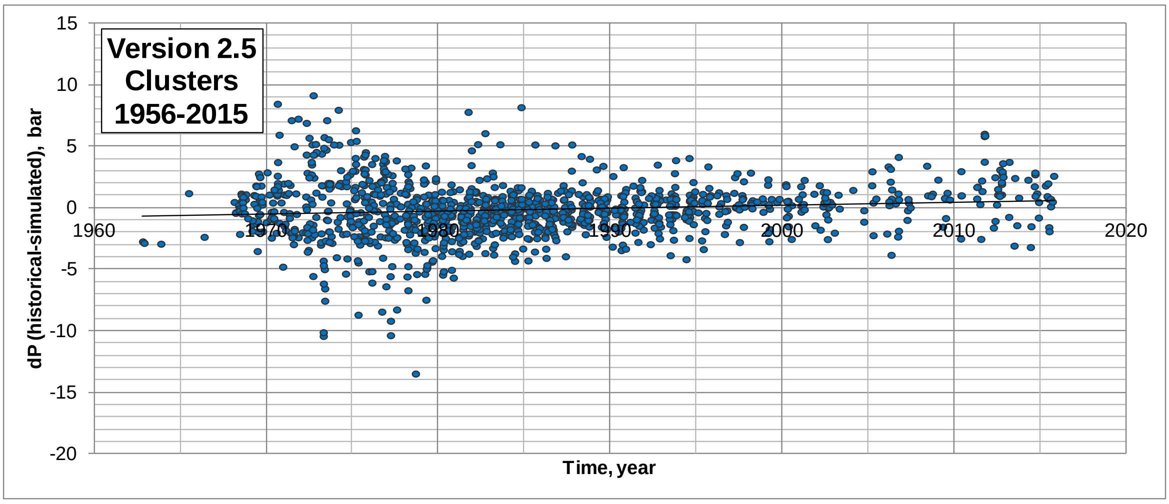


Figure 6-26 **Pressure mismatch plot for Clusters**

6.4.3 DETAILED CONCLUSIONS AND RECOMMENDATIONS

The pressure match on the Clusters is very good. Exception is the cluster Eemskanaal (EKL), this cluster if rather isolated in the field and model, and the mismatch on this cluster does not change the overall conclusion. As illustrated by Figure 6-26, there is no significant trend of pressure mismatch against time, which is a strong indicator that the overall field depletion mechanism is honoured by the dynamic model.

The objective of the model, as communicated by NAM to SGS, was to predict reservoir pressure in the Groningen field. Therefore the match quality in adjacent fields is not of high importance for this review.

A further improvement of pressure match quality is desirable for some Land and Injection wells should a more accurate pressure prediction in those areas be required. This applies specifically for the adjacent fields Bedum and Midlaren and the Zuidwending East area.

Most of Observation wells have an increasing or decreasing pressure mismatch trend. However, at least 5 of them would need pressure match improvement because the maximum mismatch for 2010-2015 period is more than 3.75 bars (5% of the current reservoir pressure). The list of these wells is KHM1, MLA1, ODP1, ZWD1 and ZWD2A. Most of these wells appear to be in adjacent fields. A further improvement of pressure match quality is desirable for the Observation wells in the Groningen field, which are in the peripheral areas of the field outside the production clusters, should a more accurate pressure prediction in those areas be required.
The match quality results, as assessed by SGS, are summarised in Table 6-8 following the same scheme as in the 2013 report [1].

The pressure match quality was ranked from 1 to 3. The value of 1 (green color) is related to the maximum pressure mismatch of less than ±5 bars. The value of 2 (yellow color) shows the pressure mismatch of ±5 up to ±10 bars. The highest value of 3 (red color) indicates a mismatch of more than ±10 bars.

Table 6-8 Reservoir pressure match quality summary

Cluster/ well	Abbreviation	Match quality	Comments
Amsweer	AMR	1	1) prior 1990 simulation pressure is slightly overestimated; 2) since 1990 it is slightly underestimated, pressure difference is increasing, but it is ≤ ±5 bars, further observation is required
Bierum	BIR	1	1) prior 1980 simulation pressure is overestimated, 7 pressure difference points in 1974-1980 are < -5 bar up to -10 bars; 2) since 1980 the pressure trend is OK
Eemskanaal	EKL	2	1) prior 1987 some of the pressure difference points are < +5 bars up to +10 bars; 2) 2 points in 2011 are< -5 bars up to -10 bars, further observation is required
Eemskanaal/HRS	EKL13	1	-
De Eeker 1	EKR1	1	1) only 2 pressure difference points in 1972-1973 are < -5 bars up to -10 bars; 2)the pressure trend is OK
De Eeker 2	EKR2	1	1) 1 pressure difference point in 1973 is >-10 bars; 1 point in 1979 is < -5 bars up to -10 bars; 2) the pressure trend is OK
Froombosch	FRB	1	1) prior 2000 the pressure mismatch trend is slighlty underestimated
Kooipolder	KPD	1	1) prior 1983 only 3 pressure difference points are < +5 bars up to +10 bars
Leermens	LRM	1	-
Midwolda	MWD	1	1) simulation pressure is slightly underestimated; 2) further observation is required
Noordbroek	NBR	1	1) prior 1974 the simulation pressure is overestimated, 5 pressure difference points are < +5 bars up to +10 bars; 2) since 1974 pressure trent is OK
Nieuw Scheemda	NWS	1	1) prior 1975 simulation pressure is underestimated, 5 pressure difference points are < +5 bars up to +10 bars; 2) since 1975 pressure trend is OK
Overschildt	OVS	1	1) prior 1990 simulated pressure is slightly overestimated
Oudeweg	OWG	1	1) pressure error is within the range of < ±5 bars, further observation is required
De Paauwen	PAU	1	1) since 1990 the pressure difference is increasing, the pressure difference is still ≤ +5 bars, but the further observation is required
Ten Post	POS	1	1) since 1980 the pressure difference is increasing, the pressure difference is still ≤ +5 bars, but the further observation is required
Sappemeer	SAP	1	1) pressure error is within the range of < ±5 bars, further observation is required
Schaapbulten	SCB	1	1) pressure error is within the range of < ±5 bars, but the trend is increasing, further observation is required
Siddeburen	SDB	1	1) prior 1990 simulation pressure is slightly overestimated; the pressure difference is increasing; 2) since 1990 simulation pressure is slightly underestimated, further observation is required
Slochteren	SLO	1	1) prior 1990 simulation pressure is slightly underestimated
Spitsbergen 1	SP1	1	1) only 1 pressure difference point in 1970 is < +5 bars up to +10 bars; 2) the pressure trend is OK
Spitsbergen 2	SP2	1	-
Scheemderzwaag 1	SZ1	1	1) in 1973 1 pressure difference point is < -5 bars up to >-10 bars; 2) last measured pressure is in 2006, further observation is required
Scheemderzwaag 2	SZ2	1	1) prior 1980 simulation pressure is slightly overestimated, 4 pressure difference points are < -5 bars up to -10 bars; 2) since 1980 pressure error is < ±5 bars, but further observation is required
Tjuchem	TJM	1	-
Tusschenklappen	TUS	1	1) prior 1980 simulation pressure is slightly underestimated; 2) since 1980 the pressure difference is ≤ ±5 bars, further observation is required
Uiterburen	UTB	1	1) prior 1990 simulation pressure is slightly overestimated; 2) since 1990 the pressure trend is OK
't-Zandt	ZND	1	1) prior 1995 the simulation pressure is slightly underestimated
Zuidpolder	ZPD	1	1) only 3 pressure difference points in 1972-1973 are < +5 bars up to +10 bars
Zuiderveen	ZVN	2	1) prior 1990 simulation pressure is overestimated; only 2 pressure difference points are >-10 bars; 2) since 1990 the pressure trend is OK
Observation well	WANV1	2	1) the simulation pressure is overestimated
Observation well	WBOL1	1	-
Observation well	WBRH1	1	1) the simulation pressure is overestimated; 2) pressure error is within the range of < ±5 bars, but further observation is required
Observation well	WDZL1	1	1) pressure error is within the range of < ±5 bars (only 1 pressure difference point in 1981 is < -5 bars up to -10 bars), but the trend is increasing, further observation is required
Observation well	WFRM1C	3	1) only 1 pressure point exists, further improvement is required
Observation well	WHGL1	1	1) only 1 pressure point exists
Observation well	WHGZ1	1	-
Observation well	WHND1	2	1) the simulation pressure is overestimated
Observation well	WHRS2A	1	1) the simulation pressure is slightly overestimated

Observation well	WKHM1	3	1) 2 pressure difference points in 2014 are > +10 bars, the pressure error trend is increasing, further improvement is required
Observation well	WMLA1	3	1) further improvement is required
Observation well	WODP1	2	1) further observation/improvement is required
Observation well	WOLD1	1	1) the pressure error trend is within the range of < ±5 bars, but decreasing, the firther observation is required
Observation well	WOPK4A	3	1) 2 pressure difference points in 2007 and 2009 are > +10 bar, the further improvement is required
Observation well	WROT1A	1	1) prior 1980 simulation pressure is underestimated, some pressure difference point are < +5 bars up to +10 bars; 2) since 1975 the pressure trend is OK
Observation well	WSDM1	1	1) the simulation pressure is overestimated
Observation well	WSMR1	2	1) prior 1985 simulation pressure is overestimated; 2) since 1985 the pressure trend is OK
Observation well	WSPH1	1	1) the simulation pressure is underestimated
Observation well	WSWO1	1	-
Observation well	WTBR1A	1	-
Observation well	WTBR4	1	1) prior 1980 simulation pressure is overestimated, only 1 pressure difference point is <-5 bars up to -10 bars; 2) since 1980 the pressure error trend is OK
Observation well	WUHM1A	1	1) the simulation pressure is slightly overestimated
Observation well	WUHZ1	1	1) since 1990 the pressure error thend is increasing, the further observation is required
Observation well	WUSQ1	1	-
Observation well	WWBL1	1	1) the pressure difference points are ≤ +5 bars; 2) since 1995 no pressure data are available
Observation well	WZRP1	1	1) the pressure difference points are ≤ +5 bars, but the trend is increasing
Observation well	WZWD1	2	1) simulation pressure is underestimated, pressure difference is increasing, points since 2000 are <+5 bars up to +10 bars, further improvement is required
Observation well	WZWD2A	3	1) further improvement is required
Land well	WBDM1	3	1) further improvement is required
Land well	WBDM2	3	1) further improvement is required
Land well	WBDM3	3	1) further improvement is required
Land well	WBDM4	3	1) further improvement is required
Land well	WBDM5	3	1) further improvement is required
Land well	WKWR1A	3	1) further improvement is required
Land well	WKWR2	3	1) only 1 pressure point exists, further improvement is required
Land well	WSSM2A	3	1) further improvement is required
Land well	WSSM4	3	1) further improvement is required
Land well	WWRF1	1	-
Land well	WWRF2B	1	-
Injection well	WBRW2	3	1) further improvement is required
Injection well	WBRW2A	3	1) only 1 pressure point exists in 2000, further observation/improvement is required
Injection well	WBRW4	1	1) only 1 pressure difference point in 2011 is > +10 bars

Match quality:

1	< ±5 bars
2	±5 bars up to ±10 bars
3	> ±10 bars

As discussed in section 6.2, the coarse grid of the dynamic model can limit the accuracy of any match.

