The effects of heterogeneities on the economics of thin gas column reservoirs

L.C. Grazell

TU Delft

The effects of heterogeneities on the economics of thin gas column reservoirs

By

L.C. Grazell

in partial fulfilment of the requirements for the degree of

Master of Science
in Applied Earth Sciences

at the Delft University of Technology,
to be defended publicly on Tuesday April 3, 2018 at 1:30 PM.

Supervisor:	Prof. dr. ir. J.D. Jansen	
Thesis committee:	Prof. dr. P.L.J. Zitha	TU Delft
	Prof. dr. G. Bertotti	TU Delft
	Dr. R. Godderij	EBN B.V.
	Dr. J. Juez-Larré	TNO-AGE

This thesis contains confidential information. Confidential parts of the thesis have been removed or greyed out.

ABSTRACT

After decades of successful exploration and exploitation of gas fields in the Netherlands, the Dutch E&P industry has accumulated a substantial portfolio of gas fields that are considered economically unviable, the so-called 'stranded fields'. There are various reasons for a gas field to be classified as economically unviable, one of them being the small size of the field. With the current challenges the E&P sector is facing it is valuable to re-evaluate the criteria often used in determining a fields economic viability. One of those criteria is the column height encountered in the well, which when it becomes too small can be very sensitive to water inflow. Gaining further understanding of the relation between gas column height and gas production can be valuable in determining the potential of a gas field with a limited gas column. Consequently, the focus of this study is twofold: 1) finding the minimum gas column height required for producing a sufficient amount of gas (0.1 – 0.2 BCM) and 2) investigating the effect of specific important reservoir heterogeneities (i.e. high-permeability streaks and clay layers) on the production results (total gas production and production time).

These two research topics were approached through two separate methods: 1) a sensitivity study carried out using two types of models, a simple box model and a complex reservoir model and 2) an analysis of gas wells, and the corresponding gas reservoirs, that encounter small gas columns. Both research methods are focused on Rotliegend gas reservoirs. The results from this study show that the minimum gas column range for yielding economic gas production was found to be 20 – 40 m, depending on the field's characteristics and configurations. Furthermore, in the models used for this study the presence of a high-permeability streak may either cause an increase or decrease in the total gas production, however they are found to significantly reduce the production time which is beneficial towards the economic analysis of a potential project. Additionally, they are found to be highly beneficial in gas reservoirs with a low average permeability. The clay layer on the other hand, significantly increases the total gas production of the models, although this is accompanied by an increase in the total production time. A potential downside of the clay layer is the restricted flow of gas which is particularly problematic in horizontal reservoirs with a significant portion of the gas column situated below the clay layer. Lastly, a possibly positive correlation between transition zone and the total gas production from thin gas columns reservoirs was found in the well analysis, on which further investigation is recommended in order to be able to draw more meaningful conclusions.

ACKNOWLEDGEMENTS

I would like to express my appreciation to the people who have helped and guided me through the final stages of finishing my master's degree in Petroleum Engineering. During the process of writing my thesis I have been in the privileged position of working together with three parties; TU Delft, EBN B.V. and TNO-AGE. This has given me the opportunity to experience three different types of professional environments and work with multiple supervisors, from whom I have learned so much.

First of all, I would like to express my appreciation to my assessment committee: Prof. dr. ir. J.D. Jansen, Prof. dr. P.J.L. Zitha, Prof. dr. G. Bertotti, Dr. R. Godderij and Dr. J. Juez-Larré for taking the time to review my work. A special thanks to Prof. dr. ir. J.D. Jansen, Dr. R. Godderij and Dr. J. Juez-Larré for their guidance through this process and sharing with me their expertise. In addition, I would like to thank Lies Peters for training me in the use of Petrel and Eclipse 100 Black Oil Simulator, for helping me to gain a solid understanding of the TNO reservoir model and finally, for reviewing my work.

Last but not least, I would like to thank my friends and family for their continued support throughout this difficult process. Special thanks go out to my mother, Gerry Levels, and partner in crime, Dennis Haak, for their loving support all the way.

This thesis is dedicated to **Jos Grazell**, a man who believed in science above all.

L.C. Grazell
Gouda, March 2018

Contents

ABSTRACT 5
ACKNOWLEDGEMENTS 7
1 INTRODUCTION 11
2 RESERVOIR MODEL BACKGROUND 13

2.1 GEOLOGICAL BACKGROUND 13
2.1 RESERVOIR MODEL 13

3 METHODOLOGY 14

3.1 SENSITIVITY STUDY, PART 1: SIMPLE BOX RESERVOIR MODELLING 14
3.1.1 BASE MODELS 14
3.1.2 BASE MODEL VARIATIONS 14
3.1.3 DEVELOPMENT STRATEGY 15
3.1.4 RESERVOIR SIMULATIONS 15
3.2 SENSITIVITY STUDY, PART 2: REAL CASE RESERVOIR MODELLING 16
3.2.1 RESERVOIR MODEL HISTORY MATCH 16
FIELD A 18
FIELD B 18
FIELD C 18
FIELD D 18
3.2.2. RESERVOIR MODEL AND SIMPLIFICATIONS 19
3.2.3 DEVELOPMENT STRATEGY 19
3.2.4 RESERVOIR SIMULATIONS 20
3.3 ANALYSIS OF THIN GAS COLUMN WELLS 20

4 RESULTS 22

4.1 SENSITIVITY STUDY, PART 1: SIMPLE BOX RESERVOIR MODELLING 22
4.1.1 HORIZONTAL BOX MODEL (HBM) 22
4.1.2 TILTED BOX MODEL (TBM) 27
4.2 SENSITIVITY STUDY, PART 2: REAL CASE RESERVOIR MODELLING 32
4.2.1 CRM - MINIMUM GAS COLUMN HEIGHT 32
4.2.2 CRM – HIGH-PERMEABILITY STREAK 33
4.2.3 CRM – CLAY LAYER 34
4.2.4 CRM – DECREASING HETEROGENEITY 35
4.3 ANALYSIS OF THIN GAS COLUMN WELLS 37
4.3.1 WELL A 38
4.3.2 WELL B 40
4.3.3 WELL C 43
4.3.4 WELL D 45
4.3.5 WELL E 47
4.3.6 WELL F 50
4.3.7 GENERAL FINDINGS 52

5 DISCUSSION 53

5.1 GAS COLUMN CUT-OFF VALUE 53
5.2 RESERVOIR FEATURES 53
5.3 RESERVOIR CONFIGURATION & PRODUCTION STRATEGY 54

6 CONCLUSIONS & RECOMMENDATIONS 55

REFERENCES 56

APPENDICES 57

APPENDIX A1 INDIVIDUAL VISUAL REPRESENTATION OF FIELD A 57
APPENDIX A2 INDIVIDUAL VISUAL REPRESENTATION OF FIELD B 57
APPENDIX A3 INDIVIDUAL VISUAL REPRESENTATION OF FIELD C 58
APPENDIX A4 INDIVIDUAL VISUAL REPRESENTATION OF FIELD D 58
APPENDIX B1 BASE HORIZONTAL AND TILTED BOX MODEL 59
APPENDIX B2 HORIZONTAL AND TILTED BOX MODEL WITH HIGH-PERMEABILITY STREAK 60
APPENDIX B3 HORIZONTAL AND TILTED BOX MODEL WITH CLAY LAYER 61
APPENDIX B4 HORIZONTAL AND TILTED BOX MODEL WITH HIGH-PERMEABILITY STREAK AND A CLAY LAYER 62
APPENDIX C1 RESERVOIR MODEL HISTORY MATCH FIELD A 63
APPENDIX C2 RESERVOIR MODEL HISTORY MATCH FIELD B 64
APPENDIX C3 RESERVOIR MODEL HISTORY MATCH FIELD C 65
APPENDIX C4 RESERVOIR MODEL HISTORY MATCH FIELD D 66
APPENDIX D PERMEABILITY DISTRIBUTION IN RESERVOIR MODEL (CRM1) AFTER HISTORY MATCH 67
APPENDIX E PRODUCTION PROFILES OF THE HORIZONTAL BOX MODEL VERSIONS, HBM1-4 68
APPENDIX F PRODUCTION PROFILES OF THE TILTED BOX MODEL VERSIONS 1-4 70
APPENDIX G1 CRM-A TOTAL GAS PRODUCTION AND PRODUCTION TIME 72
APPENDIX G2 CRM-B TOTAL GAS PRODUCTION AND PRODUCTION TIME 73
APPENDIX G3 CRM-C TOTAL GAS PRODUCTION AND PRODUCTION TIME 74
APPENDIX G4 FIELD D TOTAL GAS PRODUCTION AND PRODUCTION TIME 75
APPENDIX H FIELD A - D GAS INITIALLY IN PLACE PER GAS COLUMN 76
APPENDIX I1 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM1-CRM6 – A 78
APPENDIX I2 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM1-CRM6 – B 81
APPENDIX I3 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM1-CRM6 – C 83
APPENDIX I4 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM1-CRM6 – D 86
APPENDIX I5 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM7 & CRM8 – A & B 89
APPENDIX I6 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM7 & CRM8 – C & D 92

1
INTRODUCTION

The Dutch exploration and production (E&P) sector has risen and flourished since the discovery of the Groningen field in 1959. Decades of successful gas production have passed which generated an enormous economic interest for the state's revenues and as a result the Netherlands is now considered a mature E&P area; with over 70 % of the total gas reserve (> 4,500 billion cubic metres (BCM) of gas initially in place (GIIP)) recovered[1]. In order to keep the Groningen natural gas as a strategic reserve, the government implemented a new policy known as "the small field policy", which switched the focus to the E&P of smaller gas fields. However, over the past years the Dutch gas sector is facing an increased number of challenges, such as the limited number of newly discovered fields, low gas prices, public resistance and restricted production from the Groningen field. The decrease of discoveries of new gas fields since the 1990's has led to a slow but continuous decline of production[2]. This has raised the urgency to explore other options in an attempt to slow down the decrease in production, such as reassessing the potential of the stranded gas fields. Around 100 of the 440 gas fields that are found in the Netherlands are classified uneconomic[1] and are labelled 'stranded', which together account for ~200 BCM GIIP. One of the reasons for these fields to be classified as uneconomic is their small GIIP estimated, which is often less than 0.5 BCM[1]. With regards to the topic of making optimal use of the gas reserves found in the Dutch subsurface, one question that arises is whether there is a way to bring (some of) these small fields into production? Answering this question implies the evaluation of a complex interplay between economic measures and technological development, amongst others. A sensible way to approach this question is by re-evaluating the criteria employed in determination of a fields economic viability. One such criteria is the gas column height encountered in the well which will be the focus of this study. Focusing on the gas column height, instead of GIIP, incorporates the gas reservoir's dimensions. This allows the evaluation of the strong effect of water inflow on production from gas reservoirs with a small gas column. The following two research topics will be the objective of this thesis:

- The absolute minimum gas column required to produce sufficient amounts of gas (0.1 – 0.2 BCM).
- The effect of specific reservoir heterogeneities (i.e. high-permeability streak and clay layer) on the production results (total gas production and production time) of gas wells that encounter a small gas column.

The Rotliegend reservoir was chosen as the main target reservoir since it is the most common natural gas reservoir in most of the producing fields, as well as in the portfolio of stranded fields.

This research was divided into two parts:

- The first part consisted of a sensitivity analysis in which the role of specific factors, such as reservoir features/configuration and gas column height, to the ultimate recovery is investigated. The sensitivity analysis was done in two types of models, a simple box model and a complex reservoir model, containing four real case gas fields in the Netherlands with different gas column heights (this model was provided by TNO-AGE). The simple box model is used as a method to isolate the research factors, leaving aside the extreme complexity of real case reservoirs, whereas the complex reservoir model is used to test the researched factors in a heterogeneous, complex gas reservoir.

- The second part comprised a detailed well analysis of Rotliegend gas reservoirs in the Netherlands. The goal of this study was to find and study real existing gas wells, and corresponding reservoirs, which have successfully produced from small gas columns. A comprehensive description of these cases is presented in order to establish the key factors that contributed to the gas production.

2
RESERVOIR MODEL BACKGROUND

[For confidential reasons this content has been removed]

2.1 GEOLOGICAL BACKGROUND

Although several hydrocarbon plays have been characterized in the Netherlands, most of the gas reservoirs are found in the Rotliegend play, which owes its excellent potential to deposits from the Carboniferous and Permian Period. The Carboniferous deposits allowed for the formation and migration of the hydrocarbons, whereas the Permian rocks facilitated high reservoir quality and strong sealing capability; facilitating about 95 % of all gas reserves in the Netherlands[5]. The source rocks that generated nearly all gas found in the Dutch subsurface are the Late Carboniferous Westphalian coals and carbonaceous shales which were buried at 4,000 - 6,000 m depth from which the gas migrated of which most got trapped in a configuration that is of a simple horst block structure caused by post-depositional tectonic activity in Permian sandstones[3,4].
The Permian deposits found in the Netherlands are divided into three groups: 1) the Lower Rotliegend Group 2) the Upper Rotliegend Group and 3) the Zechstein Group. The last two groups are responsible for creating high quality reservoirs with an overlying sealing structure on top. The Upper Rotliegend forms the reservoir rocks and can be further subdivided into the Slochteren Formation and the Silverpit Formation which are each other's lateral equivalent. The Slochteren Formation consists of well-developed sandstones and conglomerates of eolian and fluvial decent and, due to its good porosity and permeability, is considered the most important source of gas reservoirs in the Netherlands. The Silverpit Formation consists of claystones, fine siltstones and evaporates and is of poor reservoir quality. They transition from one into the other in the North part of the Netherlands which results in areas where the two formations intertwine and fingers of the Silverpit Formation can be found in the Slochteren Formation. In these areas, the following sedimentary succession is found: Ten Boer Formation, Upper Slochteren Formation, Ameland Formation and Lower Slochteren Formation. The Ten Boer and Ameland Formation are part of the Silverpit Formation and form poor quality reservoir rock whereas the Upper Slochteren and Lower Slochteren Formation are part of the Slochteren Formation and form high quality reservoir rock, although most gas is produced from the Upper Slochteren Formation. The marine evaporates (halite and anhydrite deposits) from the Zechstein Group form the overlying sealing structure in the Rotliegend Play.

2.1 RESERVOIR MODEL

[For confidential reasons this content has been removed

3

METHODOLOGY

This section describes the methodology used for the box and real case field modelling and the analysis of gas wells with a limited gas column.

3.1 SENSITIVITY STUDY, PART 1: SIMPLE BOX RESERVOIR MODELLING

The first part of the sensitivity study is carried out with two box models which were created specifically for this study. The design of these box models was based on the reservoir model such that it would be a simplistic representation.

3.1.1 BASE MODELS

Two versions of the box model were designed, a horizontal and tilted version, to represent the two types of fields found in the study area of the TNO-AGE model (Field A and D are (near) horizontal and Field B and C are tilted). The horizontal box model is a reservoir of 2000 m by 2000 m and 160 m thick, with the top of the formation placed at - 4,000 m depth. The tilting box model is a reservoir of 2500 by 2300 m and 90 m thick that is tilted at an angle of 3 degrees, with the crest of the formation placed at – 4,000 m depth. The gas well in the horizontal box model was placed in the middle of the reservoir, whereas the gas well in the tilted reservoir was placed near the crest of the reservoir where it encounters the top formation at – 4,025 m (see Appendix B1). The assigned petrophysical parameters are based on the average parameters found in the reservoir model with a porosity of 10 %, a net-to-gross of 80 % and a permeability of 15 mD (Table 3.1). Furthermore, the same ratios for the vertical permeability, the permeability below the gas-water contact and the vertical permeability below the gas-water contact were used as in the TNO-AGE reservoir model.