Another limitation of the dynamic model and the history matching is that the historical gas production is applied on Cluster basis. The constraint set in the dynamic model for history matching is cumulative gas production for each cluster. The simulation performs offtake of the gas using the lift tables assigned to the wells and the productivity of each individual well. Calculated well offtake by the model may be different than historical well offtake.

In the dynamic model, pressure build-ups were not simulated explicitly. The simulation steps from one time-step to the next one are set as specified in the MoReS history match table (offtake by month). Wells are producing, in the model, continuously without shut-ins for pressure measurements. In reality, measured reservoir pressure in a well is recorded while the well is shut in. For that reason, the historical pressure would be, as expected by SGS, slightly higher compared to the simulated pressure. This is another limitation to the accuracy of the pressure match.

SGS recommends to add more calibration points for reservoir pressure matching, as there is a limited amount of static pressure measurements in period 2010 to 2015 for the Clusters.

6.4.3.1 Water production match quality

A water production match quality analysis was performed by SGS for the Groningen field Clusters.

The historical versus simulated cumulative water production plot is presented in Figure 6-27. It is observed that the simulated water production is slightly underestimated compared to the historical data.

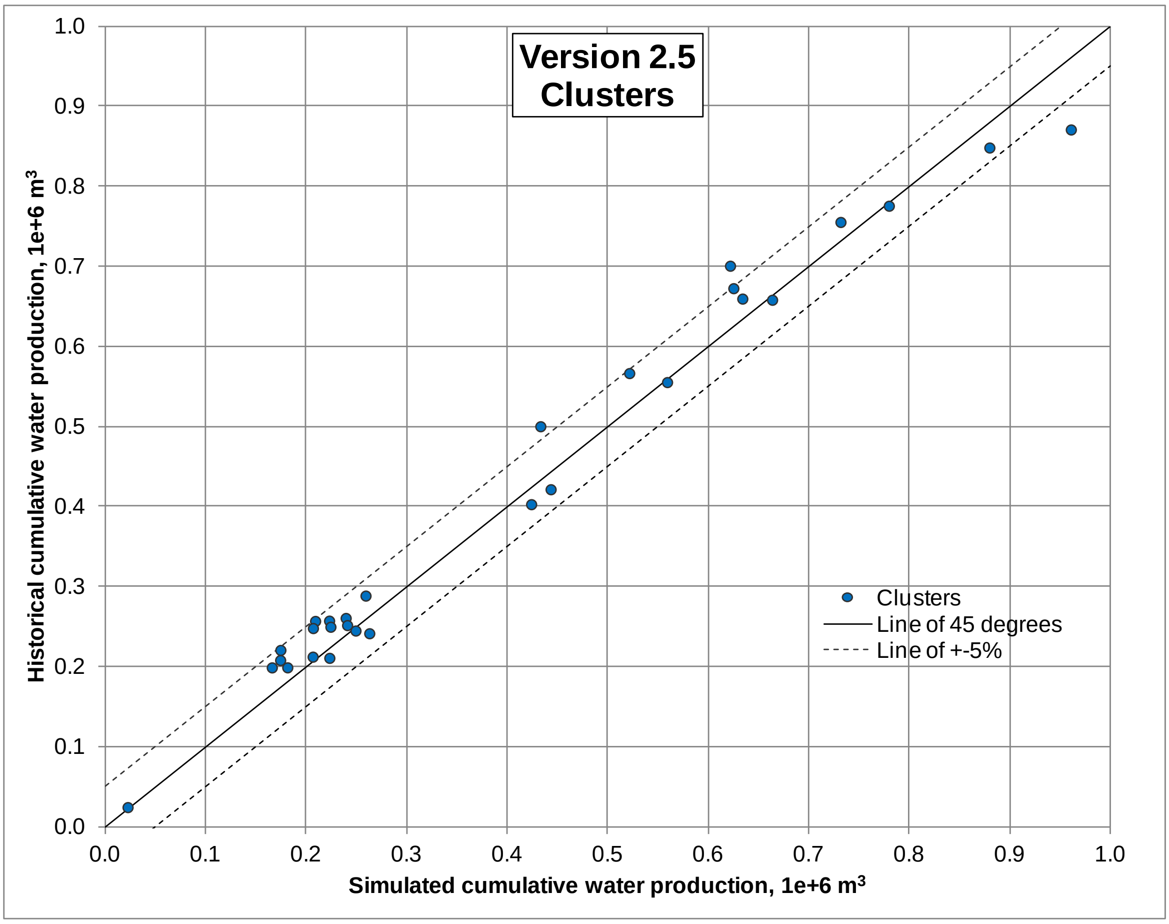


Figure 6-27 Historical vs. simulated cumulative water production for Clusters

The difference between simulated and measured cumulative water production is mostly in a range of ± 5%.

SGS also reviewed for each Cluster the water production match against time. In Figure 6-28 the water production match is shown for Cluster Ten Post (POS) as an example of a Cluster by Cluster match.

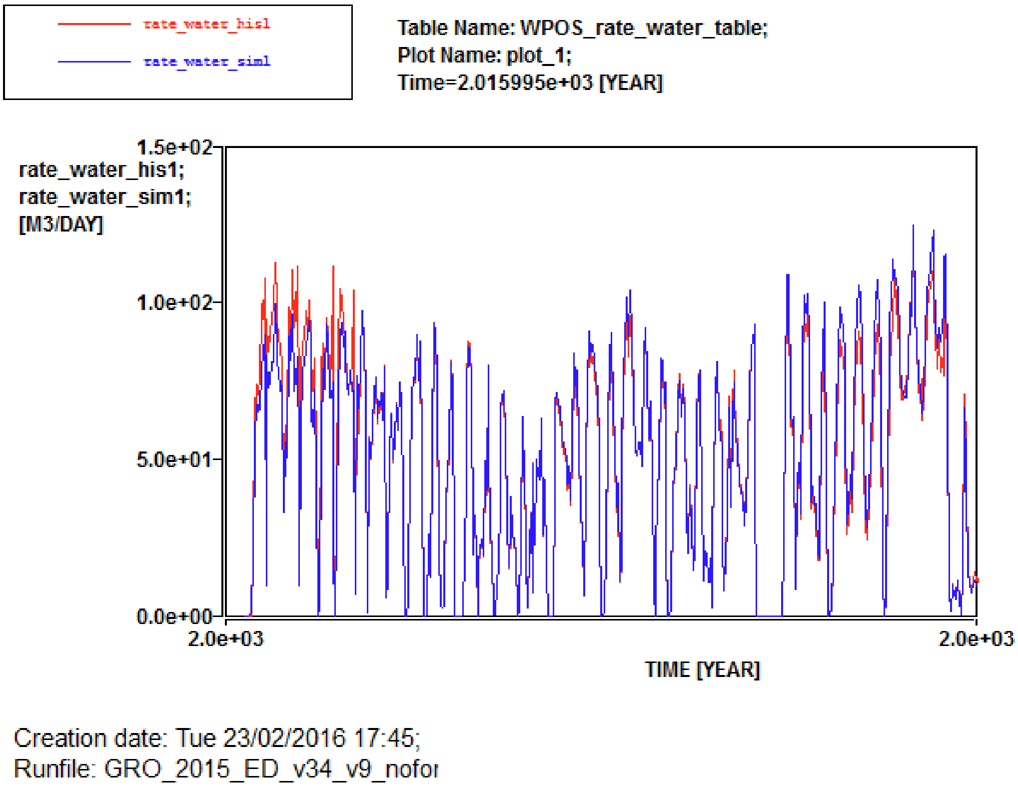


Figure 6-28 Historical (red) and simulated (blue) water rates vs. time for Ten Post Cluster

There was no data provided by NAM on the salinity of the produced water to distinguish if the produced water is only vapour water or also free formation water. The history match was performed by NAM by changing the water salinity as matching parameter in McKetta-Wehe correlation as described in section 6.3.4.

SGS considers the match quality to be good, albeit the method can be argued on, since the water salinity for water volume prediction in the model does not correspond to measured data. Documentation by NAM on their considerations is recommended by SGS.

6.4.3.2 Water movement match quality

A match quality analysis of the formation water movement in the model was performed by SGS.

In order to match the water movement with the simulated GWC, as performed by NAM, the GWC has been tracked using “synthetic” RFT’s. For each well with a PNL survey, the simulated GWC corresponds to the PNL data at the time for the given well. All data points from the existing PNL surveys (36 wells) of the dynamic model were included into the analysis performed for Clusters, Observation wells and Land wells separately. The model shows deviation of water level of mainly ± 20 m from the observed data (see Figure 6-29).

No detailed review of SGS was performed how well the water level rise is matched on a well by well basis, NAM has provided satisfactory documentation on some of those matches. SGS has performed a visual inspection of the water saturation in the MoReS model, showing that overall the water level rise is limited.

SGS considers the match quality good in view of the coarse vertical resolution of the dynamic model.