3.1.2 BASE MODEL VARIATIONS

For both the horizontal and tilted box model, three subsets of models were created in order to study the effect of different types of heterogeneity on gas production. The elements introduced were a high-permeability streak in the top of the reservoir (Appendix B2), a clay layer without the high-permeability streak (Appendix B3) and a combination of the high-permeability streak and the clay layer (Appendix B4). One important modification made in the models containing the clay layer (which contains both a porosity and net-to-gross of 0 %)

Table 3.1 Reservoir characteristics of the box models

	Horizontal Box Model	Tilted Box Model
Dimension	2000 x 2000 x 160	2500 x 2300 x 90
Column height (m)	80	85
Porosity (without clay layer)	0.1	0.1
Net-to-gross (without clay layer)	0.8	0.8
Horizontal Permeability	15	15
Horizontal Permeability below GWC	$^1/_{100}$ of horizontal permeability	$^1/_{100}$ of horizontal permeability
Vertical Permeability	$^1/_{100}$ of horizontal permeability	$^1/_{100}$ of horizontal permeability
Vertical Permeability below GWC	$^1/_{100}$ of horizontal permeability below GWC	$^1/_{100}$ of horizontal permeability below GWC
High-permeability streak	200	200
Porosity (with clay layer)	0.11	0.11
Net-to-gross (with clay layer)	0.85	0.85

was that the porosity and net-to-gross were adjusted accordingly (using eq. 3.1) such that the GIIP in the system would remain constant (see also adjustment in Table 3.1). An overview of the different box model versions, including the corresponding model names, is given in Table 3.2.

$$\boldsymbol{Pore\ Volume = Bulk\ Rock\ Volume * \emptyset * N/G} \qquad \textbf{Eq. (3.1)}$$

3.1.3 Development strategy

To setup a prediction scenario in these models a development strategy was implemented, in which the gas production target, minimum gas production rate, minimum bottom hole pressure and water restriction rule were defined (see Table 3.3). The values of these parameters were all based on the values that were determined in the development strategy of the reservoir model. The development strategy also includes the actions which are executed when the minimum production values were not obtained or when the water restriction value was exceeded. When the minimum gas production target or bottom hole pressure were not achieved the well was shut in. In case of the water restriction value, the first violation will result in a partial shut-off of the perforation interval, whereas the second violation will cause the well to be completely shut in.

3.1.4 Reservoir simulations

To understand the impact of gas column height and find the absolute minimum value, a set of simulation cases with decreasing gas column height was defined. The simulations were run in a fixed order using Eclipse 100 Black Oil Simulator, starting with the base versions of the homogeneous box models, model HBM1 and TBM1. In order to simulate a shorter gas column height, the gas-water contact was displaced 5 m upwards. This was repeated until the gas column height reached 0 m, after which the same sequence was done with the subsequent versions of the box models (HBM2 – HBM4 and TBM2 – TBM4).

Perforation strategy

The decrease of the gas column required additional steps throughout each simulation run. Increasing the water level means that unless some adjustments were made to the initial perforation interval, the water level would quickly reach the lowest bottom perforation, increasing the water influx unrealistically, and killing the well. To avoid that, the perforation interval was progressively reduced in length. However, raising the bottom perforation was not always done linearly with the upwards shift of the water level. The decrease of perforation length not only limits water inflow but also gas inflow, that is why for each particular simulation case the perforation interval was optimized. As a rule of thumb, a minimum of ~ 25 m was left between the gas-water contact and the bottom perforation. However, as the gas column became smaller this minimum distance was reduced to 5 m, as 25 m for decreasing gas columns becomes unreasonable at some point and impossible for gas

Table 3.2 Box model versions and corresponding names.

	Horizontal Box Model	**Tilted Box Model**
Homogeneous reservoir	HBM1	TBM1
Homogeneous reservoir with high-permeability streak	HBM2	TBM2
Homogeneous reservoir with clay layer	HBM3	TBM3
Homogeneous reservoir with high-permeability streak and clay layer	HBM4	TBM4

Table 3.3 Overview production targets and restrictions per field

	Gas production target	Gas production minimum	BHP minimum	Water production limit	Action upon offense water limit
Box Model	1,200,000 m^3/d	50,000 m^3/d	15 bar	50 m^3/d	1st time: partial shut off perforation interval 2nd time: shut in well

columns < 25 m. Furthermore, the optimization of the perforation length did not only depend on gas column height, but also on the type of reservoir (horizontal versus tilted) and the presence or not of the reservoir heterogeneities (i.e., presence/absence of high-permeability streak and/or clay layer). Furthermore, the same reasoning was applied to determine the progressively upwards shut off of the lowest sections of the perforation interval when the water production exceeds the limit. A sufficiently large section of the perforation interval was shut off in order to significantly reduce the water inflow, yet minimizing the impact on the gas inflow. Again, the most optimal configuration was chosen accordingly for each step. Figure 3.1 shows a simplistic example of a perforation configuration used.

3.2 Sensitivity Study, part 2: Real case reservoir modelling

In the second part of the sensitivity study the reservoir model of four existing gas fields was used. First the reservoir model was updated by running a history match with more recent production data [redacted] Then a similar development strategy as for the box model was implemented to carry out the sensitivity analysis. However, instead of adding elements that increased the reservoir heterogeneity (as done with the box models), the heterogeneity of the real case model was stepwise reduced.

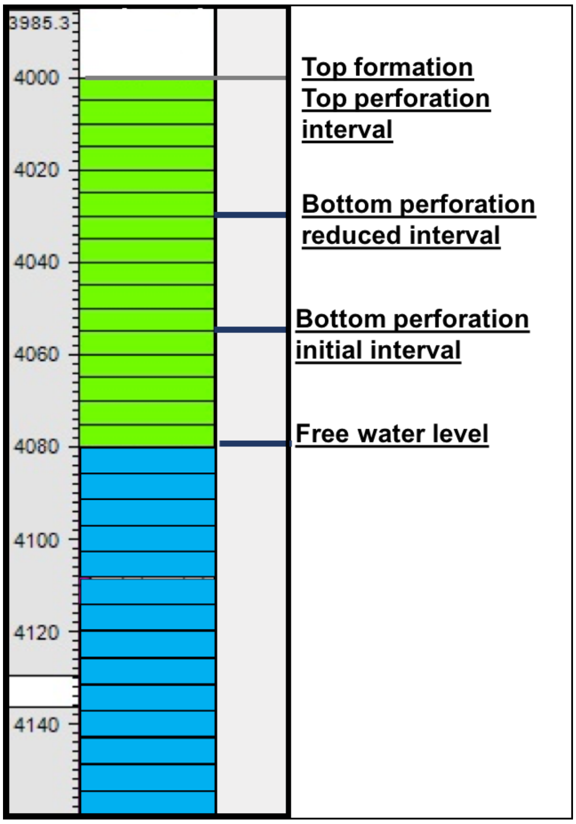


Figure 3.1 General perforation interval configuration in gas well.

3.2.1 Reservoir model history match

The reservoir model used in this study was compared to recent daily gas production and monthly water production data as well as static bottom hole pressures measured during shut-in periods. Discrepancies found between the observed production data and the model output, made it necessary to update the history match of the model in order to resolve these discrepancies. Several adjustments were considered and tested, which include an increase of the general permeability of a gas reservoir, an increase of the permeability of the high-permeability streaks, application of a pore volume multiplier, a decrease of the water contact and an increase of the permeability strictly beneath the present shale layer. For each gas field an optimal solution was found for the gas production and bottom hole pressure data, and to a lesser extend for the water production. The production data spans over a range of six years.

Field A

In the original run of the model gas production from Field A starts deviating from

the target production rates approximately 2.5 years after the start of production and as a result at this point the simulated bottom hole pressures drops to the minimum point. A volume calculation was done to check whether the GIIP in the model was comparable to the GIIP reported by the operator (Table 2.3). This showed that the GIIP in the model was [redacted] BCM which was significantly lower than the [redacted] BCM reported by the operator. A possible explanation for this is the uncertainty in the geologic interpretation of the reservoir as this model was built as an independent model. The field is relatively flat which makes the gas volume in the reservoir very sensitive to small changes in top and/or bottom boundaries of the formation.
Initially a pore volume multiplier was tested to increase the GIIP. This however did not result in a significant change in gas production that could match the observed data. Subsequently, the gas-water contact was lowered by 10 m as it was found to be 4 m too high compared to the operator's report (Table 3.4). This practical solution circumvents the need to make drastic changes to the geological model. With that the GIIP was increased up to 3.5 BCM leading to a good match with the observed data (Appendix C1).

Field B
Field B had only two years of production, therefore this field had no previous history match in the original reservoir model. Only monthly gas and water production and no bottom hole pressure data were available. This made the accuracy of the history match carried out here less reliable. In the original model, the observed gas production rate is not reached and the bottom hole pressure drops to the minimum value quickly to produce on maximum drawdown pressure. Due to a negatively biased correlation between the porosity and permeability, a general permeability multiplier of six was necessary to obtain a solid history match (Appendix C2). This correlation was negatively biased due to the limited amount of core measurements taken from a limited interval of the reservoir, likely not including the high-permeability streaks. In addition, log data showed that the property upscaling used in the model was too coarse which lead to the averaging of the high-permeability streak across a larger interval, which resulted in an insufficient gas flow to the well.

Field C
At the start of the production period a relatively good match with the observed data is made, however the bottom hole pressure drops to the minimum value after two years and consequently the target gas production is not obtained for the last months. Therefore, additional adjustments of the model were needed. Differently from Field A and B, the GIIP of Field C closely matches the GIIP reported by the operator therefore the original gas-water contact in the model was not changed. As can be seen in the original model the permeability below the clay layer was lowered to 10 % of the original permeability (Table 2.3). This value was increased to 12.5 % of the original permeability which had a significant effect on the production as this enabled a match to the observed gas production and increased the bottom hole pressure without deviating from the measured bottom hole pressure points (Appendix C3).
When a good history match was achieved, an additional step was added before proceeding to the base case prediction scenario. Chapter 2 describes the presence of two water contacts for Field C, which results in two gas columns. This however increases the

Table 3.4 Column height and GIIP in original and history matched model

	Original model		**History matched model**	
	Gas column height (m)	**GIIP (BCM)**	**Gas column height (m)**	**GIIP (BCM)**
Field A	[redacted]	[redacted]	[redacted]	[redacted]
Field B	[redacted]	[redacted]	[redacted]	[redacted]
Field C	[redacted]	[redacted]	[redacted]	[redacted]
Field D	[redacted]	[redacted]	[redacted]	[redacted]

Table 3.5 Summary of the adjustments made to the original model to obtain a history match

	Adjustment
Field A	Lowered contact by 10 m.
Field B	Increased general permeability by a factor of 6.
Field C	Increased permeability beneath shale layer from 10 to 12.5 % of the permeability.
Field D	Increase the general permeability by a factor of 1.75.

complexity of the reservoir and the factors to be taken into account for interpretation of the results of this study. Since the purpose of this research is to carry out a sensitivity study and not to optimize the accuracy of the model, the lowest gas-water contact was eliminated from the model and all the reservoir units were given the same water contact giving one final gas column of 75 m. Consequently, this reduced the GIIP from 2.8 to 1.8 BCM (Table 3.4).

Field D

Field D shows the best initial match between its observed production data and the original model and only a small adjustment in the overall permeability is required to obtain a match. The average reservoir permeability was increased by a factor of 1.75 which gave the best match (Appendix C4). For this case the same arguments apply as for Field B. The correlation between porosity and permeability is biased due to core measurements unevenly taken over the reservoir interval and consequently the correlation is negatively biased and in all likelihood inaccurate.

A summary of the adjustments made in the reservoir model for the history match is given in Table 3.5. The final history matched permeability distribution can be found in Appendix D.

Water production

Finding a good match between the observed and simulated water production has proven to be a difficult task without altering the good match with the gas rate and bottom hole pressure. The simulated water production not only significantly deviates from the observed data, it also follows a completely different trend. Attempts to reduce the difference in rate and trend have included changing the aquifer permeability and changing the perforation strategy. This however all had very little effect.

In addition to this, it seems that the observed water production rates are unreliable to be used as a criterion for the history match. The validity of the observed water production data is not clear since water production rates show a decreasing trend for all four fields. This is opposite to the normal cases where water production increases gradually with time until they

Table 3.6 Overview production targets and restrictions per field

	Gas production target	Gas production minimum	BHP minimum	Water production limit	Action on offense water limit
FIELD A	1,100,000 m^3/d	50,000 m^3/d	15 bar	50 m^3/d	1st time: partial shut off perforation interval 2nd time: shut in well
FIELD B	230,000 m^3/d	50,000 m^3/d	15 bar	50 m^3/d	1st time: partial shut off perforation interval 2nd time: shut in well
FIELD C	1,500,000 m^3/d	50,000 m^3/d	15 bar	50 m^3/d	1st time: partial shut off perforation interval 2nd time: shut in well
FIELD D	1,200,000 m^3/d	50,000 m^3/d	15 bar	50 m^3/d	1st time: partial shut off perforation interval 2nd time: shut in well

increase rapidly at the time when the water breakthrough takes place. Furthermore, the observed water production for Field A, C and D displays a sudden drop in the beginning of year 4, which coincides with the start of production of Field B. All this suggests that the reported water production rate may not be individually measured rates, but rather the water production rate from a group of wells allocated to the four gas fields afterwards. Based on that it was decided to not use the water production data for history matching (Appendix C1-4).

3.2.2. Reservoir model and simplifications

Eight different versions of the reservoir model were created and used in the sensitivity study, starting with the history matched reservoir model. In each subsequent version, the model is simplified by homogenizing one reservoir parameter. The complete list of model versions and their corresponding model names (which will be used for reference in subsequent chapters) can be found in Table 3.7. The values of the simplified parameters were determined by taking the average value of the heterogeneous model (excluding the clay layer as this has a porosity, net-to-gross and permeability of 0 % and 0 mD). The values for porosity and net-to-gross are different between versions that exclude the clay layer and versions that do not. Eq. (3.1) was used to re-calculate porosity and net-to-gross in the versions without the clay layer in order to not significantly change the GIIP in the system. See Table 3.8 for the full list of homogenized parameter values per field.

3.2.3 Development strategy

Similar to the box model, the base case reservoir model was provided with a development strategy production targets and restrictions under which it was run. All fields were assigned a gas production target, a minimum gas production rate, a minimum bottom hole pressure and a water production restriction. Although the gas production target differs per gas field, the minimum gas production rate, minimum bottom hole pressure and water production restriction for each field are the same at 50,000 m^3/d, 15 bar and 50 m^3/d respectively.
The production targets were based on the observed production data and the minimum production rate is an average economic and technical value for a well producing through a 3.5” tubing. Furthermore, the water production restriction is based on the average water treatment capacity of 2.5 trucks per day and is implemented to prevent unrealistic and uneconomic simulations. A partial perforation interval shut-off is set up to be carried out each

Table 3.7 Reservoir model versions and corresponding simulation case code names

Reservoir model version	Model version name	Field A	Field B	Field C	Field D
1. Base reservoir	CRM1	CRM1-A	CRM1-B	CRM1-C	CRM1-D
2. Homogeneous permeability	CRM2	CRM2-A	CRM2-B	CRM2-C	CRM2-D
3. Homogeneous porosity	CRM3	CRM3-A	CRM3-B	CRM3-C	CRM3-D
4. Homogeneous net-to-gross	CRM4	CRM4-A	CRM4-B	CRM4-C	CRM4-D
5. Removal of clay layer	CRM5	CRM5-A	CRM5-B	CRM5-C	CRM5-D
6. Permeability below free water level equal to permeability above free water level	CRM6	CRM6-A	CRM6-B	CRM6-C	CRM6-D
7. Horizontal to vertical permeability ratio increased from $^1/_{100}$ to $^1/_{10}$	CRM7	CRM7-A	CRM7-B	CRM7-C	CRM7-D
8. Horizontal to vertical permeability ratio increased from $^1/_{10}$ to $^1/_1$	CRM8	CRM8-A	CRM8-B	CRM8-C	CRM8-D

Table 3.8 Average reservoir input parameters simplified reservoir model

	Field A	Field B	Field C	Field D
Average Permeability	6.2	1.5	16.5	13.2
Average Porosity	0.1	0.09	0.11	0.11
Average Net-to-gross	0.8630	0.6410	0.7260	0.9070
Average Porosity (no clay layer)	0.09	0.08	0.1	0.1
Average Net-to-gross (no clay layer)	0.7200	0.5630	0.6830	0.7930

time a well reached this imposed limit of water production (Table 3.6). The high-permeability streaks and all layers below are shut off in order to significantly reduce the water inflow. The high-permeability streaks have been found to be the major cause of water production and test runs proved that shutting off only perforations below the high-permeability streaks had very little effect. If the limit of 50 m^3/d is reached a second time the well is shut in and production will come to an end.

3.2.4 Reservoir simulations

The numerical simulations were carried out in Eclipse 100 Black Oil Simulator. For the real reservoir configuration model (CRM1, Base Case) as well as each simplified model (CRM2-8), a sequence of runs was carried out by which the gas columns height was decreased upwards by 5 m until a thickness close to 0 m was reached.

Perforation strategy

As is described in Chapter 3.1.4 the perforation intervals were adjusted according to the gas column length as well as the reservoir type and presence/absence of certain reservoir features. The same was done in the sensitivity study of the reservoir models. For each simulation case the best perforation interval was selected based on the field geometry, heterogeneity and the gas column length using the same reasoning as in Part 1 of the sensitivity study, i.e. the reduction of the perforation interval was not done in proportion to the reduction of the gas column length, and strongly depends on the specific simulation case. The partially shut off perforation interval that is applied when the water restriction rule is exceeded the first time is also adjusted in the development strategy according to the gas column height. It follows the same logic as described in part 1 of the sensitivity study and the interval is not reduced in equal steps. The gas fields in the base reservoir model include high-permeability streaks which initially are a dominant factor in determining the reduced perforation interval. However, this influence decreases as the water level is shifted upwards and eventually extinguishes when the water level is moved past these streaks. See Figure 3.1 for an example of the general perforation configuration in the gas wells.

3.3 Analysis of thin gas column wells

The well analysis was carried out simultaneously with the sensitivity study and includes an inventory of wells with a small gas column that have successfully produced from Upper Rotliegend reservoirs in the Netherlands. Based on an original data base with close to one thousand records, which was quality checked in order to reduce the amount of errors, only 277 records had a complete and detailed information on the gas-water contact, top/bottom formation, GIIP and ultimate recovery at reservoir level (Figure 3.2). This study is focused on Upper Rotliegend reservoirs with 1 or 2 producing wells, an initial gas column height of 45 m and less and an ultimate recovery above 0.1 BCM. These selection criteria reduced the number of wells down to six.
Further research was done on these six wells and their corresponding gas reservoirs from which they produce. This also involved a fact check, in which the presented data such as column height, cumulative production, GIIP and reservoir properties were checked on

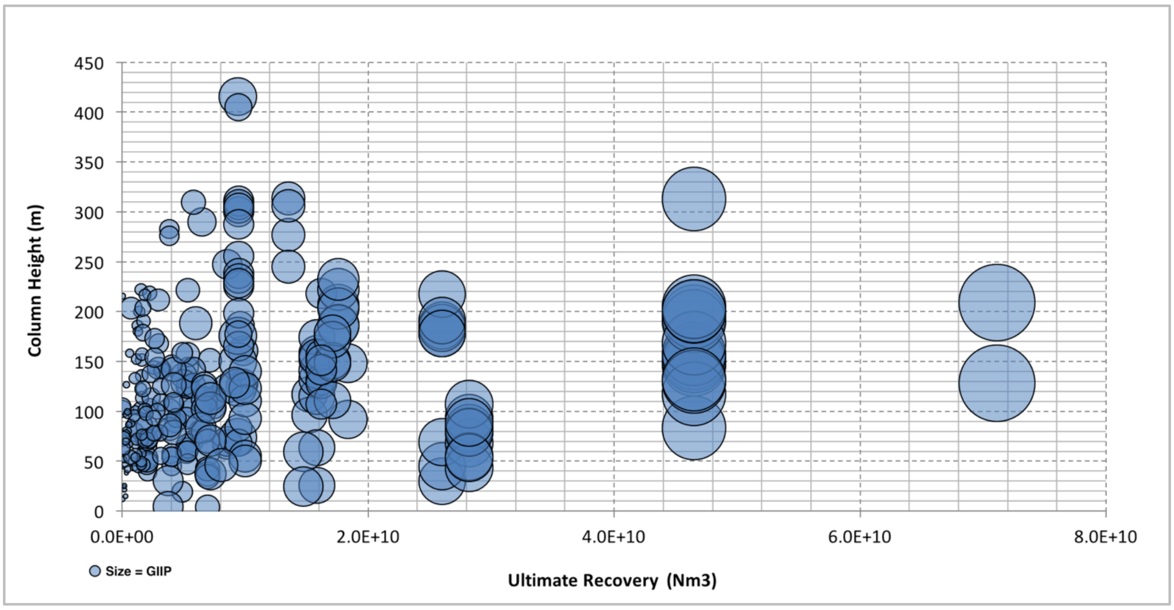


Figure 3.2 Database of 277 records used for finding suitable case studies in the well analysis.

accuracy in the available documentation provided by the operators. Furthermore, additional field and production history information was collected as well as contour maps, cross sections and composite well logs. These figures were edited where necessary to ensure anonymity and to increase clarity. With the available resources, it was attempted to give a complete and detailed overview for each gas well and the corresponding reservoir.

4

RESULTS

4.1 SENSITIVITY STUDY, PART 1: SIMPLE BOX RESERVOIR MODELLING

Results from the box models for a horizontal and tilted reservoir are presented in this section. The effects of the gas column height and different types of reservoir heterogeneity on the production results are analyzed.

4.1.1 HORIZONTAL BOX MODEL (HBM)

The performance of the base case horizontal box model and the three subsequent versions are assessed based on the total gas production and the length of the production period (Figure 4.1 and 4.2). In both figures the position of the relevant reservoir features are indicated to illustrate where they connect to the well. Table 4.1 gives an overview of the four box models and the corresponding reservoir features. Furthermore, the production profiles of each simulation case are used to gain further understanding of the results and can be found in Appendix E.

Three key observations are derived from the results:

1) A minimum gas column of 15 – 25 m is required to reach the threshold gas production (0.1 – 0.2 BCM).
2) A high-permeability streak results in higher total gas production and shorter production time for fields able to produce above the minimum threshold.
3) A clay layer increases the total gas production, due to restricted water inflow, if the perforations are situated above or no more than 5 m below the clay layer.

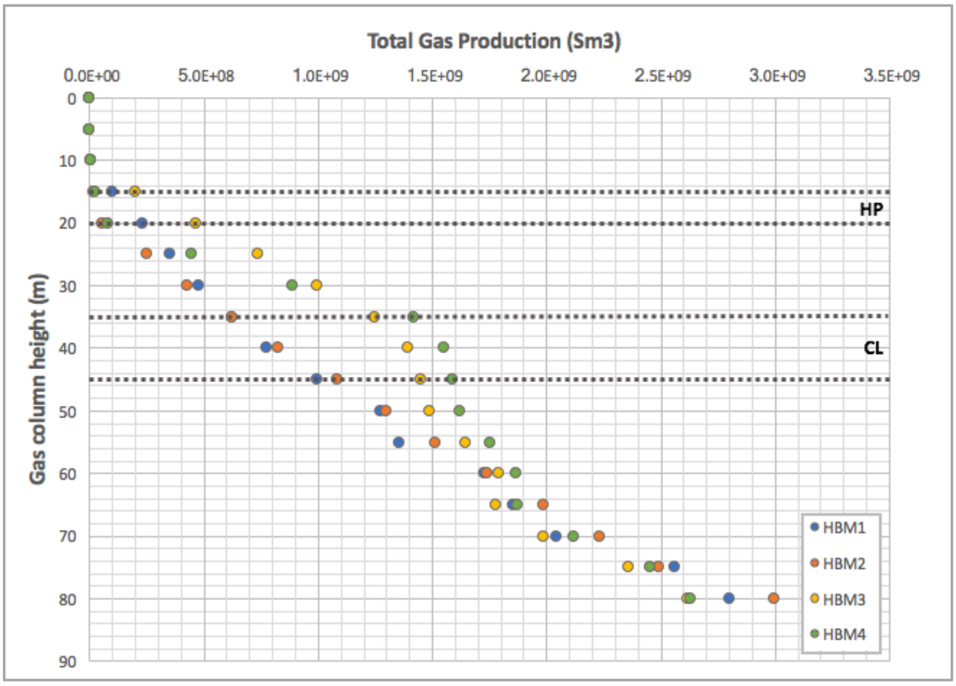


Figure 4.1 Total gas production of horizontal box models, HBM1-4.
(HP) High-permeability streak; (CL) Clay layer.

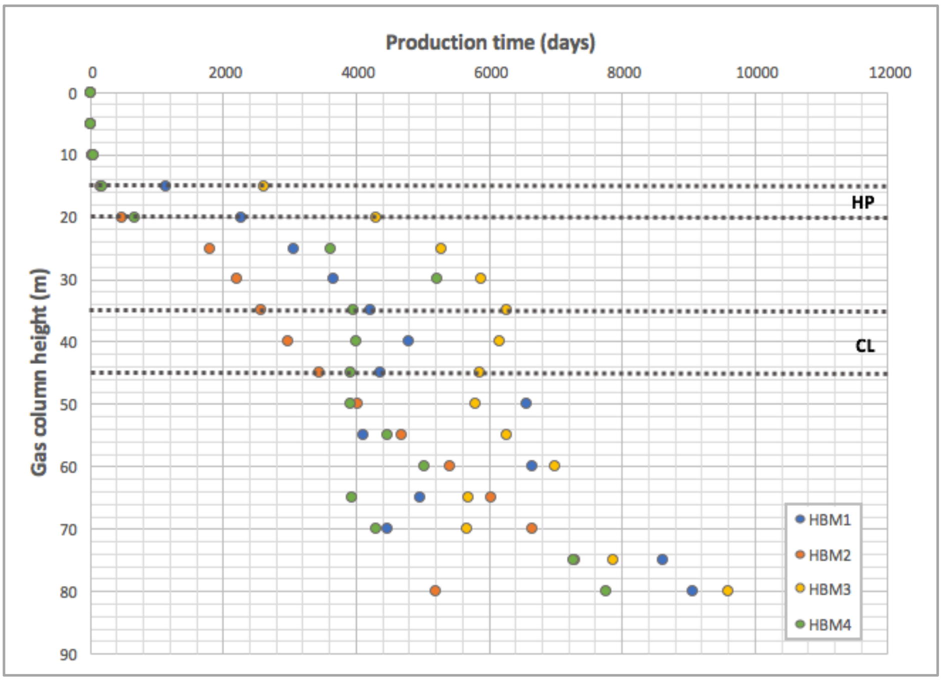


Figure 4.2 Production time of horizontal box models, HBM1-4.
(HP) High-permeability streak; (CL) Clay layer.

4.1.1.1 HBM - Minimum gas column height

The results show that a minimum gas column of 15 to 25 m is required to achieve a minimum ultimate recovery of 0.1 to 0.2 BCM, the chosen cut-off criteria for assessing a project's economic viability. This is due to the fact that smaller gas columns suffer from excessive water production or low production rates. The production profiles show that the models with a 5 m gas column experience an immediate high water inflow of > 150 m^3/d that stops production after one day (Appendix E). Meanwhile models with a 10 m gas column, although do not experience this high water inflow, show a very low initial gas production rate which quickly declines after 30 – 40 days below the minimum allowed gas production rate.

Table 4.1
Reservoir features per box model

	High-permeability streak	Clay layer
HBM1	x	x
HBM2	√	x
HBM3	x	√
HBM4	√	√

Models with gas columns equal to or above 15 m allow a significantly longer period of production and a larger ultimate gas production, however it depends on the version of the model at which gas column height the threshold value is reached. Models HBM1 and HBM3 (both with no high-permeability streaks) achieve the gas production threshold value, whereas production from models HBM2 and HBM4 (both with a high-permeability streak) is hindered due to high water inflow. The high water inflow in models HBM2 and HBM4 is due to existence of a high-permeability streak, which when situated just below water contact, leads to an increase in water production, early shut off of the perforation and drop of the production rate below the allowable threshold. Reservoirs with a gas column higher than 25 m tend to significantly extend the production lifetime.

4.1.1.2 HBM – High-permeability streak

The effect of a high-permeability streak is further tested in model HBM2. Compared to model HBM1 the overall performance of model HBM2 is much better for those cases where the gas column exceeds 30 m. Additionally, model HBM2 shows a drastic reduction in the production time compared to HBM1 which is a much more significant difference of the production results of HBM2. Comparing the production profiles of models HBM1 and HBM2 (Appendix E)

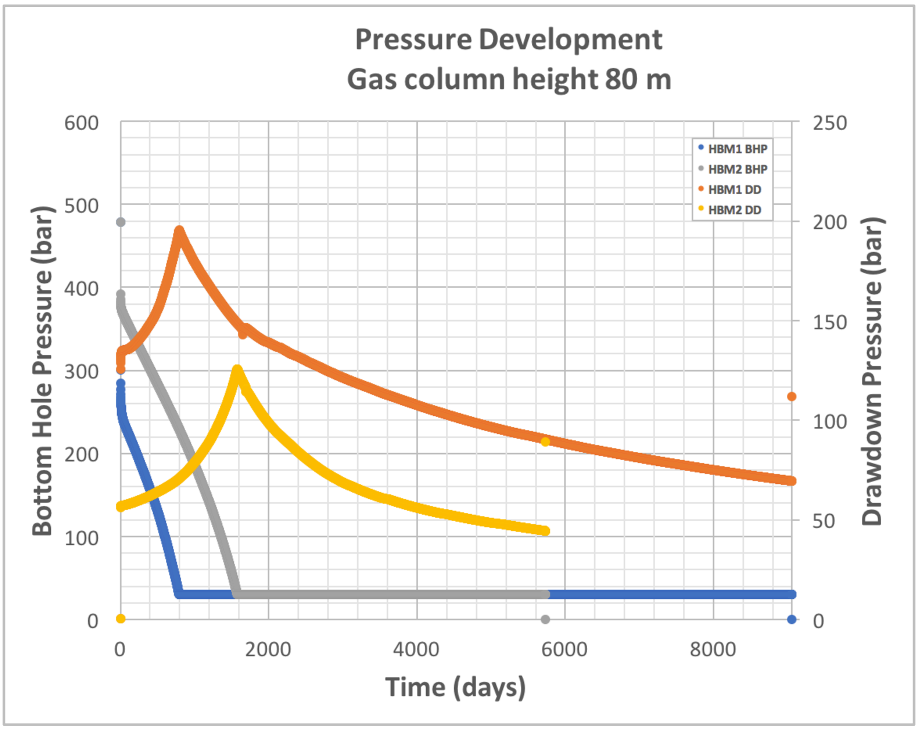


Figure 4.3 HBM1 and HBM2 bottom hole (BHP) and drawdown (DD) pressure development over time. Models with gas columns of 80 m.

shows there is one critical difference; the plateau production phase for model HBM2 is longer than for model HBM1 and consequently the point of water breakthrough, which takes place at roughly the same time in these two models, occurs in the decline phase for model HBM1 and in the plateau production phase for model HBM2. This is an important difference as model HBM2 produces a larger amount of gas in the beginning of the production lifetime for which model HBM1 requires an extended period of time to make up for the gap in total gas production.

These observations are explained by the lower resistance in the reservoir of model HBM2. Figure 4.3 shows bottom hole pressure and drawdown over the production lifetime for models HBM1 and HBM2 with a gas column of 80 m. It shows that model HBM2 requires a smaller drawdown and consequently produces with higher bottom hole pressure than model HBM1 which demonstrates that the reservoir of model HBM2 experiences less resistance. Furthermore, the water saturation around the well over the field production time was analysed in order to investigate water coning. It was expected that the lower drawdown in model HBM2 would result in a less strongly developed water cone around the well than in model HBM1. The water saturation around the well was compared at several points in the production lifetime, including the point just before water breakthrough and the end of the production time. The expected observation was however only partially confirmed and can be seen in Figure 4.4 which shows the water saturation around the well for models HBM1 and HBM2 with a gas column of 80 m at two moments in time; day 1645 (just before water breakthrough in model HBM1 and near water breakthrough in model HBM2, which occurs at day 1693) and at the end of production lifetime (different for both models; day 9057 and 5200 for model HBM1 and HBM2 respectively). Water saturation at day 1645 shows little difference, although at the end of production the water cone around the well in model HBM1 has continued to grow, whereas the water cone in model HBM2 has flattened out. Therefore, the expected relation between drawdown pressure and water coning around the well is only partially demonstrated.