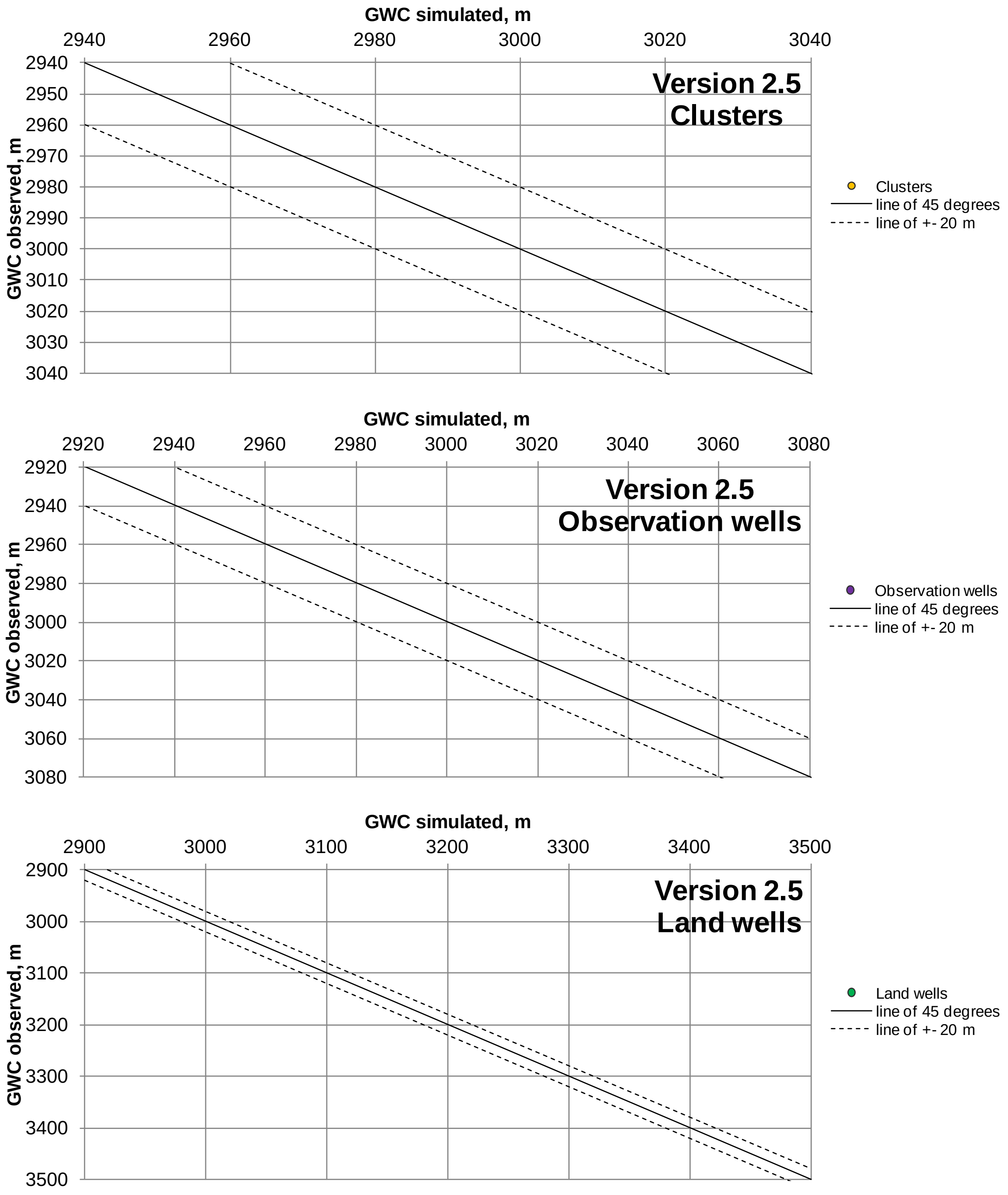


Figure 6-29 **Comparison of observed and simulated GWC**

6.5 FORECAST

6.5.1 ANALYSIS AND OBSERVATIONS

NAM's "FM_2P_27Bcm" MoReS deck (section 6.1) includes a gas production table on Cluster basis from January 2016 till December 2035. Genrem (detailed surface network model) and Resmod (simplified reservoir model) software were used to generate this table. As NAM communicated to SGS, this table represents a single gas offtake scenario which is used for the Winningsplan 2016.

The prediction scenario was applied by "running" the MoReS model on "history match mode". Cumulative gas production from the generated gas production table is thereby defined as constraint for the forecast simulation.

SGS has not critically reviewed the surface network model element of the production forecast models but has qualitatively reviewed the methodology used to generate the forecasts by inspecting documents supplied by NAM (Appendix A, section 10.7). Focus of the SGS review has been to verify if the defined gas offtake scenario could be achieved. The SGS review, as noted before, focused on reservoir pressure distribution over time in the field.

SGS takes into account that the actual gas offtake scenario as will be realised in the future may be influenced by future developments, be it technical or regulatory or otherwise, so it is only a single scenario.

25 out of 30 Clusters are involved into the forecast. 5 Clusters were shut in prior January 2016 (see Table 6-9) and remained shut-in during the forecast scenario.

Table 6-9 List of Non-producing Clusters

Cluster	Cumulative gas production historical by January 2016, 1e+6 m^3	Shut-in year
NWS	46,994	2008
NBR	46,122	2009
MWD	42,238	2009
UTB	40,334	2008
EKL13	3,327	2014

The simulated pressure behaviour for historical and forecast periods is shown Figure 6-30. A single well from each Cluster was picked randomly to present the forecast part of the plot. One pressure point per year of the selected wells is presented in the plot.

From Figure 6-30 the forecasted reservoir pressure range is observed. It illustrates that, while currently the reservoir pressure is almost the same over the entire field, in future there is expected to be a trend of differential depletion across areas of the field, based on the offtake scenario. To further illustrate the differential depletion, SGS made plots from the MoReS model: the top views of the 10th layer of "pressure property" in the MoReS model by January 2016, 2020 and 2025 presented in Figure 6-31 - Figure 6-33. These figures show the increasing differential depletion between the Southern and Northern parts of the field.

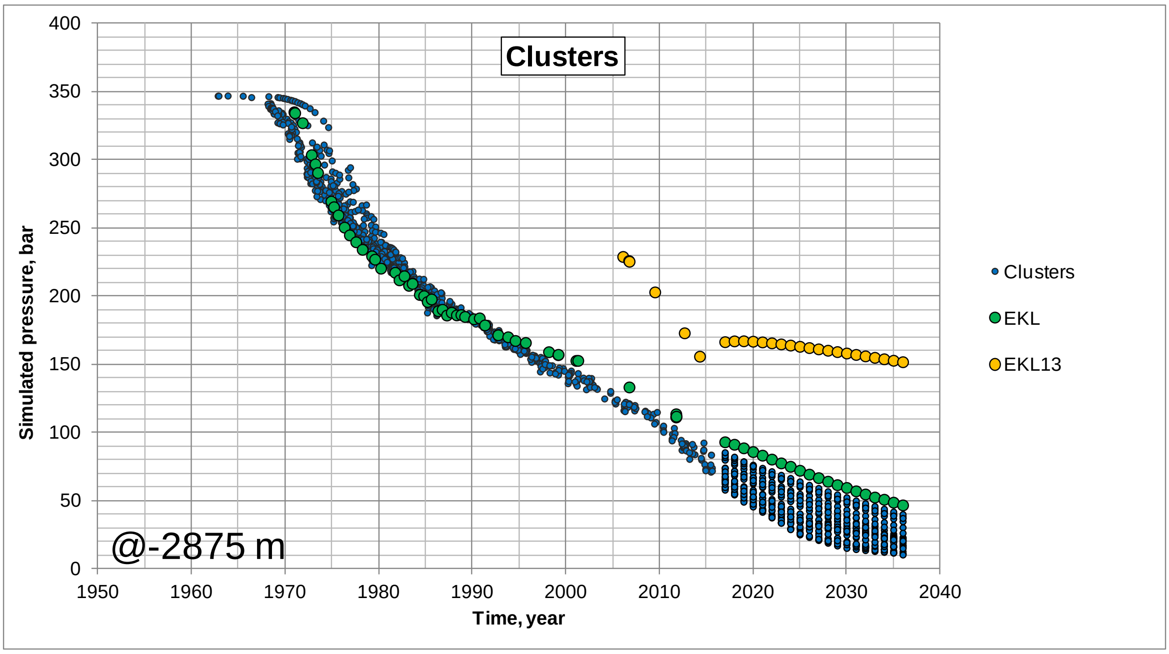


Figure 6-30 Reservoir pressures by Cluster - historical and forecasted

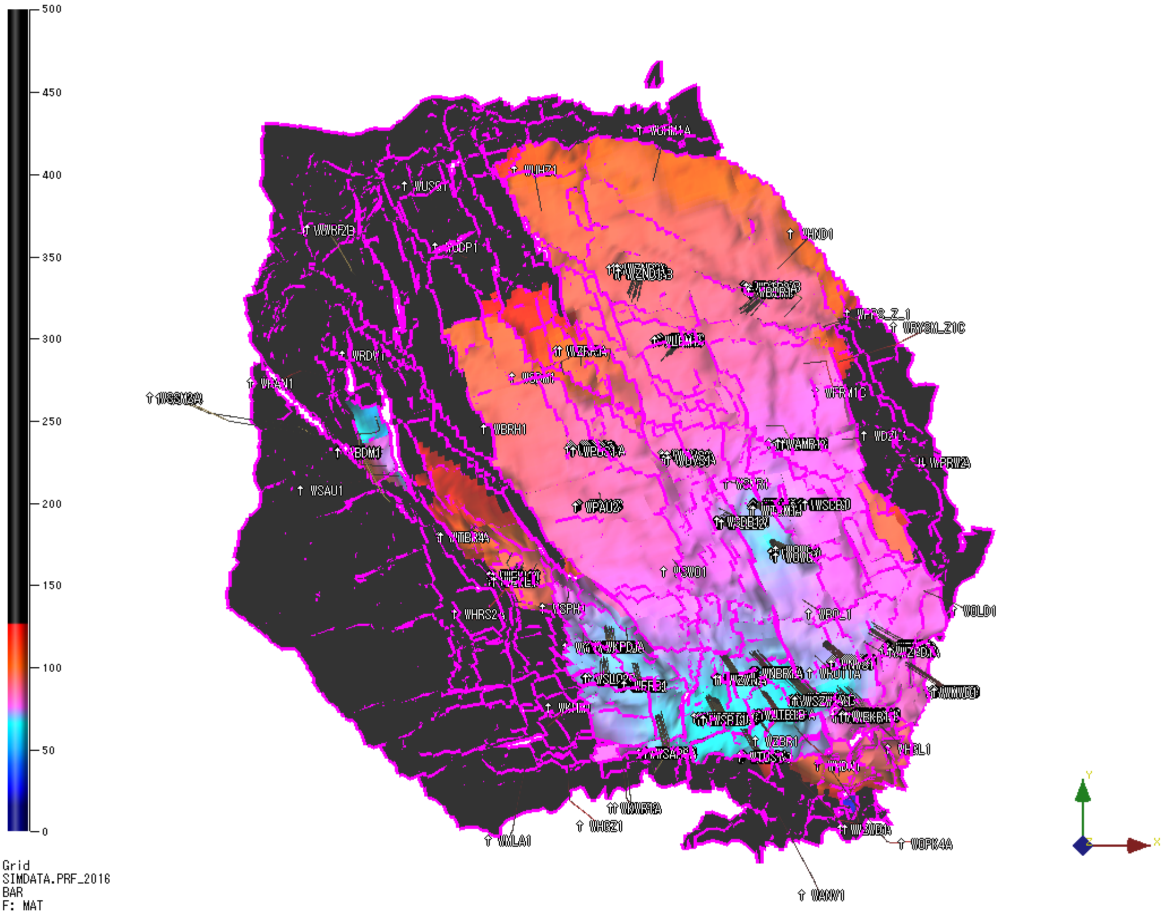


Figure 6-31 Forecasted reservoir pressure (10th layer top view) by January 2016

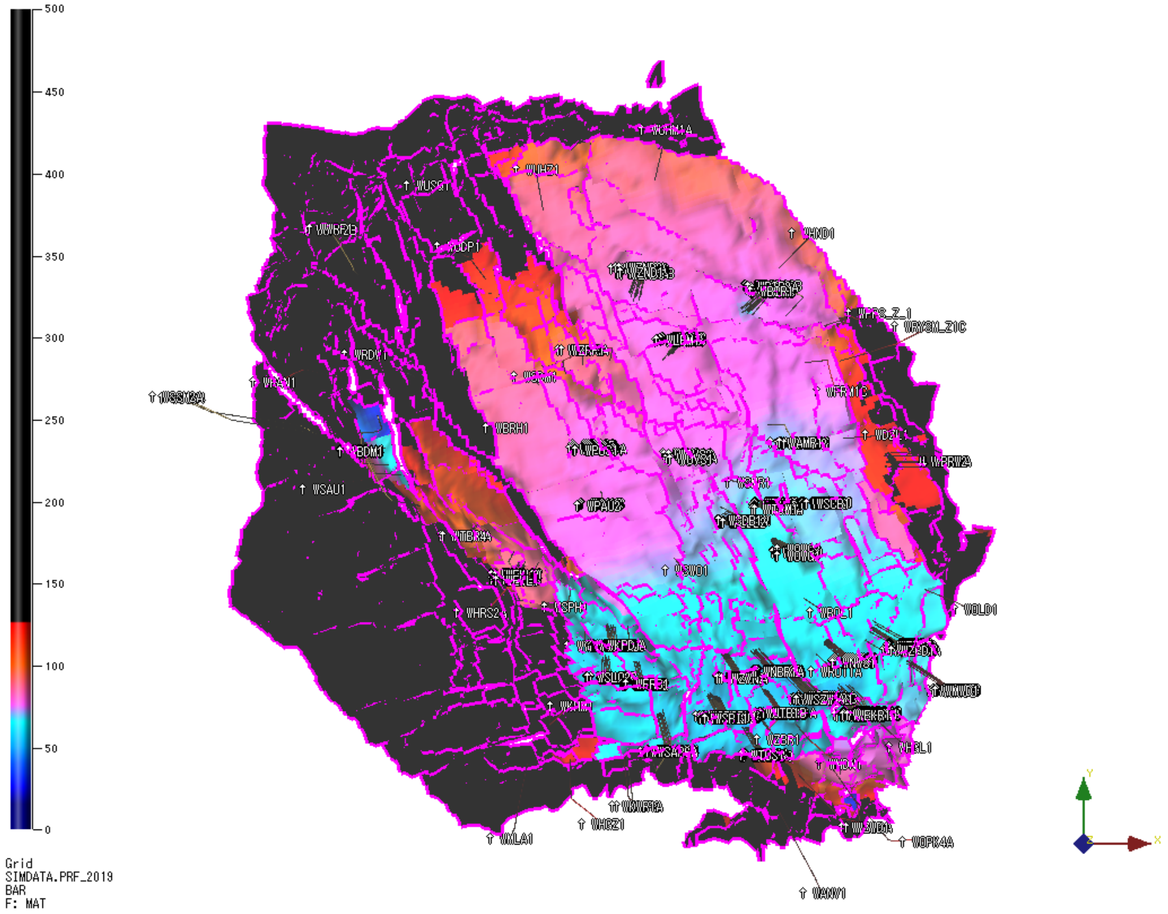


Figure 6-32 Forecasted reservoir pressure (10th layer top view) by January 2020

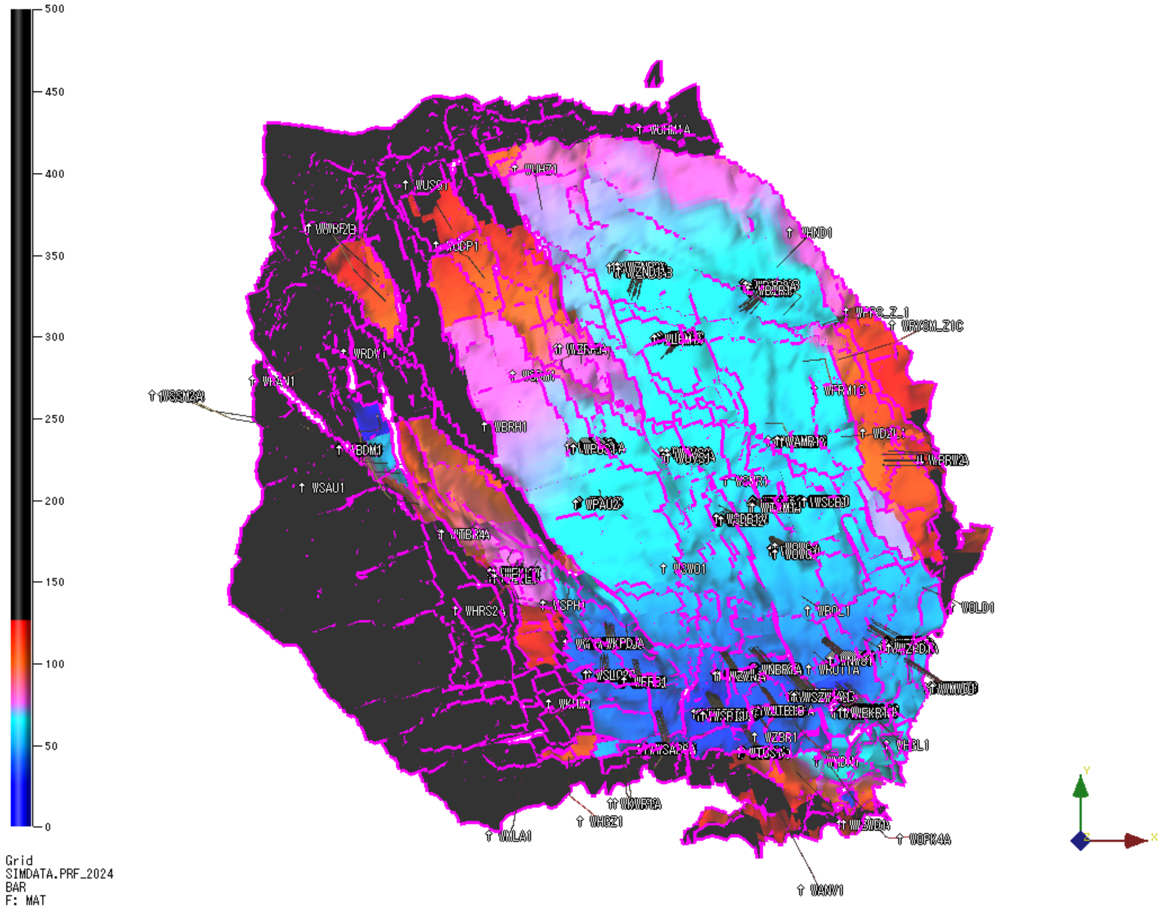


Figure 6-33 Forecasted reservoir pressure (10th layer top view) by January 2025

SGS reviewed the forecasted gas production and pressures on a well by well basis as further quality check of the model.

The wells do not have a very smooth transient between historical and forecasting, which can be explained by the changing production policy in the field. The, resulting from the model, gas rate, BHP and THP for 2 production wells are presented in Figure 6-34 as examples.

It is observed for well SAP8 that the BHP goes to very low values towards the end of the forecast.