4.1.1.3 HBM – Clay layer

Model HBM3 assesses the effect of the presence of a clay layer on the production results. From Figure 4.1 and 4.2 it becomes clear that the clay layer in this model significantly impacts the gas production and production time when compared to models that do not

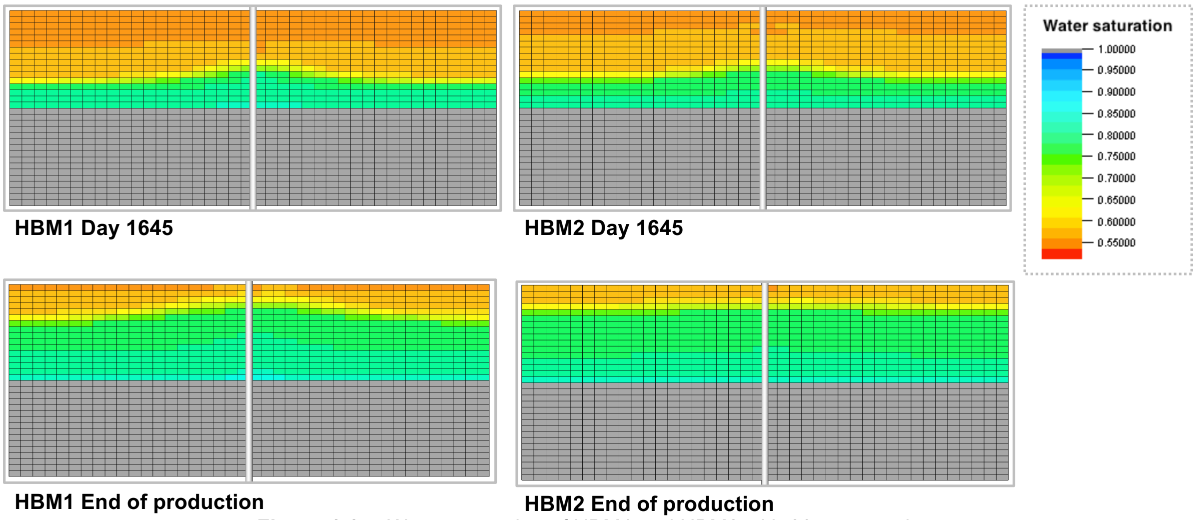


Figure 4.4 Water saturation of HBM1 and HBM2 with 80 m gas column at day 1645 and end of production

include a clay layer (models HBM1 and HBM2). It shows much higher gas volumes produced for model HBM3 with gas columns up to 60 m but also an overall increased production time. The main differences in the production profiles are that the plateau production phase is shorter, and the water rate increases much slower than for model HBM1 and HBM2 and consequently no water breakthrough occurs in almost all simulation cases. Therefore, the full perforation interval remains open for the entire time of production. This allows a more gradual gas rate decline, and up to a gas column of 60 m the extended production time results in higher gas volumes produced. Contrary to model HBM2 water saturation plots do indeed show weaker developed water cones around the well for model HBM3. As an example, Figure 4.5 and 4.6 show models HBM1 and HBM3 with a 40 and 80 m gas column respectively just before water breakthrough occurs in model HBM1 (day 220 and 1645 respectively) and at the end of production. Model HBM3 shows much lower water saturations and less strongly developed coning structures around the well than model HBM1.

These findings remain constant over the entire gas column interval and consequently it is difficult to pinpoint the reason why model HBM3 only produces larger gas volumes in models with gas columns up to 60 m. It is possible that as the gas column height is increased below the clay layer, the sweep efficiency in the gas-bearing part of the reservoir below the clay layer, which is isolated from the gas reservoir above the clay layer, becomes impaired and consequently the gas gets trapped due to limited connection to the perforations. A maximum of two perforations (equal to an interval of 10 m) below the clay layer were implemented for

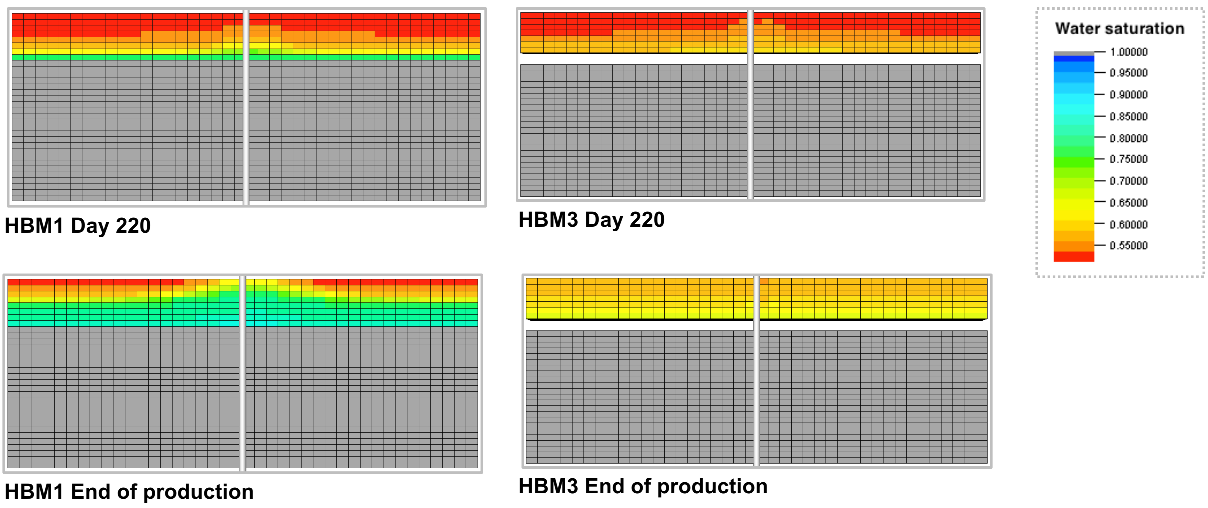


Figure 4.5 Water saturation around the well in HBM1 and HBM3 with a 40 m gas column at day 220 and at end of production.

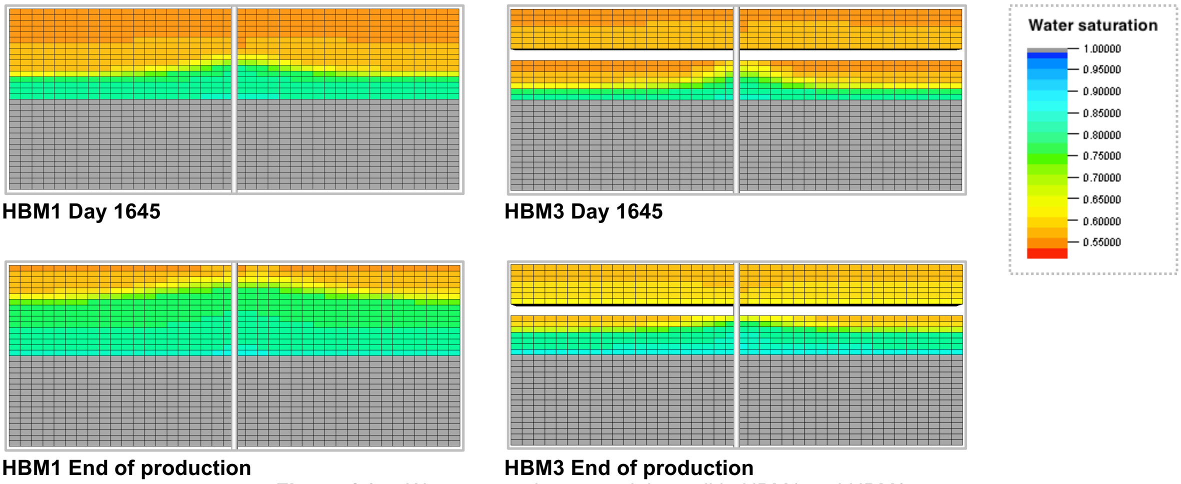


Figure 4.6 Water saturation around the well in HBM1 and HBM3 with an 80 m gas column at day 1645 and at end of production.

the largest gas columns. Adding additional perforations might improve the sweep efficiency for the increasing gas reservoir, although this will also increase water inflow and the balance between these two factors should be investigated thoroughly.

4.1.1.4 HBM – High-permeability streak and clay layer

Model HBM4 contains both the high-permeability streak and the clay layer and was included to test a different configuration of heterogeneity in the model and an increased number of heterogeneous elements. The results reflect, as expected, a combined effect of models HBM2 and HBM3. The graph of total gas production of model HBM4 in Figure 4.1 shows the same trend as the graph of model HBM3, only shifted to the right (i.e. higher total gas production) for columns of 35 m and larger. Furthermore, the graph of model HBM4 corresponds to two characteristic points seen in the graphs of models HBM2 and HBM3. At a gas column of 35 m the presence of the high-permeability streak causes an increase in the total gas production, compared to model HBM3 (without the high-permeability streak), whereas at a gas column of 60 m the presence of the clay layer causes a decrease in total gas production, like in model HBM3. In addition, the production time for model HBM4 also follows a similar pattern as model HBM3, however the entire graph is shifted to the left giving model HBM4 significantly lower production times than HBM3, which is in line with the results obtained for model HBM2.

The combined effect of the two reservoir features is also visible in the production profiles. The target gas production rate is easily reached which results in a quickly developed plateau production phase which has a longer duration than the plateau production phase in model HBM2. Water rate build up is relatively slow, like in model HBM3, and consequently does not cause water breakthrough which facilitates production from the entire perforation interval.

Therefore, it is demonstrated that the horizontal box model shows a positive response to this configuration of heterogeneity. The negative effects of an individual reservoir feature are cancelled out or reduced by the other reservoir feature. This results in a higher gas volume produced and lower production time required.

4.1.2 Tilted Box Model (TBM)

The same simulation setup was repeated for the tilted box model. The gas production results and total production time are shown in Figure 4.7 and 4.8 and the position of where the reservoir features connect to the well are indicated in these figures. Table 4.2 provides a quick overview of which reservoir feature is found in which version of the tilted box model. Lastly, the production profiles, which provide important insight information into the results, are given in Appendix F.

The results of the tilted box model give the following three key observations:

1) The minimum gas column required to reach the threshold total gas production (0.1 – 0.2 BCM) is 20 – 30 m, depending on the version of the model.
2) The high-permeability streak reduces total gas production and the clay layer increases total gas production.
3) Combining the high-permeability streak and clay layer in this model (TBM4) gives the lowest gas production results out of the four models.

Table 4.2
Reservoir features per box model

	High-permeability streak	Clay layer
TBM1	x	x
TBM2	√	x
TBM3	x	√
TBM4	√	√

4.1.2.1 TBM - Minimum gas column height

The shallowest gas column for which the threshold gas production (0.1 – 0.2 BCM) is reached is 20 – 30 m. This is slightly larger than the minimum required gas column in the horizontal box model. The production profiles show the same reasons for low production in the models with a 5 and 10 m gas column as in the horizontal box model, namely severe water inflow for the 5 m scenarios and low gas productivity resulting in an early shut down of production in the 10 m gas column models. Although models TBM1 and TBM3 show a significant increase in production time when the gas column is increased to 15 m, they only reach the threshold production rate for gas columns height above 20 m. Models TBM2 and TBM4 experience significant water inflow leading to the cessation of production after ~ 150 days. The production time is extended under the same circumstances as the gas column is increased and at 30 m the minimum gas production is reached.

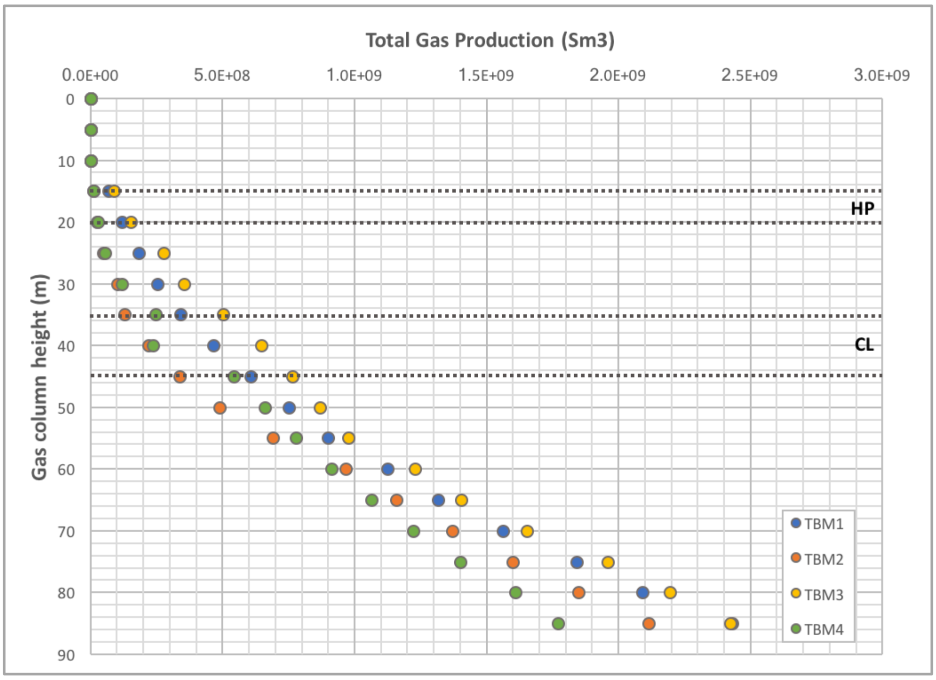


Figure 4.7 Total gas production of tilted box models, TBM1-4.
(CL) Clay layer; (HP) High-permeability streak.

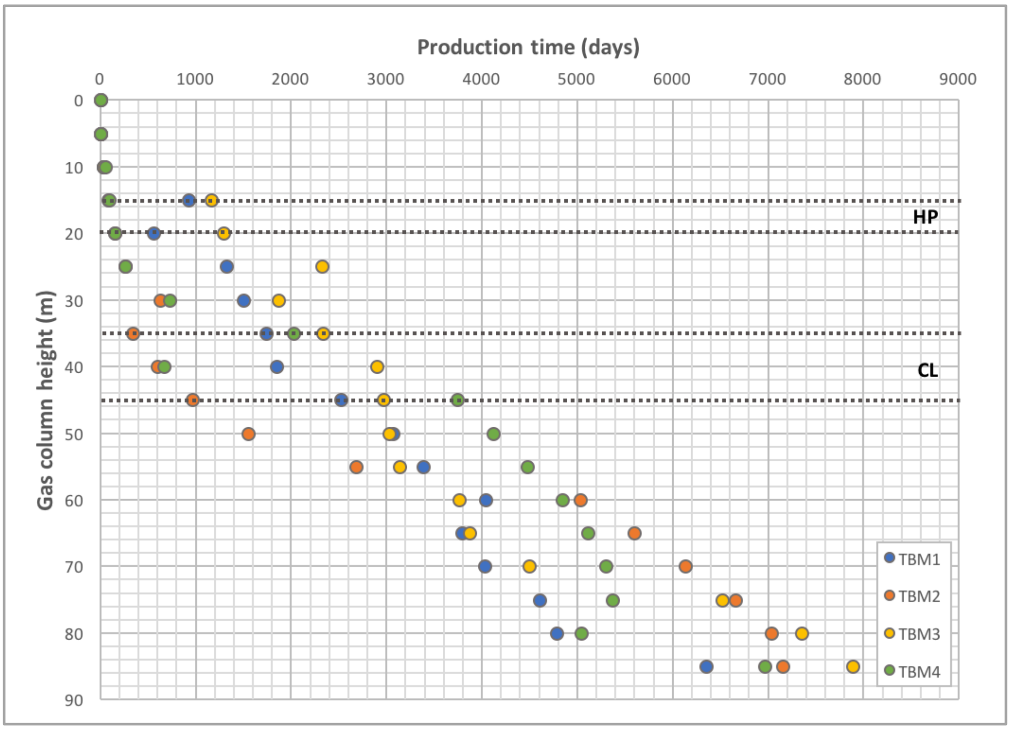


Figure 4.8 Production time of tilted box models, TBM1-4.
(CL) Clay layer; (HP) High-permeability streak.

4.1.2.2 TBM – HIGH-PERMEABILITY STREAK

Model TBM2 corresponds to the tilted box model with a high-permeability streak. The total gas production here is substantially lower than in model TBM1, particularly for the smaller gas column heights. Production time of model TBM2 is also significantly lower for those models with a gas column up to 55 m, after which the production time shows a big shift and increases to significantly higher values than model TBM1. The production profiles show the difference in the plateau production phase between models TBM1 and TBM2 (Appendix F), found over the entire gas column interval (0 – 80 m). Model TBM1 has a shorter plateau production phase than model TBM2 and enters the decline phase before water breakthrough. Vice versa, model TBM2 shows a longer plateau production phase than TBM1 which is only ended by water breakthrough. The bottom hole pressure of model TBM1 shows a quicker decline than model TBM2 (Figure 4.9) and consequently reaches the minimum constant bottom hole pressure value sooner which causes the plateau production phase to go into the decline phase (before water breakthrough). The bottom hole pressure in model TBM2 does not reach the minimum pressure value until water breakthrough occurs. During the bottom hole pressure decline phase the drawdown of model TBM1 is also higher than the drawdown of model TBM2 meaning more force is required in order to reach and sustain the target gas rate in model TBM1 than model TBM2. This is, like in the horizontal box model, indicative of lower resistance in the model containing a high-permeability streak. Although the effect of a high-permeability streak on the resistance of flow in the reservoir in the tilted box model is similar to the effect found in a horizontal box model (i.e. lowered reservoir resistance for the reservoir containing high-permeability streak), this does not result in the same effect on the production results. The stimulated flow in the tilted box model, caused by the presence of a high-permeability streak, is also in direct contact with the aquifer due to the dipping reservoir. This either results in multiple quick water breakthroughs (up to a gas column height of 55 m), severely reducing the production time and causing lost gas production or it causes low gas productivity after water breakthrough (for gas column height of > 55 m), which cannot yield the same total gas production as model TBM1, even though production time is significantly increased.

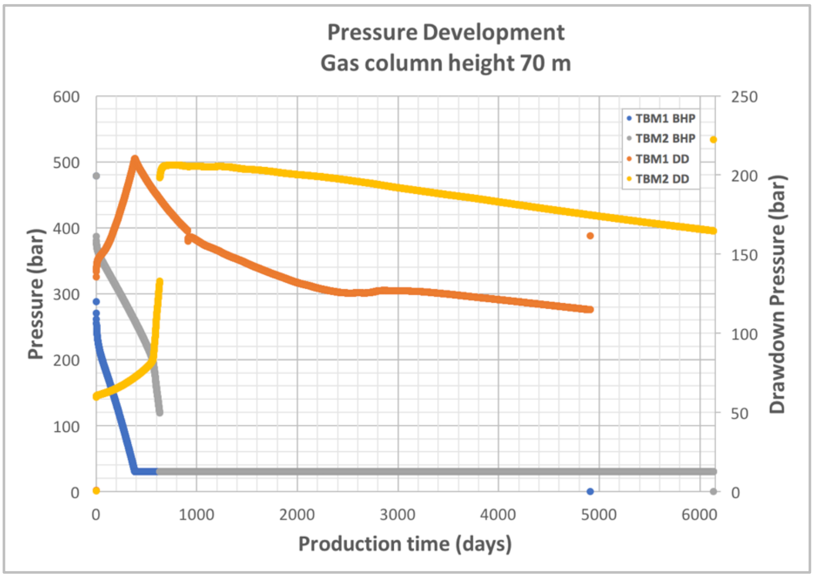


Figure 4.9 Models TBM1 and TBM2 bottom hole (BHP) and drawdown (DD) pressure change. Models with gas columns height of 70 m.

4.1.2.3 TBM - Clay layer

The effect of a clay layer in a tilted box model can be seen in model TBM3. The total gas production in this model is higher and has a longer production period than for model TBM1 (Figure 4.7 and 4.8), although the degree of increased gas production and production time strongly varies per model version. The production profiles (Appendix F) show that model TBM3 has a shorter plateau production phase which is even completely absent for those models with shorter gas columns (< 40 m). Model TBM3 also shows a much slower water rate build up and consequently does not experience water breakthrough, i.e. production takes place from the full perforation interval during the total production time. This results in higher total gas production and longer production times for the models' full gas column interval. This is slightly different from model HBM3, which only obtains higher total gas production up to a gas column of 60 m, possibly due to the fact that in the horizontal box

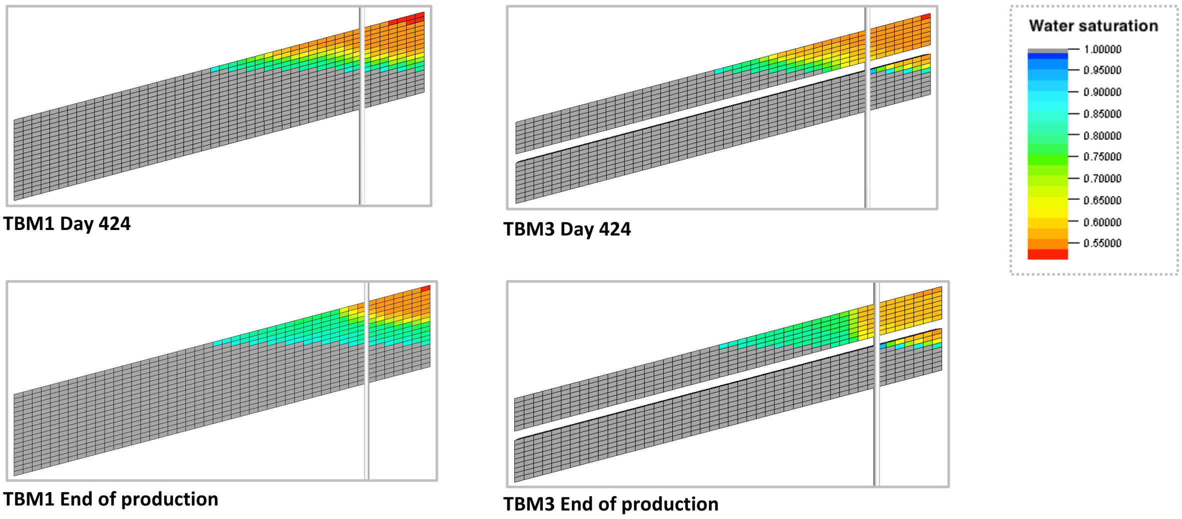


Figure 4.10 Water saturation around the well in TBM1 and TBM3 with a 40 m gas column at day 424 and at end of production.

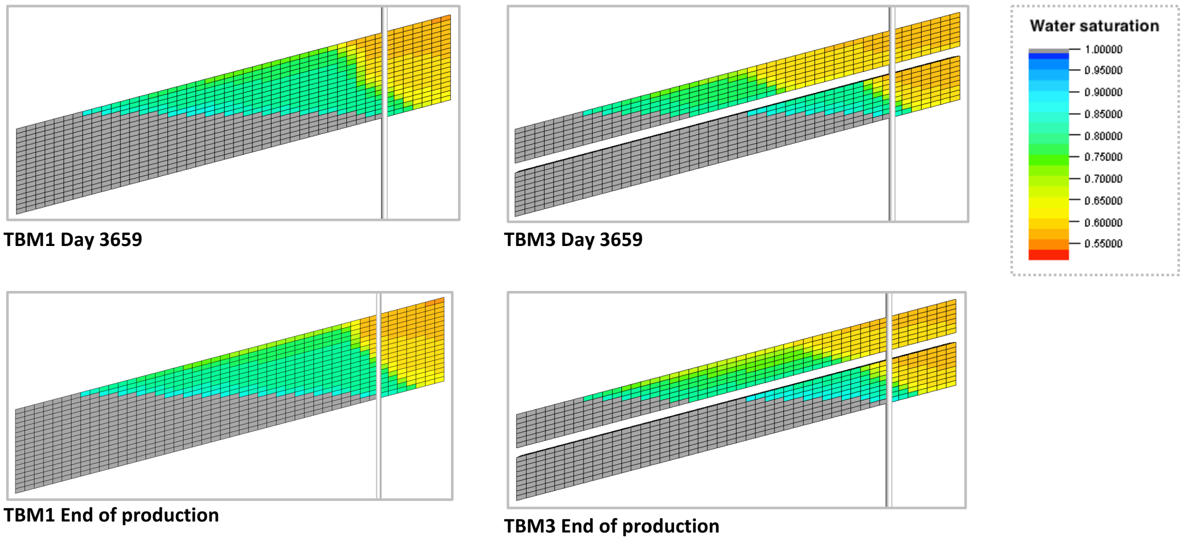


Figure 4.11 Water saturation around the well in TBM1 and TBM3 with an 80 m gas column at day 3659 and at end of production.

model the gas below the clay layer is connected to a very small part of the perforation interval.

The slow water rate build up shows that the clay layer functions as a barrier between aquifer and wellbore by reducing vertical inflow of water into the lower section of the well intersecting the clay layer. Figure 4.10 and 4.11 show the saturation plots around the well for models TBM1 and TBM3 with a 40 m and 80 m gas column at water breakthrough in model TBM1 (day 424 and 3659 for gas column height of 40 and 80 m respectively) and at end of production. They show that water in model TBM1 is more easily drawn to the well area than in model TBM3. Higher water saturations can be observed around the bottom of the well for model TBM1 in both Figure 4.10 and 4.11, whilst Figure 4.11 also shows a steeper water front in model TBM1 that reaches closer to the well than the flatter water front in model TBM3. Figures 4.10 and 4.11 also show lower water saturation (i.e. higher gas saturation) in the crest of the reservoir in model TBM1 than model TBM3, which indicates a poorer sweep efficiency in this area for model TBM1 than model TBM3.

4.1.2.4 TBM – High-permeability streak and clay layer

The combined effect of the high-permeability streak and clay layer was tested in model TBM4. Results show that this scenario of the tilted box model does not perform well; for all gas column heights, the total gas production is always lower than in the base case, model TBM1, and the results are conflicting with what was found in models TBM2 and TBM3 (Figure 4.7). In this particular configuration, the negative effect of a high-permeability streak (especially for the smallest gas columns), is more dominant than the hampering effects of the clay layer, which allows a higher total gas production in model TBM3. Over the interval of 0 – 40 m the total gas production is more or less the same as the total gas production of model TBM2 and the clay layer seems to have no effect on production at all. This most probably due to the fact that the clay layer is situated in the aquifer until a gas column of 40 m is reached. Between the interval of 40 – 55 m, when the clay layer is situated at the bottom of the reservoir, the clay layer starts positively influencing the production, as total gas production of model TBM4 is higher than model TBM2, although it does not reach up to the volumes produced by model TBM3. Lastly, over the interval of 60 – 80 m the total gas production becomes the least performing model scenario. A potential explanation for the low performance of this model is the fact that the presence of the high-permeability streak draws in water quickly, causing water breakthrough, while the clay layer restricts both water and gas flow to the limited perforation interval which is shut off all the way up to the high-permeability streak. Model TBM3, which does not contain a high-permeability streak, does not experience this quick water inflow, consequently preventing partial shut off of the perforation interval. It is therefore reasonable to assume that a different configuration of these reservoir features (e.g. switching the high-permeability streak to a lower position and the clay layer to a higher position) will result in a different outcome.

4.2 Sensitivity study, part 2: Real case reservoir modelling

Results from the complex reservoir model are presented in a similar manner as for the box model, by focusing on the main topics; 1) the minimum gas column height and 2) the presence/absence of a high-permeability streak and/or clay layer. To limit the number of figures in the report, the total gas production and production time per model are given in Appendix G1-G4, and only a representative example of total gas production in CRM-A is shown in figure 4.12. Furthermore, the production profiles are found in Appendix I1-I4.

Contrary to the modelling strategy used for the box models, where new elements were introduced for each step, here the complex numerical models are simplified (homogenized) in a stepwise manner to a near homogeneous reservoir. The process of homogenizing also includes the removal of the fixed relation of permeability below to above water contact ($^1/_{100}$) and increasing the K_v/K_h ratio to 1. This is different from the box models where the base case scenario (models HBM1 and TBM1) already included the fixed ratio of permeability below and above the water contact of $^1/_{100}$ and the K_v/K_h ratio is $^1/_{100}$. Table 4.3 gives an overview of which parameter is changed in which consecutive model (1 to 8).

Table 4.3 Reservoir features per box model

Model	Field	Homogeneous permeability	Homogeneous porosity	Homogenous net-to-gross	Removal clay layer	Permeability below free water level equal to permeability above free water level	K_v/K_h $^1/_{10}$	K_v/K_h $^1/_1$
CRM1	A, B, C, D	x	x	x	x	x	x	x
CRM2	A, B, C, D	√	x	x	x	x	x	x
CRM3	A, B, C, D	√	√	x	x	x	x	x
CRM4	A, B, C, D	√	√	√	x	x	x	x
CRM5	A, B, C, D	√	√	√	√	x	x	x
CRM6	A, B, C, D	√	√	√	√	√	x	x
CRM7	A, B, C, D	√	√	√	√	√	√	X
CRM8	A, B, C, D	√	√	√	√	√	√	√

The following three main observations are derived from the results of the reservoir model:

1) A minimum gas column height of 20 – 42 m is required to produce economic gas volumes (0.1 – 0.2 BCM).
2) The high-permeability streaks have a beneficial effect on the production results (total gas production and/or production time).
3) The net effect of a clay layer is minimal, due to the presence of a weak aquifer.

4.2.1 CRM - Minimum gas column height

From the total gas production results (Figure 4.12 and Appendix G) it can be seen that the minimum required gas column varies between 20 – 42 m in order to reach the threshold gas production, depending on the gas field and the version of the model (Table 4.4). This is higher than wat is found in the box model (~15 – 30 m). The minimum required gas column for the tilted reservoirs in the complex reservoir model (CRM-B, and CRM-C) are comparable with

Table 4.4 Minimum gas column required for economic gas production

	Minimum gas column range
Field A	34 – 39 m
Field B	23 – 49 m
Field C	20 – 30 m
Field D	37 – 42 m

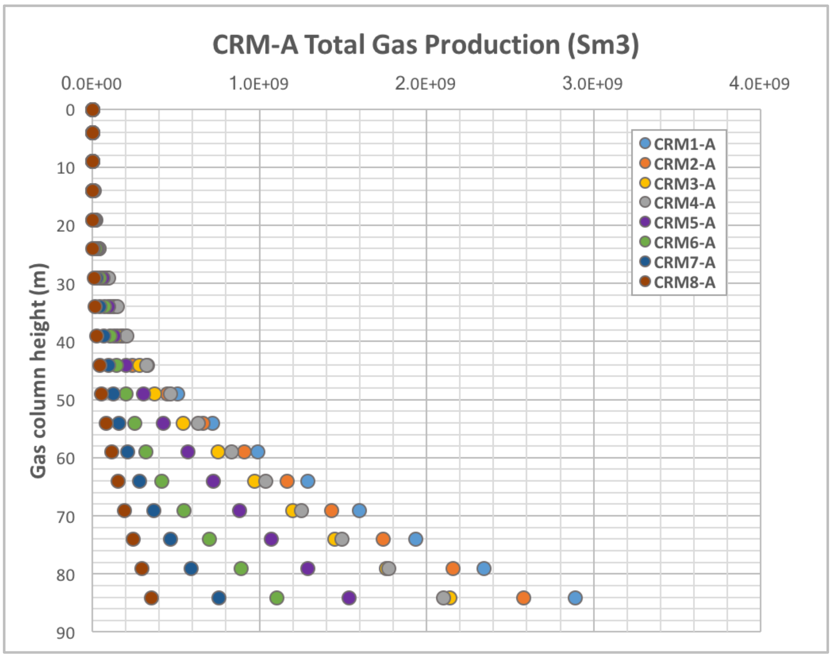


Figure 4.12 Total gas production model CRM-A.

the minimum gas column found in the tilted box model. The results from the near-horizontal reservoirs, CRM-A and CRM-D, on the other hand are not comparable to the results of the horizontal box model, as the minimum required gas column height is much higher in the complex reservoir model than in the box model. This is possibly due to the geometry of the near-horizontal gas reservoirs in the complex reservoir model, which have irregular layers possibly causing unconnected or bypassed GIIP.

Furthermore, the tilted base case gas reservoirs (CRM1-B and CRM1-C) require a thinner gas column in order to reach the gas production target than the base case near-horizontal reservoirs (CRM1-A and CRM1-D). The production profiles of the tilted reservoirs (Appendix I2 and I3) show that field CRM1-B and CRM1-C (with minimum gas column height of 23 and 20 m respectively), produce at target gas rate with relatively thin gas columns (< 15 m) whilst this plateau production phase remains undisturbed from water breakthrough. On the contrary, field CRM1-A, which requires a minimum gas column height of 34 m, is unsuccessful at reaching its target production rate in the model scenarios with thinner gas columns (Appendix I1). Field CRM1-D, which shows a minimum gas column height of 42 m, does reach the target production rate, even in the scenarios with the thinner gas columns, however, it reaches an early water breakthrough stopping the plateau production phase and shortening the production time (Appendix I4). This difference in minimum gas column height required between the near-horizontal and tilted reservoirs is explained by the difference in GIIP distribution and field geometry. Field CRM1-A and CRM1-D have near zero GIIP values at a gas column of 0 m (Figure 4.13). However, due to the field's geometry, field CRM1-B and CRM1-C do not have 0 BCM GIIP in the reservoir when the gas column is reduced to zero (Figure 4.13). There will still be some GIIP in the top corner of the reservoir (above top formation found in well), provided that the wellbore is not drilled precisely at the crest. This will support production from thin gas columns.

4.2.2 CRM – High-permeability streak

One common characteristic found in all four gas fields is the presence of one or several high-permeability streak(s) in the top part of the reservoir. The effect of these high-permeability streaks can be observed by comparing the results of models CRM1 and CRM2 (Fig 4.12 and Appendix G). Results show that in general the presence of one or more high-permeability streaks tend to have a positive impact on the total gas production. The most positive effect is observed in models CRM1-A and CRM1-B which show higher total gas production than for models CRM2-A and CRM2-B, combined with a reduction in production time of varying degree.