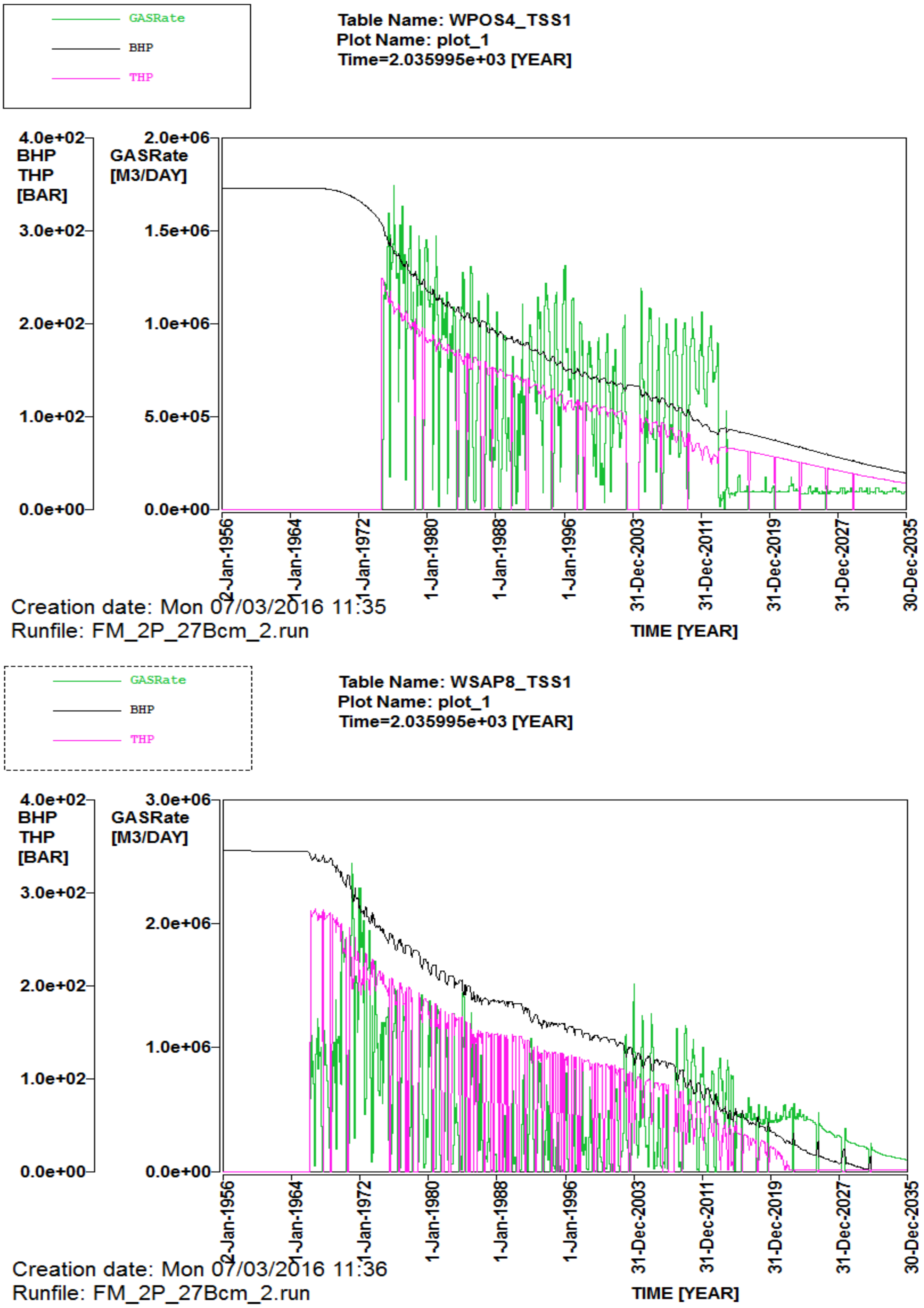


Figure 6-34 MoReS model output of pressures and gas rate for wells POS4 and SAP8

Simulated monthly gas production for full Groningen field is shown in Figure 6-35.

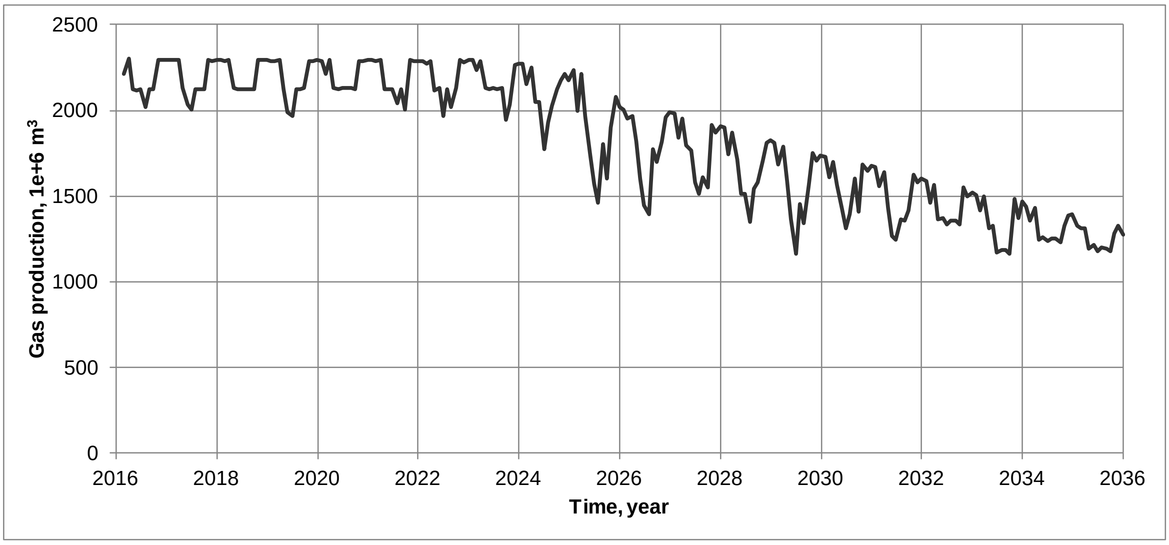


Figure 6-35 **Forecasted monthly gas production for Groningen Clusters**

SGS checked that the offtake schedule per cluster, as determined by NAM using the surface model, can be met for at least the period 1 January 2016 until 31 December 2025.

A strong pressure depletion was observed for Clusters EKR1 (since 2029), EKR2 (since 2029) and SAP (since 2031) (see Figure 6-34). BHP and THP dropped down up to 2 bar and 1.19 bar respectively. This leads to a mismatch on cumulative gas production later in the forecast (after 2025) (i.e. a difference between values from the forecast table and the simulation) as shown in Figure 6-36. This is caused by the wells not being able anymore to produce the specified cluster offtake.

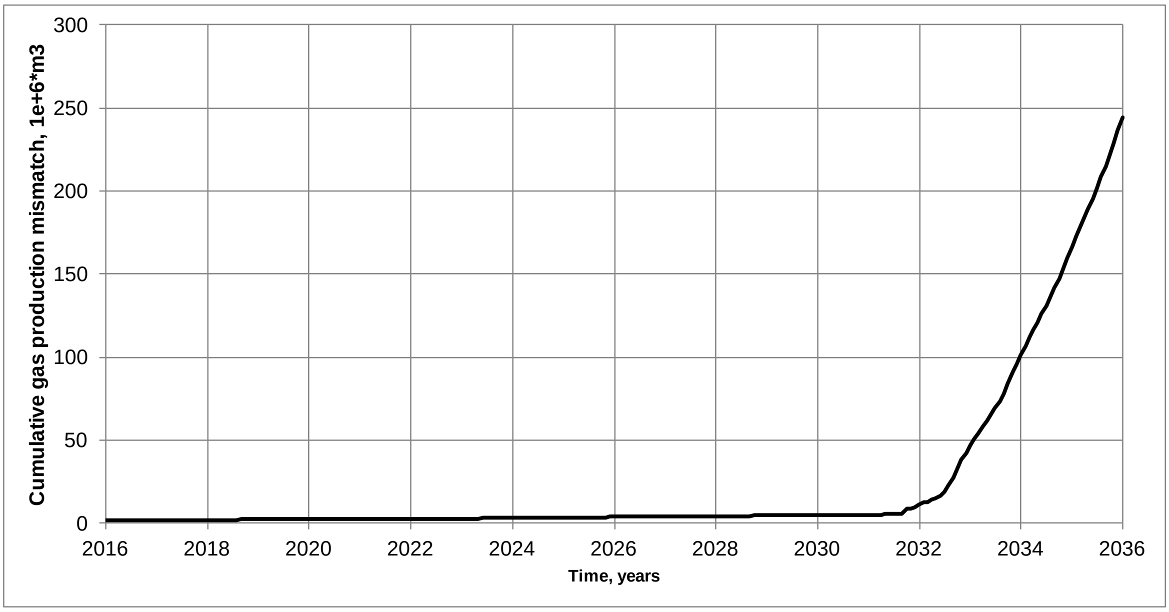


Figure 6-36 **Cumulative gas production mismatch for SAP Cluster - forecast**

The very low reservoir pressure in the forecast are likely to be caused by using two reservoir models in parallel for the forecasting, Resmod and MoReS.

SGS has not critically reviewed the liquid loading aspects of the wells. An analysis of the minimum gas rates at which wells still produce is presented in Appendix C. Some of these gas rates appear to be quite low, but no further review has been performed by SGS

The simulated forecast gas volumes are summarised in Table 6-10. The table illustrates the areas which are planned to produce higher and lower gas volumes in the future, and the relationship of offtake to GIIP.

6.5.2 DETAILED CONCLUSIONS AND RECOMMENDATIONS

The production forecasting method is considered by SGS appropriate for predicting future reservoir pressure distribution over time in the field for the period 2016 to (and including) 2025, assuming the offtake schedule for the Groningen production clusters, as determined by NAM, will be realised.

For the forecast period after 2025, the production forecast (cluster offtake) is to be reviewed using the MoReS model.

It is observed that the production plan of NAM is expected to lead to considerable differential depletion across areas of the field. Such high differential depletion has not occurred over the last 35 years.