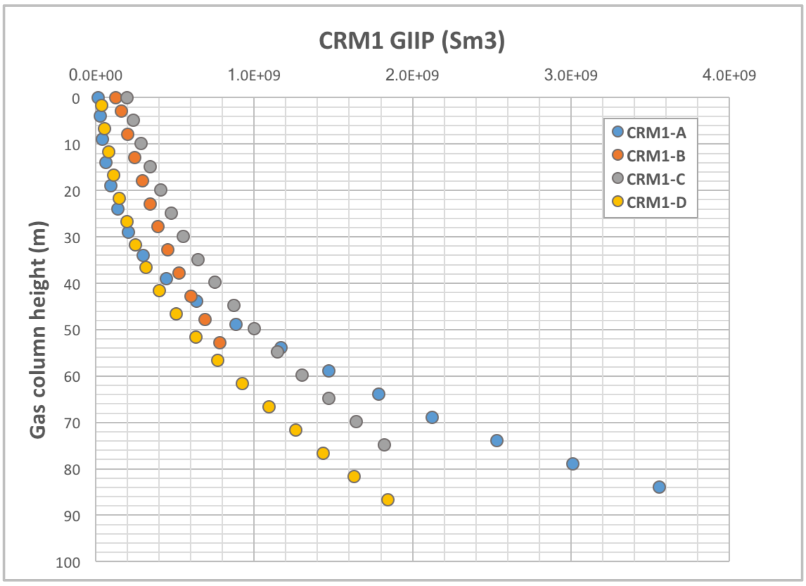


Figure 4.13 GIIP of CRM1

The positive effect of a high-permeability streak in models CRM1-C and CRM1-D fields on the other hand is less straightforward, as often a reduction of the total gas production for models CRM1-C and CRM1-D can be observed. However, the production time is significantly lower in models CRM1-C and CRM1-D than models CRM2-C and CRM2-D; the extend of which far exceeds the differences in gas production between these model scenarios.

The production profiles of models CRM1 and CRM2 are in agreement with what is found in the results of the box model, namely that the high-permeability streaks are an important factor for production at target gas rate and extending the plateau production phase. All four gas fields show longer plateau production phases in the model CRM1 version of the gas field which coincides with: 1) a lower bottom hole pressure, that declines to the minimum value at a slower pace than model CRM2; and 2) a smaller drawdown required to achieve production at the target gas rate (see Figure 4.14 for an illustration of the pressure development of models CRM1-C and CRM2-C, which is representative of the relative positions of the bottom hole pressure and drawdown for all four gas fields).

Furthermore, the results show that the lower resistance in the reservoir has a larger effect on the gas production results of fields with a lower average permeability. Models CRM1-A and CRM1-B show significantly higher total gas production than models CRM2-A and CRM2-B (especially CRM1-B). Models CRM-A and CRM-B have the lowest average permeability (6.2 and 1.5 mD respectively; see also Table 3.8) compared to models CRM-C and CRM-D (16.5 and 13.2 mD respectively). These average values were used to homogenize the permeability distribution in the field. This is also clearly visible in the production profiles of models CRM1 and CRM2. Model CRM-B shows a substantially larger difference in the length of the plateau production phase between CRM1-B and CRM2-B than the fields with higher average permeability which demonstrates the necessity of the high-permeability streaks in order to obtain the target production rate. This strongly indicates that high-permeability streaks are a more important contributing factor to the gas production from fields with lower average permeability than from gas fields with higher average permeability.

4.2.3 CRM – Clay layer

The removal of the clay layer in model CRM5 for all four fields clearly shows a decrease of the total gas production as well as the length of production time. Although these results are almost entirely in agreement with what was found in the box model, the production profiles of the reservoir model (Appendix I) show a reversed trend compared to the production profiles from the box model. The production profiles of model CRM4 gas fields (with clay layer) show a longer plateau production phase than the production profiles of the model CRM5 gas

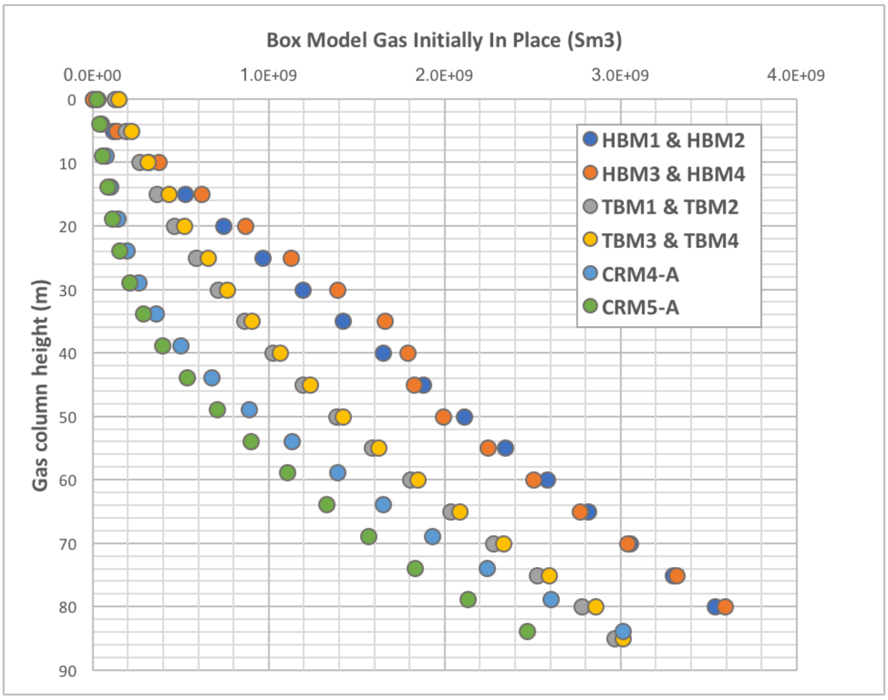


Figure 4.15 GIIP of HBM, TBM, CRM4-A & CRM5-A

fields (without clay layer).

The different outcomes in the production profiles have two reasons: 1) the reservoir contains a weak aquifer and 2) the GIIP has changed between models CRM4 and CRM5. The production profiles of CRM4 and CRM5 show very little difference in the inflow of water between these two models. This is due to the weak aquifers in the system. The production profiles of the box models clearly show a reduction of water inflow when the clay layer is removed, which consequently prevents a water breakthrough. Therefore, it seems the production does not benefit from the presence of a clay layer as water inflow already has a low impact on production.

The higher total gas production and production time for CRM4 is consequently not explained by reduced water inflow, but by the change in GIIP. As has been explained, the porosity and net-to-gross values were adjusted for the models where the clay layer was removed. However, changing these values has an impact on permeability, therefore for this model they could not be changed such that the GIIP was kept completely the same. The changed porosity and net-to-gross values has had a larger impact on the GIIP in the reservoir model, than in the box models. This is demonstrated in Figure 4.15 which shows the GIIP difference in the box and reservoir model with and without the clay layer. In the box model, the clay layer is absent in version 1 and 2 and present in version 3 and 4. The clay layer in the reservoir model is removed between CRM4 and CRM5 and field CRM-A is a representative example for all four gas fields (see also Appendix H for GIIP in all gas fields). The figure shows a larger discrepancy in GIIP values for the reservoir model than the box model which is likely related to the differences found in production results for the reservoir model.

4.2.4 CRM – Decreasing heterogeneity

In general, it is found that decreasing the heterogeneity in a stepwise manner decreases the total gas production (Figure 4.12 and Appendix G), although there are a few important exceptions that should not be overlooked. Switching from a heterogeneous permeability distribution to a homogeneous permeability value causes an increase in the total gas production in model Field CRM-D which has already been discussed in Chapter 4.2.2. Furthermore, in three out of four gas fields (CRM-A, CRM-D and CRM-C up to a gas column height of 50 m), homogenizing the net-to-gross value results in higher total gas production. Changing the heterogeneous property distribution to one constant value results in a change of GIIP when parameters of porosity and net-to-gross are changed. Appendix H shows the GIIP per field for all model scenarios, CRM1-8. It shows that for field CRM4-A, CRM4-D and

CRM4-C with a gas column of $\leq$ 55 m the GIIP is higher than the GIIP from these fields in CRM3. The GIIP between CRM3-B and CRM4-B however, remains more or less constant as also the GIIP between CRM3-C and CRM4-C with a gas column > 55 m. Furthermore, there is also significant decrease in GIIP between CRM2 and CRM3, when the porosity is homogenized which coincides with lower total gas production for CRM3. Consequently, it is very difficult to analyze the results from the scenarios with a constant porosity and net-to-gross value as the production results seem to be correlated to the change in GIIP.
On the other hand, the decrease in total gas production between CRM5-8 is not related to GIIP and it is shown in the total gas production that each step of simplification results in lower gas production and shorter production time. In other words, increasing (vertical) mobility decreases gas production. Production profiles (Appendix I5 and I6) show that increasing vertical mobility also increases water flow which causes early water breakthrough, lower well productivity and shortens production time.
Lastly, field CRM-C shows a large shift in the results between a gas column of 50 and 55 m. At this gas column height of 55 m and larger, CRM2-C is the only model scenario that increases the gas production (instead of net-to-gross). The shift in the results is also largest in this model scenario, CRM2-C. The production profiles show that the gas rate decline of CRM2-C with a gas column height of $\geq$ 55 m is much slower than in the previous cases and the decline phase is extended for each subsequent column height. This increases the production time significantly compared to previous cases which results in the significantly higher total gas production.
However, the explanation as to why the gas rate decline phase develops like this remains unclear. The most relevant factors that potentially cause this shift have been investigated; the pressure development, Kh around the well, water production and GIIP increase over the entire column interval are amongst them. No irregularities have been found. In order to be able to pin point the exact reason why this occurs, further research on the model should be done.

4.3 Analysis of thin gas column wells

The inventory study on the large data set yielded only six candidates (Figure 4.15) on which an in-depth well analysis was carried out in order to gain a better understanding of the factor(s) that made these six wells successful producers.

Note that in Figure 4.15 the GIIP volume for well A is unknown and therefore the bubble size in figure 4.15 is fictitious and was merely used to let the record of well A appear in the figure. Where possible, the description of each well is complemented with a contour map, cross section and composite log combined with a complete field overview including a description of the reservoir geometry and properties. A summary of the field parameters/properties is given in Tables 4.5 and 4.6

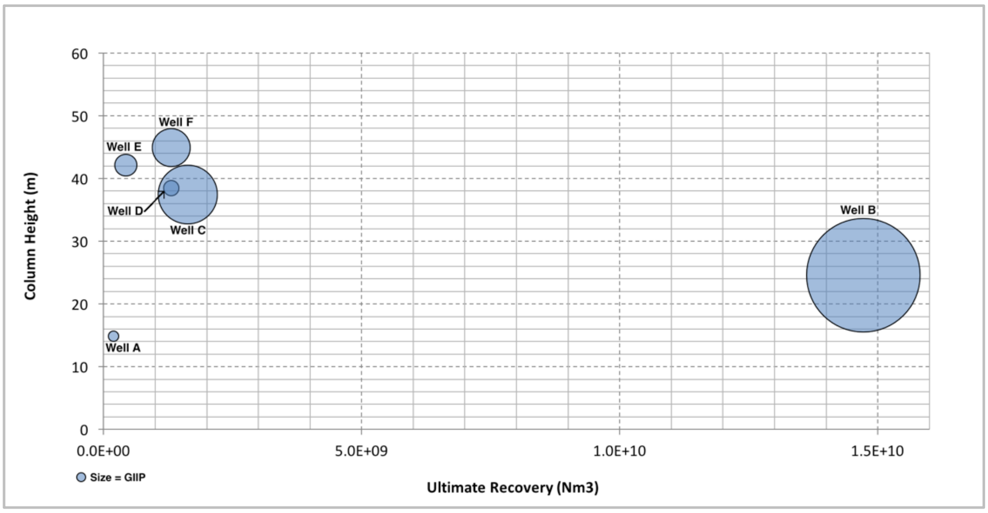


Figure 4.15 The final six wells that resulted from the initial dataset

Table 4.5 Summary of production data per well

	GIIP (BCM)	Ultimate Recovery (BCM)	Recovery Factor (%)
Well A		0.19	
Well B	20.10	14.70	73.2
Well C	5.50	1.63	29.7
Well D	0.39	0.13	77
Well E	0.80	0.44	55
Well F	2.35	0.13	56

Table 4.6 Summary of reservoir characteristics per well

	Height (m)	Porosity (%)	Sw (%)	Net-to-gross (%)	Permeability (mD)	Vertical permeability (mD)	No. wells
Well A	15	16.9	44.9		180.9		1
Well B	25	14	46	98	1.9		2
Well C	37.5	10.7	64	93	1		2
Well D	38.5	15.4	46	82	4.8 (3 - 6)	0.6	1
Well E	42	15	46	100			1
Well F	45	16	50	95	20		1

4.3.1 WELL A

Figure 4.16 Contour map indicating Well A.

Figure 4.16 shows the contour map of the reservoir that corresponds to Well A which contains the smallest column height of all wells that were retained in the final selection. A column height of 15 m is reported by the operator in a reservoir that is bounded by faults and produced as a single well development. The reservoir shows average values for the porosity, permeability and gas saturation of 16.9 %, 180.9 mD and 55.1 % respectively. The reservoir can be split into two geological formations namely the Rotliegend and the Ten Boer sandstones. The Zechstein formation seal the top of the Ten Boer (Figure 4.17). Figure 4.18 shows the seismic cross section of the area with the location of the well. Only horizon F was specified as the Zechstein formation in the report where this cross section was found, however from the composite log it is evident that the Ten Boer and Rotliegend formation are situated below the Zechstein and consequently are not indicated in this cross section.

From this reservoir, a total volume of 0.2 BCM was produced mostly derived from the Rotliegend formation (0.19 BCM). The operator attributes the successful production of this reservoir due to the existence of a large transition zone of 12 m. It is reported that the last 4 m of the gas column corresponds to the top of the transition zone. A water saturation of 70 – 80 % is found at the gas-water contact which over an interval of 12 m below the gas-water contact increases to 100 %. This large transition zone is found to be more common in the area where this gas field is situated. Despite the fact that there is no report on the reservoirs GIIP, the ultimate recovery of 0.2 BCM seems very significant for such a small gas column.

Figure 4.17 Composite log Well A.

Figure 4.18 Cross section Well A.

4.3.2 WELL B

Figure 4.19 Contour map indicating Well B.

Figure 4.19 shows the contour map of the reservoir from which Well B is produced and its corresponding location. As can be seen from the map it is defined as a fault-closed low relief structure and it consists of aelian and fluvial/lacustrine sediments deposited in a desert environment. The production strategy of this reservoir included a two well development of which Well B was the second which was completed (five years after the first well) at the lowest part of the reservoir. A 25 m gas column was reported by the operator for Well B in the Upper Slochteren interval, which is overlain by the Ten Boer interval. Figure 4.20 shows a seismic cross section along Well B and clearly indicates the Ten Boer interval beneath which the interval of interest (Slochteren) is situated. Petrophysical characteristics determined in this well are relatively good with an average porosity of 14 % (determined over the net interval), a hydrocarbon saturation of 54 % and a net-to-gross of 98 %. Although the average permeability was reported around 1.9 mD, there are some reservoir intervals with a permeability as high as 344 mD.

The GIIP of this reservoir is about 2 BCM with a high recovery factor of 73 %. A significant amount of gas was found below the free water level. The composite log (Figure 4.21) shows at least an additional 40 m of gas column below the free water level, which was not considered producible.

Figure 4.20 Cross-section Well B

Figure 4.21 Composite log Well B

4.3.3 WELL C

Figure 4.22 Contour map indicating Well C.

The position of well C is shown on the contour map in Figure 4.22. The gas column in the well is 37.5 m thick and it is strictly produced from the Slochteren formation in the Rotliegend group which consists of predominantly course clastic materials, i.e. sandstone and conglomerate. As can be seen in Figure 4.23 the field is situated in a (northeast) dipping high block which is bounded by a northwest-southeast running fault, also shown in Figure 4.22. The average porosity over the net interval is reported at 10.7 % (within a range of 3.7 – 24.5 %), the average water saturation at 64 % (within a range of 40 – 100 %), the permeability at 1 mD and a net-to-gross of 93 % was found. An infill well was drilled some years after Well C was drilled, however it remains uncertain whether this well reached the reservoir structure at a higher or lower position. Although Well C produced a considerable volume of gas (1.63 BCM), this was a low recovery (29.7 %) from a much larger GIIP estimated at 5.5 BCM. The low recovery factor is explained by a poor reservoir quality (caused by conglomerates) and the larger volume of water produced.