Table 6-10 Forecast of cumulative gas production per cluster

Cluster	Cumulative gas production Jan 2016, 1e+6 m^3	Cumulative gas production Jan 2016, 1e+9 m^3	Cumulative gas production Jan 2035, 1e+6 m^3	Cumulative gas production Jan 2035, 1e+9 m^3	GIIP, 1e+9 m^3
Groningen_NE					
BIR	127,538	576.7	175,396	706.4	969.7 (33.2%)
LRM	118,200		125,009		
OVS	120,060		127,361		
ZND	110,915		153,667		
AMR	100,026		124,965		
Groningen_NW					
POS	124,035	186.0	132,171	201.9	495.4 (16.9%)
PAU	61,980		69,713		
Groningen_E					
OWG	114,423	432.3	134,391	517.1	464.6 (15.9%)
SDB	111,071		133,504		
TJM	106,925		128,104		
SCB	99,879		121,138		
Groningen_SW					
KPD	95,028	566.2	124,153	718.5	354.8 (12.1%)
FRB	59,695		79,210		
SLO	56,102		75,617		
SAP	49,953		61,952		
ZVN	48,845		69,832		
SP2	48,560		60,869		
SP1	46,082		58,394		
TUS	44,024		56,256		
UTB	40,333		40,333		
SZ1	40,672		47,824		
SZ2	36,882		44,033		
Groningen_Central					
ZPD	76,379	169.5	107,312	200.4	206.5 (7.1%)
NWS	46,992		46,992		
NBR	46,121		46,121		
Groningen_SE					
MWD	42,237	114.1	42,237	140.9	121.1 (4.1%)
EKR1	36,852		50,219		
EKR2	34,994		48,491		
Gron_Eemskanaal					
EKL	95,127	95.1	104,504	104.5	104.1 (3.6%)
Gron_Harkstede					
EKL13	3,327	3.3	3,327	3.3	11.9 (0.4%)
Total:	-	2,143	-	2,593	-
RF	-	73%	-	89%	-

Notes:

% in GIIP column indicates the GIIP fraction for a compartment out of the total GIIP for Groningen field (2923.7 1e+9 m^3)

🟧 Compartment

7 INTEGRATED CONCLUSIONS AND RECOMMENDATIONS

The overall results of the SGS evaluations and the opinions from SGS are presented in this section. It is noted that these conclusions and recommendations are identical to those reported in the separate Opinion Letter and in the Executive Summary of this report.

Static Model

The overall approaches to the update of the static model are supported by SGS.

The main geological, geophysical and petrophysical features of the Groningen Rotliegend reservoir appear to have been correctly captured in the static model. The updates to the static model performed for the Winningsplan 2016 are relatively minor, and can be considered as improvements compared to the models used for the Winningsplan 2013. The main recommendation from SGS made in 2013 has been followed up by NAM and implemented in the current model. New recommendations for further improvements to the modelling and suggestions for additional analysis and clarification are provided in the overall conclusions below.

Dynamic Model and History Match

The update to the dynamic model is supported by SGS.

The (computer assisted) history matching methodology, which employs Shell proprietary software, has been adapted to include subsidence data. This has resulted in an acceptable history matched reservoir model. A single history match realisation, which has been selected by NAM to be used to generate future production forecasts (predictions), has been presented to SGS for review. The two main recommendations from SGS made in 2013 have been followed up by NAM and implemented in the current model. New recommendations for further improvements to the modelling and suggestions for additional analysis and clarification are provided in the overall conclusions below.

Predictions

The production forecasting method is considered appropriate for predicting future reservoir pressure distribution over time in the field for the period 2016 to (and including) 2025, assuming the offtake schedule for the Groningen production clusters, as determined by NAM, will be realised.

SGS has not critically reviewed the surface network model element of the production forecast models but is supportive of the methodology used to generate the forecasts, notably for the period 2016–2025.

The main recommendation from SGS made in 2013, regarding prediction in late field life, has been, at least partially, followed up by NAM and implemented in the current model. SGS has not reviewed this aspect in detail as it is not relevant for the period 2016–2025.

It is observed that the production plan of NAM is expected to lead to considerable differential depletion across areas of the field. Such high differential depletion has not occurred over the last 35 years.

Overall Conclusions

In general, the static and dynamic models meet the quality criteria, established above. The dynamic models are appropriate for preparing production forecasts of future reservoir pressure distribution over time in the field.

The items below are the main “exceptions” to the above supportive opinion, hence represent areas where SGS recommends further improvements to the modelling by NAM:

- While the use of seismic inversion for static modelling is supported by SGS, an improvement of the method for porosity determination from seismic in the water bearing part of the reservoir is recommended. The “porosity cube” from seismic inversion should be used instead of the “acoustic impedance cube” and the method to determine porosity from seismic needs to be properly validated.
- The difference in the gas volumes between the static and the dynamic model of the Groningen field is within the uncertainty range of 5% (range determined by NAM for the Winningsplan 2013), but more justification and reconciliation by NAM of the difference is desirable in future modelling.
- The pressure match in the peripheral areas of the field, outside the Groningen field production clusters, has been improved compared to the Winningsplan 2013 model. Further improvement is desirable, should a more accurate pressure prediction in those areas be required.
- The objective of the model, as communicated by NAM to SGS, was to predict reservoir pressure in the Groningen field. Therefore the model is not appropriate for predicting the reservoir pressures in some small adjacent fields which are included in the dynamic model area but are outside the Groningen field. This applies specifically for the adjacent fields Kiel-Windeweer, Feerwerd, Annerveen-Veendam, Bedum, Midlaren and the Zuidwending East area.

Of lower importance, additional analysis and clarification by NAM would be beneficial on the following items:

- For future static modelling (seismic interpretation), provide an audit trail of the residual correction process and time to depth conversion of the final model. Detailed fault modelling in a few regions of the field requires attention.
- The detailed distribution of reservoir properties in the static model would benefit from additional analysis on regional trends and on the quality of input data used for modelling these reservoir properties.
- Clear documentation on the changes to the “Net-to-Gross” cut-offs, on the permeability model used and on the formation water parameters used.
- “Sensitivity analysis” on the dynamic modelling of the fault seals, the aquifer parameters, and the permeability model, to support the choice of parameters as used in the single history match realisation used for the forecasts of the Winningsplan 2016.

Limitation

The geomechanical aspects of the reservoir rock and any possible induced subsidence and seismicity effects were not part of the review scope, consequently this report does not contain any conclusions regarding seismicity and subsidence as a consequence of NAM’s gas production activities.

8 UNITS & GLOSSARY

Unit system

All units used are metric units.

Nm^3	Normal cubic meter (the standard conditions for Groningen gas, the volume at 0 ^oC and 1,01325 bar) – unit used for all gas volumes
Bcm	10^9 (American billion) Normal cubic meter
bar	metric unit of pressure (= 10,000 Pa)
cP	centipoise (unit of dynamic viscosity)
^oC	degree Celsius (unit of temperature)
m	meter (unit of length)
m^3	cubic meter (unit of volume)
mD	milli-Darcy (unit of permeability)
mg/l	milligram per liter (unit of mass concentration)
mg/kg	milligram per kilogram (unit of mass concentration)
kg/m^3	kilogram per cubic meter (unit of density)
ppm	part per million (unit of concentration – two separate definitions)

List of abbreviations

AI	Acoustic Impedance
BHP	Bottom hole pressure
BVH	Bulk Volume Hydrocarbon
CAHM	Computer assisted history match
CGR	Condensate-Gas Ratio
Deck	Set of files used as input for dynamic modelling calculations (“MoReS deck)”
EHC	Equivalent Hydrocarbon Column
φ	Porosity
FC	Forecast
FDP	Field Development Plan

FWL	Free Water Level
GIIP	Gas volume initially in place (before start of production)
GR	Gamma-Ray
GBV	Gross Bulk Volume
GRV	Gross Rock Volume
GWC	Gas water contact
HAFWL	Height above Free Water Level
HCPV	Hydrocarbon Pore Volume
HM	History Match
krg@Swc	Gas relative permeability at critical water saturation
λ	Pore-size distribution index
LGE	Lee, Gonzales and Eakin
MoReS	Modular Reservoir Simulator (Shell proprietary software)
NAM	Nederlandse Aardolie Maatschappij B.V.
NTG	Net-to-Gross ratio
PI	well Productivity Index
PNL	Pulsed Neutron Log (tool to detect formation water behind casing in a well)
Promise	Stochastic inversion of acoustic impedance (Shell proprietary)
pu	Porosity unit
Realization	Combination of (uncertain) subsurface parameters (structure, contacts, etc.)
REDUCE++	Program for upscaling
RF	Recovery factor
RFT	Repeat Formation Tester (*often used as a generic name for formation pressure measurements*)
RMS	Root mean square
SCAL	Special Core Analysis (refers to both relative permeabilities and capillary pressures)
Scenario	Combination of development parameters (well count & locations, constraints, etc.)
SGS	Sequential Gaussian Simulation (geologic modelling method)
SGS	Societe Generale de Surveillance (SGS Horizon is a part of the SGS Group)
SHF	Saturation height function
Srg	Residual gas saturation
Sw	Water saturation
Swirr	Irreducible water saturation
THP	Tubing head pressure
WGR	Water-gas ratio

9 REFERENCES

[1] Groningen_Model_review_report_Nov2013_final.pdf *(SGS report 2013)*
[2] Groningen Field Review 2003, Volume 4 Reservoir Properties, NAM200308000869, Dec 2003
[3] NTG_cutoff_methodology_2003.docx (*NAM document received by SGS 5 Oct.2015*)
[4] Poro_Perm_transforms_2015.docx (*NAM document received by SGS 5 Oct.2015*)
[5] SH_HF.docx (*NAM document received by SGS 5 Oct.2015*)
[6] GFR2015_SGSH_20151120_part1.pdf, GFR2015_SGSH_20151120_part2.pdf
[7] SR.15.13479.pdf (*GFR2015 "Clean-sheet" Dynamic Model*)
[8] William D. McCain Jr., John P. Spivey, Christopher P. Lenn, 2010. *Petroleum reservoir fluid property correlation*, PennWell Corp.
[9] Curtis H. Witson and Michael R. Brule, 2000. *Phase behaviour*, First printing, Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers Inc.
[10] https://www.spec2000.net/09-cappres.htm
[11] *Dynamo/MoReS Online User Manual*, Release 2014.1, May 21, 2014.
[12] Dynamic model review 2015 – Saturation functions section.pdf
[13] ZRP-3A note for file on brine composition.doc
[14] GFR2015_SGS_20151120_part2.pdf

10 APPENDIX A

10.1 OVERVIEW OF MATERIALS (MODELS AND DATA) RECEIVED AND USED IN THIS REVIEW

The findings and conclusions of this report are based on the materials (data, interpretations and models) provided by NAM. Below is an overview of the main material supplied by NAM and used in this review. It is not considered by SGS to be an exhaustive overview of all data and information provided but this appendix documents the most important models, documents, and data used for the review.