Figure 4.23 Seismic cross-section Well C.

4.3.4 WELL D

Figure 4.24 Contour map indicating Well D.

Figure 4.24 shows the contour map of the field from which Well D produces, which is a single-well development. The contour map shows the division of the field in five reservoir blocks all forming fault/dip closures of which only the main block is efficiently depleted as the well is situated in this block. Figure 4.25 shows a cross section of the main block and two other reservoir blocks, where the gas-water contact is at the same depth. The main block contains a fault towards the southeast, visible in Figure 4.24 and 4.25, which acts as a baffle to the gas flow. Both the Ten Boer and Slochteren formations were confirmed to be gas bearing in Well D, however the Ten Boer formation was considered a waste zone due to low productivity and production came solely from the Slochteren formation for which the Ten Boer formation acts as a seal. A gas interval of 38.5 m is reported with a net pay zone of 31.6 m. A transition zone of 5 m was confirmed at the bottom of the gas interval where the gas saturation decreases from 54 % in the reservoir to 27 % in the transition zone. Good petrophysical characteristics are reported for the Slochteren formation with an average porosity of 15.4 %, an average gas saturation of 54 %, a net-to-gross of 82 % and an average permeability of 4.8 mD (in a range of 3 - 6 mD) and a vertical permeability of 0.6 mD was found from well testing.

The field GIIP was established at 0.39 BCM of which 0.13 BCM was ultimately recovered giving a relatively low recovery factor of 33.4 %. However, this number is based on a GIIP that included two reservoir blocks of which one is poorly connected to the well. As was stated previously, production was mostly from the main reservoir block and therefore the operator reports a recovery factor of 77 % only using the GIIP of the main reservoir block.

Figure 4.25 Cross section Well D

4.3.5 Well E

Figure 4.25 Contour map indicating Well E.

Figure 4.25 shows the contour map the gas field corresponding to Well E, which is situated in an east dipping fault block and bounded by a normal fault on the west and by a more complex (strike-slip) fault system on the southeast. The field is a single-well development which produced from the Slochteren formation which is overlain by the Ten Boer formation (Figure 4.26 and 4.27) and comprises a total gas column length of 42 m. The field has an average porosity of 15 %, water saturation of 46 % and a net-to-gross of 100 %, however the gas saturation and permeability decrease drastically over the lower interval. It is reported that the water saturation is found to be significantly higher at a value of 82 % in the lower 20 m of the interval. This is also illustrated in Figure 4.27 which shows the composite log of Well E. Three different types of water saturation (Sw) are presented (indicated in the header by the colours green, red and blue) all with 100 % to the left of the scale and 0 % to the right of the scale. A sudden shift from right to left (i.e. from low to high water saturation) occurs at around 2600 m indicating this lower quality zone of the gas interval.

A total field GIIP of 0.8 BCM was found of which 0.44 BCM is recovered. Consequently, the recovery factor is ~55 % which is much lower than expected due to the impaired permeability and low gas saturation in the lower part of the gas zone.

Figure 4.26 Cross section Well E

Figure 4.27 Composite log Well E

4.3.6 Well F

Figure 4.28 Contour map indicating Well F

Figure 4.28 displays the contour map of the field produced through Well F, which is a single-well development. The field is bounded by a complex northwest-southeast fault system of which a schematic cross section is shown in Figure 4.29. The initial gas in place is spread over a large area of the field and the well encounters a relatively small gas column of 45 m in the Ten Boer and Slochteren formations. Contrary to the other wells it produced from both intervals where about 10 % of the flow rate came from the Ten Boer formation and 90 % from the Slochteren formation. The Ten Boer formation consists predominantly of shales with sand streaks that have a porosity of 9 %, net-to-gross of 8 % and a gas saturation of 40 %, whereas the Slochteren formation has a porosity of 16 %, net-to-gross of 95 %, a gas saturation of 50 % and a permeability of 20 mD. Furthermore, a weak aquifer was confirmed due to the observation of a slow gas-water contact rise in the field.
A total field GIIP of 2.35 BCM is reported for this field of which 1.32 BCM has been recovered. Due to the large spread of the gas in the field a lower recovery factor of 56 % was obtained as gas is easily bypassed when the gas-water contact increases and some of the gas in place will be trapped in a structural high that is not well connected to the well.

Figure 4.29 Cross section Well F

4.3.7 General findings

The six wells and corresponding reservoirs described here point out a few factors which influenced gas production. One factor that is named in three reservoirs is the presence of a significant transition zone. For Well A and D a transition zone of 12 and 5 m is reported respectively, whereas documentation regarding Well B reports a significant amount of gas below free water level for at least another 40 m. The gas below contact may have helped to reduce the water inflow from the underlying aquifer. Another factor worth mentioning is the weak aquifer found in Well F which slows down the rise of the gas-water contact. Weak aquifers are also found in the gas fields of the complex reservoir model which benefit from low water inflow. The production profiles and water inflow of Well F are unknown, however the weak aquifer suggests that Well F also experienced slow water inflow which could have contributed to the successful production.
On the other hand, conglomeratic reservoir rocks and structural highs are named as factors that may obstruct gas production, because such features have the ability to trap gas.

Given the limited number of wells found in this study, further research to obtain reliable observations/conclusions is recommended.

5
Discussion

5.1 Gas column cut-off value

The aim of this study was to find the gas column cut-off value representing the absolute minimum value required for economic gas production. Based on the results, both from the sensitivity study as well as the analysis of thin gas column wells, the lowest producible gas column may be around 15 m, however this value is likely too optimistic. The box models are idealized gas reservoirs that are used in this study to isolate the topics of interest from reservoir complexities/irrelevant heterogeneities. The value of 15 m, found in the horizontal box model, is slightly lower than the 20 m found in the tilted box model and complex reservoir model, which clearly shows that field geometry is a highly influential factor. Tilted reservoirs with straight layering can be successfully produced with gas column height as low as 20 – 23 m, which is lower than for near horizontal reservoirs which require larger columns of 34 and 42 m. Although the well analysis has only provided six wells which fit the scope of this study, they do support the findings from the modelling study, i.e. depending the reservoir/technical circumstances it is possible to produce sufficient amounts of gas from gas columns as small as 15 m. It is possible that the limited amount of case studies found here is due to other considerations than economic viability and further research here may generate more evidence towards the opportunities available in stranded fields with thin gas columns.
Furthermore, it is important to emphasize that the total gas production threshold values that were used to find the cut-off values are average economic values suitable to determine a field's viability and ensure profitability. However, a field's economic viability is dependent on more than the total gas production generated. Gas price, onshore/offshore location, net present value, investment/operational costs are amongst the factors that play an important role. Additionally, an operator may decide different on the profit margin of a gas field and it is possible that the threshold values do not comply with a company's objectives.

5.2 Reservoir features

The main two reservoir features that have been investigated in this study are a high-permeability streak and a clay layer. These two features are clearly present in the gas reservoirs from the complex reservoir model, and it was therefore interesting to analyze the effect of these reservoir features on the production results. The general outcome found for the presence of a high-permeability streak is that it is likely to reduce the total production time which may reduce the operational costs as well as the net present value of the investment. The results have shown both a reduction of production time in combination with an increase in total gas production as well as a decrease in total gas production. Although the often severely reduced production time seems to exceed the reduction of total gas volume, whether or not it can make up for the gas volumes lost requires a more sophisticated economic analysis in order to determine whether the model with a high-permeability streak is still more profitable than the situation without the high-permeability streaks.
The clay layer results are unanimous, a larger total gas production and production time is found for the reservoirs including a clay layer. Although, further investigation showed that the effect of a clay layer in the complex reservoir model is not fully clear, due to the field's insensitivity to water restriction, the box models show that a clay layer can boost the total gas production. It is therefore reasonable to assume that gas reservoirs with a stronger aquifer

influence will benefit from the presence of a clay layer, although it is recommended to carry out a modelling study with real case scenarios that contain stronger aquifers.
As with the high-permeability results, a more extensive economic analysis should be done on these results in order to verify whether the additional produced gas is in reasonable proportion to the extra costs made with the extended production time.
As discussed in the previous section, the analysis of gas wells did only yield some hints on which factors played a role in the successful gas production of the wells. The existence of a thick gas-water transition zone is possibly one of the most influential factors which more positively inhibits water breakthrough and allows higher productivity. In order to find a reliable correlation between these two factors more research on additional case studies is required.

5.3 Reservoir configuration & Production strategy

One final consideration that is important to mention for the interpretation of the results, especially when attempting to extrapolate or generalize the final conclusions, is the reservoir configuration and production strategy. The models that are used in this study have a very specific configuration, where the high-permeability streaks and clay layers are situated at a fixed position. Combined with other model choices, such as well position, field dimensions, production strategy and other variable parameters or reservoir properties (e.g. aquifer strength), this influences the results and it is reasonable to assume that these results are sensitive to change when any of these factors are changed.
The production strategy is a good example of this. It entails the boundary conditions under which the simulations were run. A specific water restriction rule and gas rate targets were set in order to establish a realistic production lifetime complemented with a perforation strategy that was designed in order to produce under the most optimal conditions (see Chapter 3 for further details). It is important to emphasize that, although the production strategy has been well considered and tested, they are susceptible to a professional's individual opinion/views on the production optimization possibilities, which can result in a different outcome. The production strategy implemented here, is such that it reflects realistic boundary conditions and the perforation strategy was designed to be the most optimal version for each specific simulation case. In some cases, it is possible that instead of the partial shut off, a total shut off of the well will be applied when water breakthrough occurs. A partial shut off involves a workover which brings additional costs. Especially with these thinner gas reservoirs it is reasonable to assume that this may not be done if it is expected that the workover will not yield enough additional gas volumes or if there is a lot of uncertainty involved.

6
CONCLUSIONS & RECOMMENDATIONS

The aim of this study was to investigate the important factors in gas production from wells with a limited gas column height and to find the absolute minimum column height required for economic production. The research has been focused on the highly productive Rotliegend gas-bearing reservoirs in the Netherlands. Based on the results presented here, the following conclusions can be drawn:

- A gas column range of 20 – 40 m is the minimum requirement for a meaningful gas production (> 0.1 BCM) from the models used in this study. This minimum height is strongly dependent on the reservoir geometry and configuration of the reservoir's characteristics. High-permeability streaks in reservoirs with active aquifers and near horizontal reservoirs with irregular layering are found to increase the minimum gas column required.
- The high-permeability streaks in the models used for this study lower the resistance of the reservoir and while they can both increase or decrease the total gas production, they are also highly effective in reducing the total production time. The high-permeability streaks are especially beneficial to the total gas production from the reservoirs with low average permeability.
- The clay layers tend to increase both the total gas production as well as production time for the reservoirs with a stronger aquifer support. They restrict the vertical mobility of both gas and water flow in the reservoir. This can delay or prevent water breakthrough and also restrict the gas flow to the well in horizontal reservoirs with a significantly large part of the gas column situated below the clay layer.
- A very mild correlation between gas production from wells with thin gas columns and a transition zone is suggested. However, the number of case studies suitable for this study is not sufficient to make a conclusive reliable statement.

Based on the outcomes of this study, the following recommendations are done:

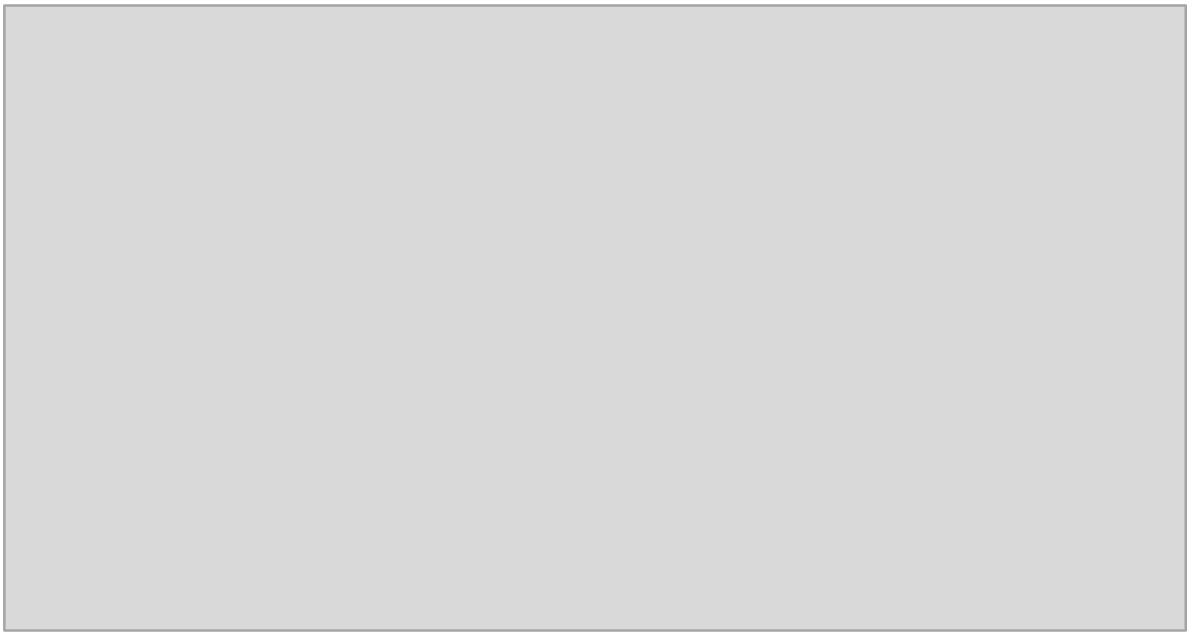
- Testing out different types of reservoir configuration in the models could be done in order assess the degree with which the results are correlated to a specific reservoir configuration.
- Repeating the sensitivity study in a complex reservoir model with a strong(er) aquifer is highly recommended to further investigate the influence of the clay layer in a strongly heterogeneous reservoir model.
- More detailed research could be carried out on the data set of gas wells in order to find more factors that play a crucial role in the production from limited gas columns.
- Future investigation should aim at studying the effect that the thickness and type of gas-water transition zone may have on the production from reservoirs with a limited gas column heights.
- It will be valuable to combine the results of this study with an in-depth economic analysis.