When particular electronic file names are listed, these are printed in blue font.

10.2 MATERIALS SENT TO SGS IN 2013

Reference is made to the report sent by SGS to NAM in November 2013, Appendix A.

All these data and models were available and may have been used in the current review

10.3 GENERAL

Documents

SGS_meeting_13July2015.pptx

10.4 STRUCTURAL MODEL

Models

2015_GFR_2ndPass2SGSH.pet : “2nd pass” petrel model

This contains, amongst others:

- Top Rotliegend horizon
- Rotliegend well tops
- Fault model

10.5 SEISMIC INVERSION

Models

- 2015_GFR_FirstPass2SGSH_final.pet : “1st pass” Petrel model

Documents:

“GRONINGEN FIELD SEISMIC INVERSION” by J.W.M.Dankbaar TGS-R, NAM. July 2003;

“Groningen Field. Jason Inversion of 3D Seismic Data”. October 2003 by Fugro-Jason

Other data / results

Absolute acoustic impedance volume from stochastic inversion 2003 (from Promise software) in depth

Porosity*thickness*net-to-gross maps per reservoir unit 2003 (from Promise software):

10.6 PETROPHYSICS

Documents:

NTG_cutoff_methodology_2003.docx
Poro_Perm_transforms_2015.docx
SH_HF.docx

Models

- 2015_GFR_2ndPass2SGSH.pet

10.7 DYNAMIC MODELLING

Documents:

Dynamo/MoReS Online User Manual, Release 2014.1, May 21, 2014
GFR2015_SGSH_20151120_part1.pdf
GFR2015_SGSH_20151120_part2.pdf
Dynamic model review 2015 – Saturation functions section.pdf
Dynamic model review 2015 - PVT section.pdf
SR.15.13479.pdf
ZRP-3A note for file on brine composition.doc
GFR2015_SGS_20151120_part2.pdf
Questions_from_SGS_20160302.docx
TRD_2014_EP201503219809_final.pdf
List_of_differences_GFR2015_v2_vs_GFR2015_v2_5.pdf (19-02-2016)
2016.02.18 - Forecasting.pdf
Calibration memo G Jager 29-6-2015.pdf
FM_2P_27Bcm_PDF.pdf
GFR2012 IPSM (final version, 18-07-2013).pdf

Models

- GRO_2015_ED_v34_v9_noforecast (*MoReS deck, dynamic model for history match, version 2.5)*
- FM_2P_27Bcm *(MoReS deck, dynamic model for forecast)*

11 APPENDIX B

11.1 WELL LOG RELIABILITY

During the review of the 2015 property model, SGS noted a relatively high level of heterogeneity on properties at short distances, i.e. on porosity between wells in the same cluster. Such heterogeneity is not expected from the regional geology. SGS performed an analysis on consistency of the interpreted logs and on well log data quality. SGS concluded that the root cause is issues related to density log measurements. It observed that most wells were logged in the 1960’s and 1970’s with less good quality tools than available currently, and that different logging companies with different tools may result in different interpretations of porosity.

Figure 11-1 shows visual analysis for two clusters as example of how the analysis was performed. A cluster showing high level of heterogeneity on properties at short distances i.e. Cluster EKL and a cluster showing a more homogenous behaviour i.e. Cluster LRM.

Figure 11-1 shows, from the Petrel model, both cluster from a 3D perspective, density and porosity logs are plotted above Lower Sands reservoir unit (Bottom Horizon USS.1), the colour scales for both properties have been set up in order to identify low porosity/high density curves anomalies in the red spectrum.

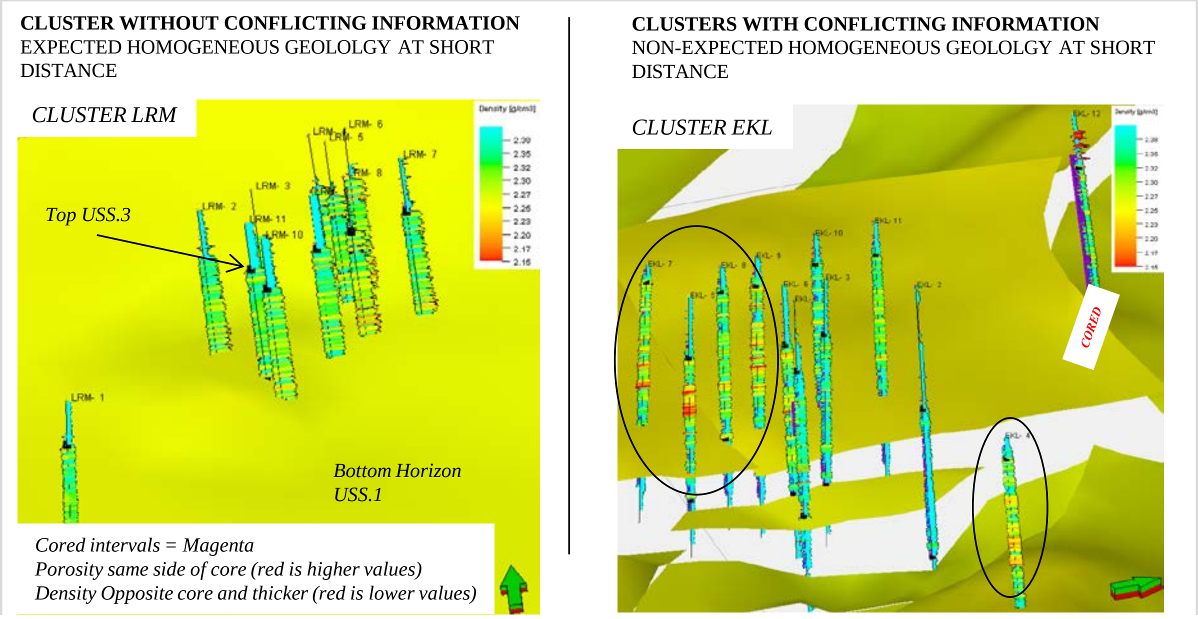
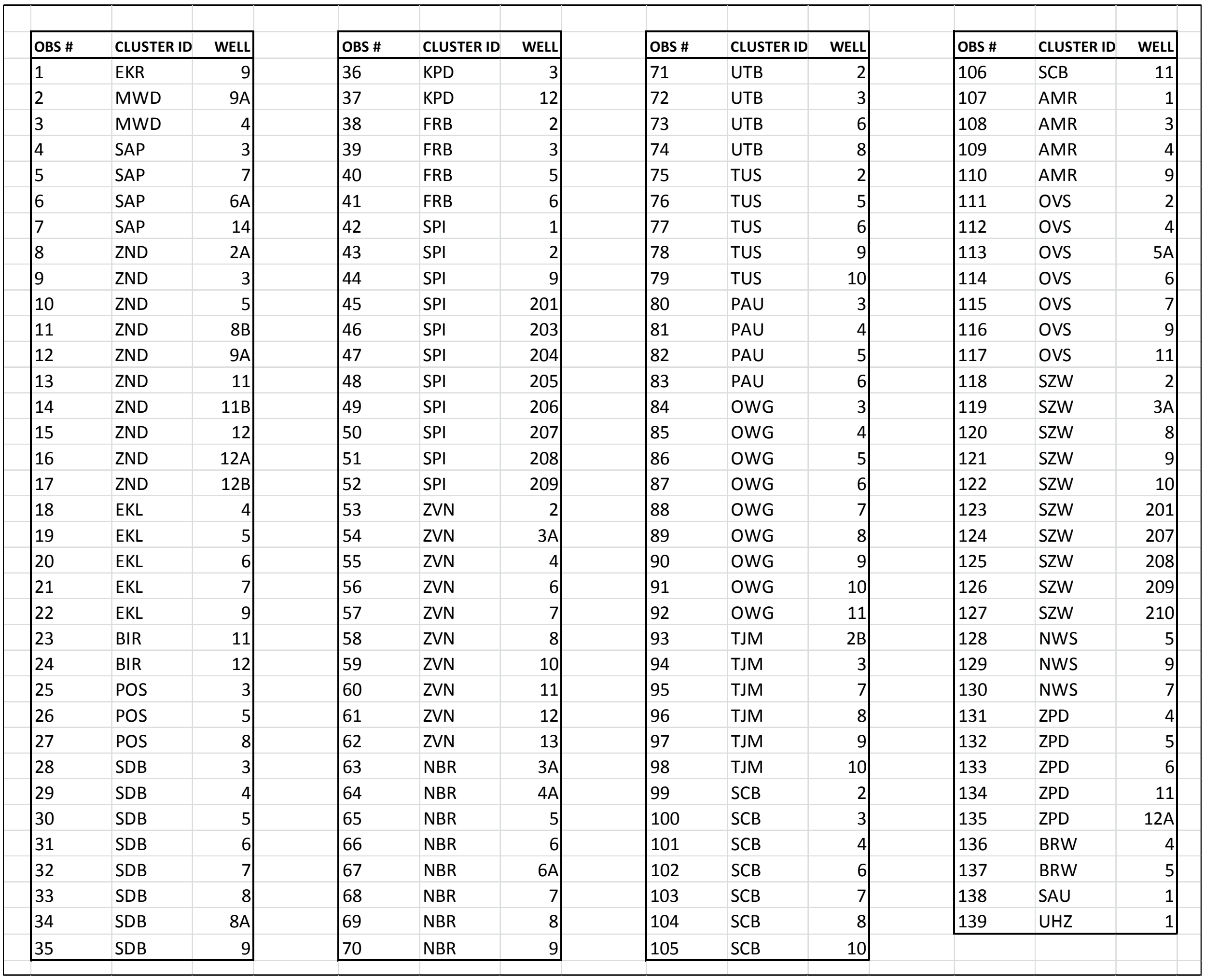


Figure 11-1 Left: Homogenous porosity in Cluster LRM. Right: Heterogeneous porosity in Cluster EKL

A list of wells having potentially anomalous logs is provided by Table 11-1.

Table 11-1 List of visually anomalous wells indicated by low density – high porosity values – SGS analysis



OBS #	CLUSTER ID	WELL
1	EKR	9
2	MWD	9A
3	MWD	4
4	SAP	3
5	SAP	7
6	SAP	6A
7	SAP	14
8	ZND	2A
9	ZND	3
10	ZND	5
11	ZND	8B
12	ZND	9A
13	ZND	11
14	ZND	11B
15	ZND	12
16	ZND	12A
17	ZND	12B
18	EKL	4
19	EKL	5
20	EKL	6
21	EKL	7
22	EKL	9
23	BIR	11
24	BIR	12
25	POS	3
26	POS	5
27	POS	8
28	SDB	3
29	SDB	4
30	SDB	5
31	SDB	6
32	SDB	7
33	SDB	8
34	SDB	8A
35	SDB	9
36	KPD	3
37	KPD	12
38	FRB	2
39	FRB	3
40	FRB	5
41	FRB	6
42	SPI	1
43	SPI	2
44	SPI	9
45	SPI	201
46	SPI	203
47	SPI	204
48	SPI	205
49	SPI	206
50	SPI	207
51	SPI	208
52	SPI	209
53	ZVN	2
54	ZVN	3A
55	ZVN	4
56	ZVN	6
57	ZVN	7
58	ZVN	8
59	ZVN	10
60	ZVN	11
61	ZVN	12
62	ZVN	13
63	NBR	3A
64	NBR	4A
65	NBR	5
66	NBR	6
67	NBR	6A
68	NBR	7
69	NBR	8
70	NBR	9
71	UTB	2
72	UTB	3
73	UTB	6
74	UTB	8
75	TUS	2
76	TUS	5
77	TUS	6
78	TUS	9
79	TUS	10
80	PAU	3
81	PAU	4
82	PAU	5
83	PAU	6
84	OWG	3
85	OWG	4
86	OWG	5
87	OWG	6
88	OWG	7
89	OWG	8
90	OWG	9
91	OWG	10
92	OWG	11
93	TJM	2B
94	TJM	3
95	TJM	7
96	TJM	8
97	TJM	9
98	TJM	10
99	SCB	2
100	SCB	3
101	SCB	4
102	SCB	6
103	SCB	7
104	SCB	8
105	SCB	10
106	SCB	11
107	AMR	1
108	AMR	3
109	AMR	4
110	AMR	9
111	OVS	2
112	OVS	4
113	OVS	5A
114	OVS	6
115	OVS	7
116	OVS	9
117	OVS	11
118	SZW	2
119	SZW	3A
120	SZW	8
121	SZW	9
122	SZW	10
123	SZW	201
124	SZW	207
125	SZW	208
126	SZW	209
127	SZW	210
128	NWS	5
129	NWS	9
130	NWS	7
131	ZPD	4
132	ZPD	5
133	ZPD	6
134	ZPD	11
135	ZPD	12A
136	BRW	4
137	BRW	5
138	SAU	1
139	UHZ	1

12 APPENDIX B

Table 12-1 Fault seal multipliers

Fault name	Seal multiplier	Comments
USQ faults:		
B43	0.01	Above FWL; seal off Usquert fault above the GWC allowing flow of water below the GWC
	0.4	Below FWL; seal off Usquert fault above the GWC allowing flow of water below the GWC
Fault_2a	0	
B10	0	
M_2	0	
B44	0	
B44a	0	
B44b	0	
MFS1_Fault_5	0	
RE_fltUSQS	0	Reservoir engineering fault: extension of fault B43 into B44 near USQ; -DIMY
ODP faults:		
mFS7_Fault_6	0.32	
mFS7_Fault_7	0	
RE_fltODP	0	Reservoir engineering fault; DIMY
RDW faults - To prevent water level rise at the TBR-4 well from the North:		
B51	0	regionally
B54	0.32	regionally
mFS9_Fault_35	0.01	
Annerveen Aquifer faults - to block pressure support from the aquifer to the NE clusters:		
INT_35a	0.79	
INT_35	0.79	
INT_65	0.79	
mFS19_Fault_22	0.79	
INT_57	0.79	
Annerveen field faults:		
Fault_8	0	
Fault_24	0.001	
Fault_52	0.001	
B30	0.001	
B29	0.001	
Veendam_Fault_1	0.5	
NE compartment faults:		
M1	0.1	
B7	0	
B1	0	
B2_Continued	0	
B2	0	
BIR faults and Rysum aquifer:		
mFS5_Fault_6	0	Top part
RE_fltRys	0	Top part; reservoir engineering fault; -DIMX
mFS5_Fault_8	0	Top part
B15	0	Top part
mFS5_Fault_9	0	Top part
mFS5_Fault_12	0	Top part
mFS6_Fault_1	0	Top part; regionally
MFS6_Fault_16	0.3	Bottom part
MFS6_Fault_28	0.3	Bottom part
MFS6_Fault_16	0.3	Bottom part; regionally
MFS6_Fault_21	0.01	Bottom part; regionally
INT_16	0.01	Bottom part
INT_12	0.01	Bottom part
B22	0.01	Bottom part
mFS12_Fault_71	0.03	Bottom part
INT_11	0.03	Bottom part
B17	0.03	Bottom part
Aamsweer west towards north faults:		
mFS12_Fault_2	0.32	
INT_6	0.32	

KPD/FRB Pop-up structures:		
M71	1	
M70	1	
M36	1	
M37	1	
M38	1	
mFS19_Fault_21	1	
SDBtoEKR Fault:		
M40	0.3	
M41	0.3	
M45	0.3	
M44	0.3	
M46	0.3	
M43	0.3	
Separate EKL compartment from the KPD/FRB/SLO compartment:		
M6	0	regionally
mFS15_Fault_32	0.2	
Faults separating EKL cluster and KHM from the western aquifers:		
B60	0.01	regionally
B61	0	
B52a	0	
B36	0	
Fault separating KHM1:		
M11	0.003	
Faults bounding the HRK/E13 pop-up structure:		
Fault_1_2	0.003	
M27	0.003	
mFS15_Fault_112	0.003	
TBR Western fault:		
B52	0	
B55	0	
B56	0	
B59a	0	regionally
B64	0	
mFS10_Fault_47	0.04	
BDM reservoir blocks:		
INT_27a	0	Close off BDM reservoir block from main Groningen
M14	0	Close off BDM reservoir block from main Groningen
B58	0	Close off BDM reservoir block from main Groningen
M22	0	Close off BDM reservoir block from main Groningen
mFS9_Fault_27	0	Close off BDM reservoir block from main Groningen
mFS9_Fault_28	0	Close off BDM reservoir block from main Groningen
M24	0	Close off BDM reservoir block from main Groningen
F4	0.002	Faults bounding BDM5 from BDM4
B40a	0.001	Faults bounding BDM5 from BDM4
M23	0.001	Faults bounding BDM5 from BDM4
RE_fltM23	0.001	Faults bounding BDM5 from BDM4; reservoir engineering fault; -DIMY
M68	0.02	Faults bounding BDM4 from BDM1 and BDM2; regionally
INT_31	0.001	Fault bounding BDM3 from BDM1 and BDM2
INT_30	0.00000003	Faults bounding BDM 1 and 2 and 3 from the aquifer
INT_32	0.00000003	Faults bounding BDM 1 and 2 and 3 from the aquifer; regionally
INT_71	0	Faults bounding RNM1 from the aquifer
INT_72	0	Faults bounding RNM1 from the aquifer
INT_29a	0	Faults bounding RNM1 from the aquifer
RE_fltRNM1	0	Faults bounding RNM1 from the aquifer; reservoir engineering fault; DIMY
INT_33	0	Faults bounding RNM1 from the aquifer
RE_fltINT33	0	Faults bounding RNM1 from the aquifer; reservoir engineering fault; DIMY
Fault bounding HGZ1:		
M31	0	
M33	0	regionally
M8	0.10	
Fault separating POS from PAU and SDB from OVS, and SCB from TJM and OWG:		
mFS10_Fault_27	0.63	
mFS11_Fault_58	0.63	

Fault preventing water influx from ZRP aquifer to SDM and BRH:		
mFS10_Fault_17	0.02	
mFS10_Fault_19	0.02	
mFS10_Fault_12	0.02	
Fault preventing outflow from the OPK4 compartment:		
B67	0.19	
INT_42	0.19	
INT_2	0.19	
Fault sealing of the MLA compartment:		
mFS18_fault_21a	0.06	
mFS18_Fault_31	0.06	
Faults sealing of KielWindeweer:		
M34	0	
M76	0	
B31	0	
M32	0	
Close off SSM:		
Fault_3_2	0	
Feerwerd	0	
Saaksum_1	0	
Close off WRF:		
B46	0	
MSF1_Fault_36	0	
B62	0	
mFS8_Fault_52	0.0001	
mFS8_Fault_57	1	
B50	1	
Close off Lauwerszee aquifers:		
mFS16_Fault_5	1	regionally
M13	0.03	
B40	0.03	
mFS16_Fault_2	0.03	
M25	1	regionally
B35	0.03	regionally
B37	0.03	
B39	0.03	
M9	0.03	
M74	0.03	

13 APPENDIX C

Table 13-1 Well BHP and gas rate for wells in clusters with very low reservoir pressure after 2025

Well	BHP<2bars since	Gas rate by Jan 2036, m3/day
EKR1	2029	76,818
EKR2	2029	22,331
EKR3	2029	26,827
EKR4A	2029	21,355
EKR5	2029	48,513
EKR7	2029	34,883
EKR8	2029	87,709
EKR9	2029	90,535
EKR10A	2029	66,121
EKR11	2029	115,076
EKR12	2029	93,735
EKR201	2029	43,360
EKR202	2029	45,023
EKR203	2030	57,393
EKR204	2030	68,638
EKR205	2030	56,419
EKR206	2029	58,225
EKR207	2030	88,248
EKR208	2029	133,047
EKR209	2029	37,254
EKR210	2029	125,314
SAP6A	2031	92,071
SAP7	2032	124,233
SAP8	2031	92,582
SAP9	2031	39,415
SAP10	2031	28,261
SAP11	2031	60,425
SAP12	2031	56,912
SAP13	2031	57,276
SAP14	-	0
SAP15A	2031	52,445