References

1. Schulte, R., Lutgert, J., Asschert, A. (2012) Stranded Gas in the Netherlands: What is the Potential? In: SPE/EAGE *European Unconventional Resources Conference and Exhibition, 20 – 22 March, Vienna, Austria*. Society of Petroleum Engineers.
2. Herber, R., de Jager, J. (2010) Oil and gas in the Netherlands – Is there a future? *Netherlands Journal of Geosciences – Geologie en Mijnbouw.* 89 (2), 119 – 135.
3. InterGeos (1991) Rotliegend of The Netherlands offshore. InterGeos Report no. EP91046.
4. De Jager, J. & Geluk, M.C. (2007) Petroleum geology. In: Wong, Th.E., Batjes, D.A.J., de Jager, J. (eds) *Geology of the Netherlands.* Aksant, pp 241 – 264.
5. Geluk, M.C. (2007) Permian. In: Wong, Th.E., Batjes, D.A.J., de Jager, J. (eds) *Geology of the Netherlands.* Aksant, pp 63 – 83.
6. EBN (2016) Focus on Dutch oil and gas 2016, Utrecht.
7. *This content has been removed.*
8. *This content has been removed.*

APPENDICES

APPENDIX A1 INDIVIDUAL VISUAL REPRESENTATION OF FIELD A



Reservoir model of field A visualized through permeability distribution

APPENDIX A2 INDIVIDUAL VISUAL REPRESENTATION OF FIELD B

Reservoir model of field B visualized through permeability distribution

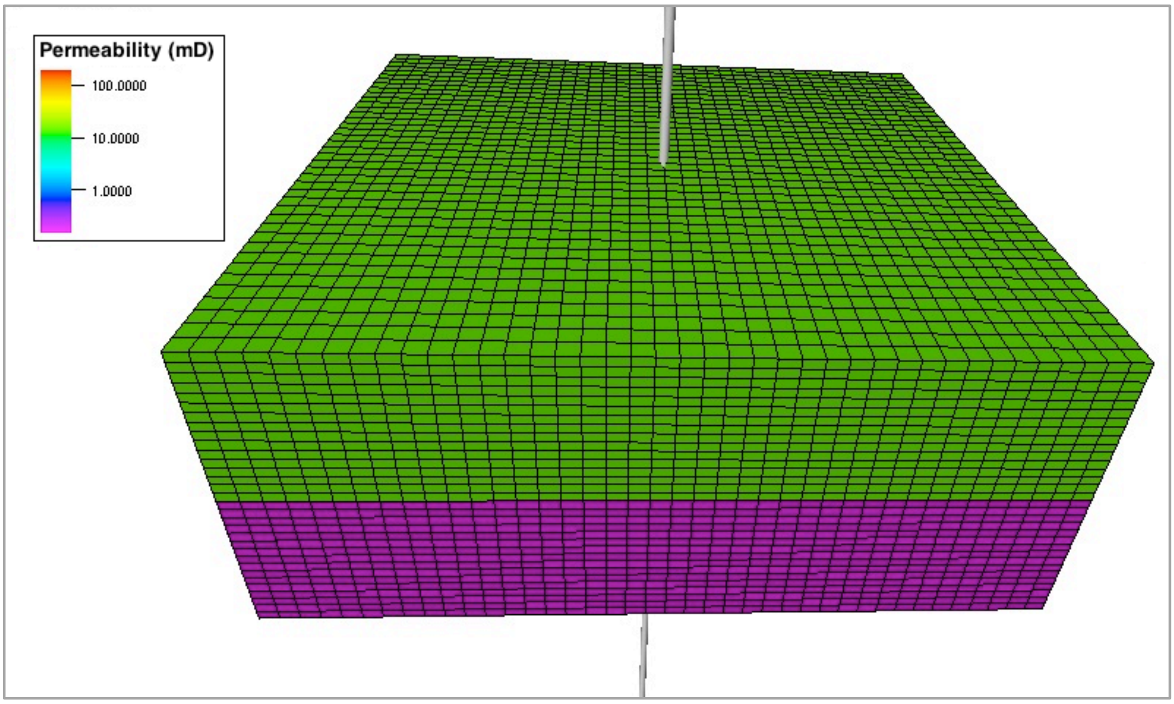
Appendix A3 Individual visual representation of Field C

Reservoir model of field C visualized through permeability distribution

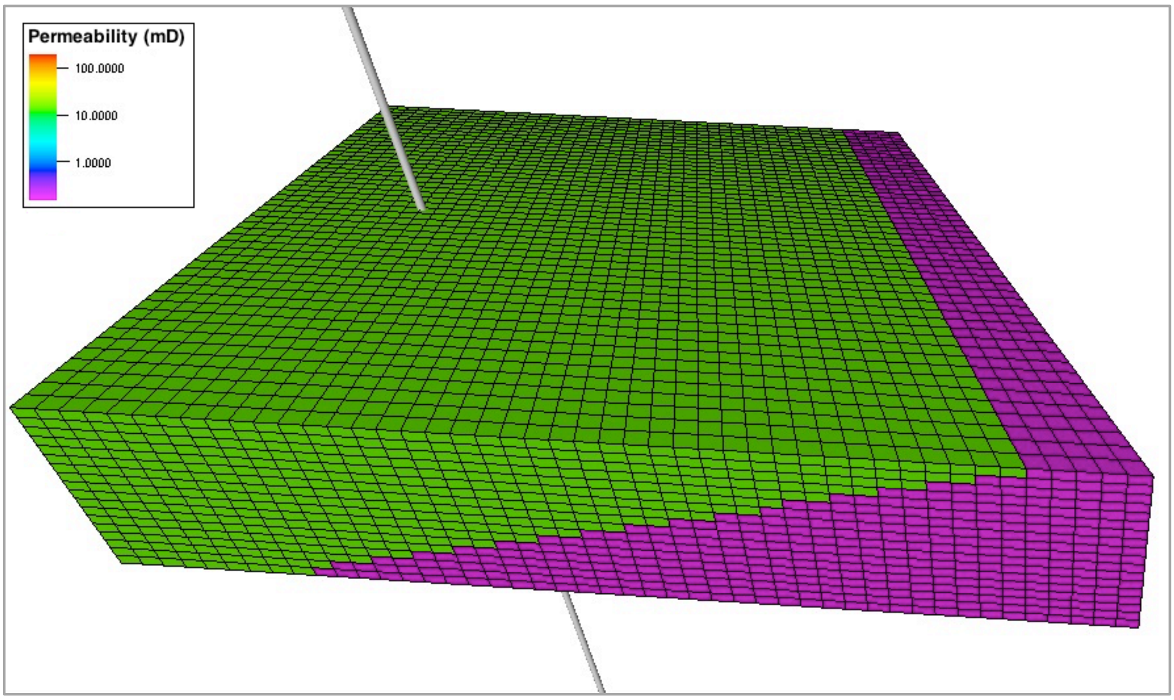
Appendix A4 Individual visual representation of Field D

Reservoir model of field D visualized through permeability distribution

APPENDIX B1 BASE HORIZONTAL AND TILTED BOX MODEL

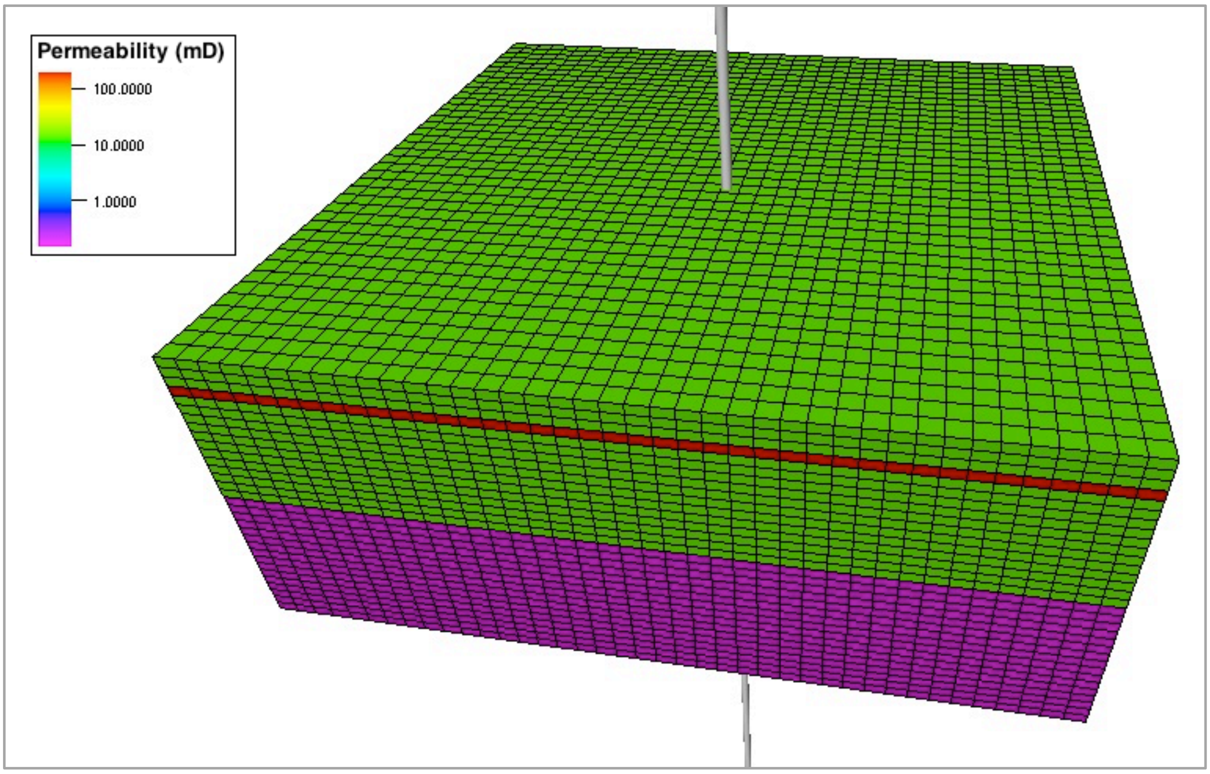


Horizontal box model Homogeneous reservoir (HBM1)

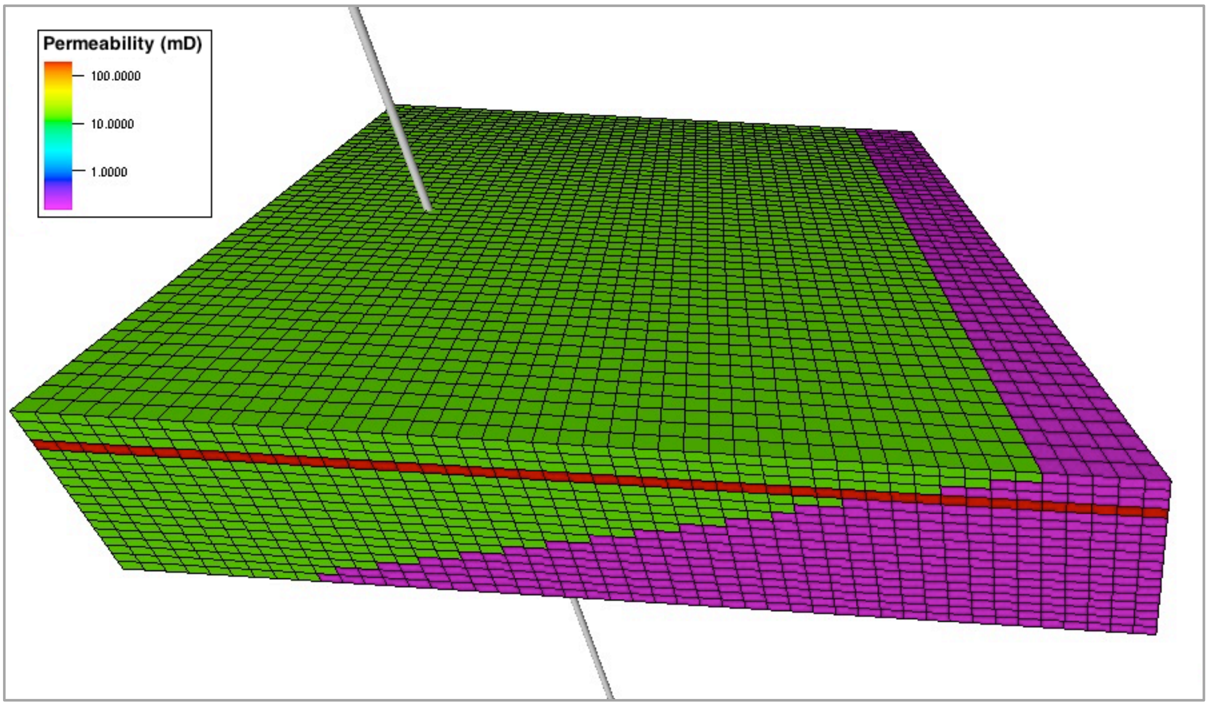


Tilted box model Homogeneous reservoir (TBM1)

APPENDIX B2 HORIZONTAL AND TILTED BOX MODEL WITH HIGH-PERMEABILITY STREAK

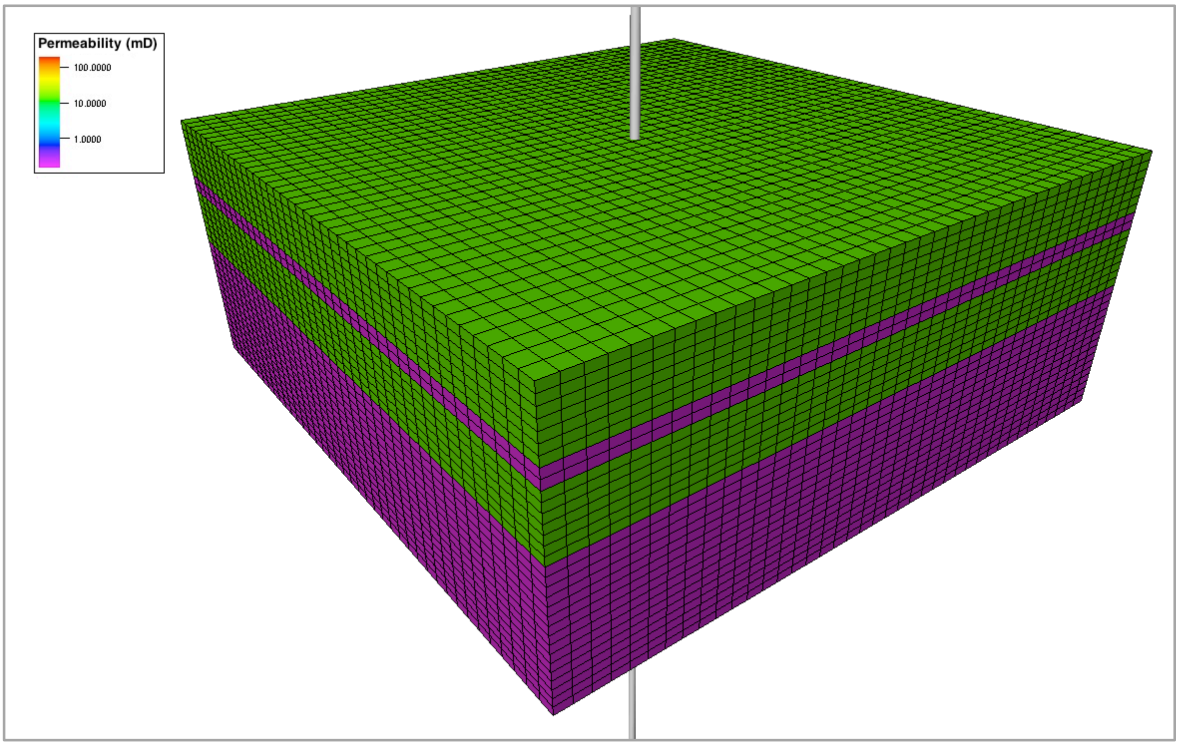


Horizontal box model Homogeneous reservoir with high-permeability streak (HBM2)

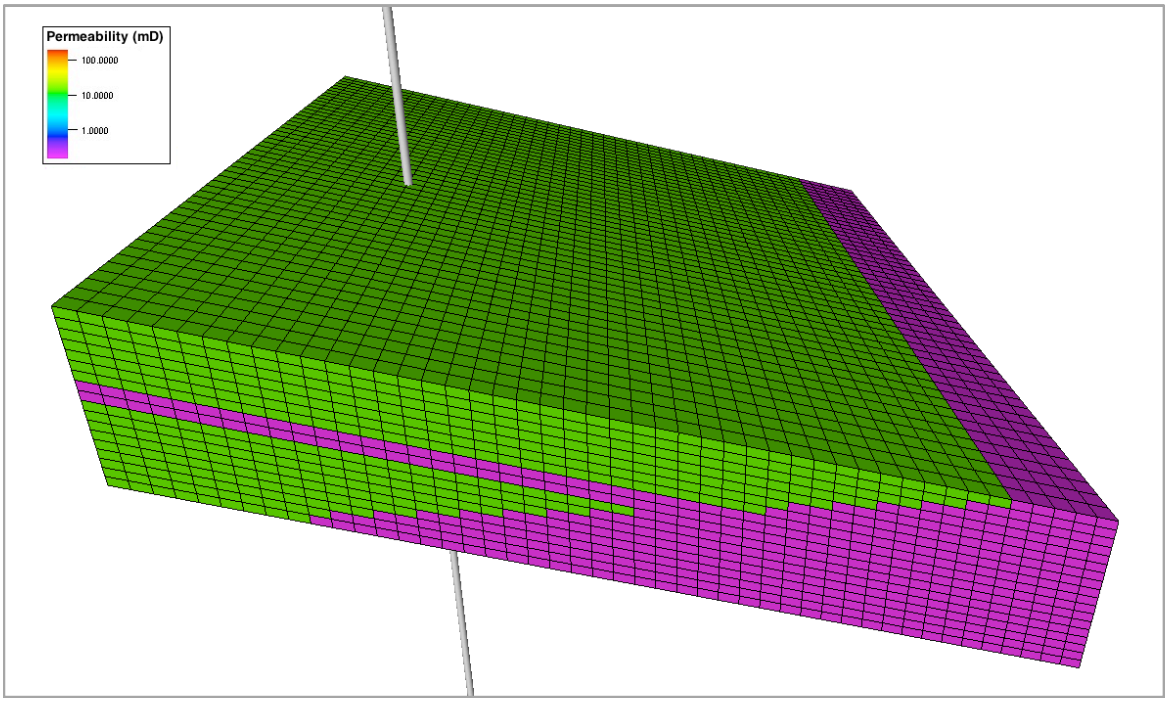


Tilted box model Homogeneous reservoir with high-permeability streak (TBM2)

APPENDIX B3 HORIZONTAL AND TILTED BOX MODEL WITH CLAY LAYER

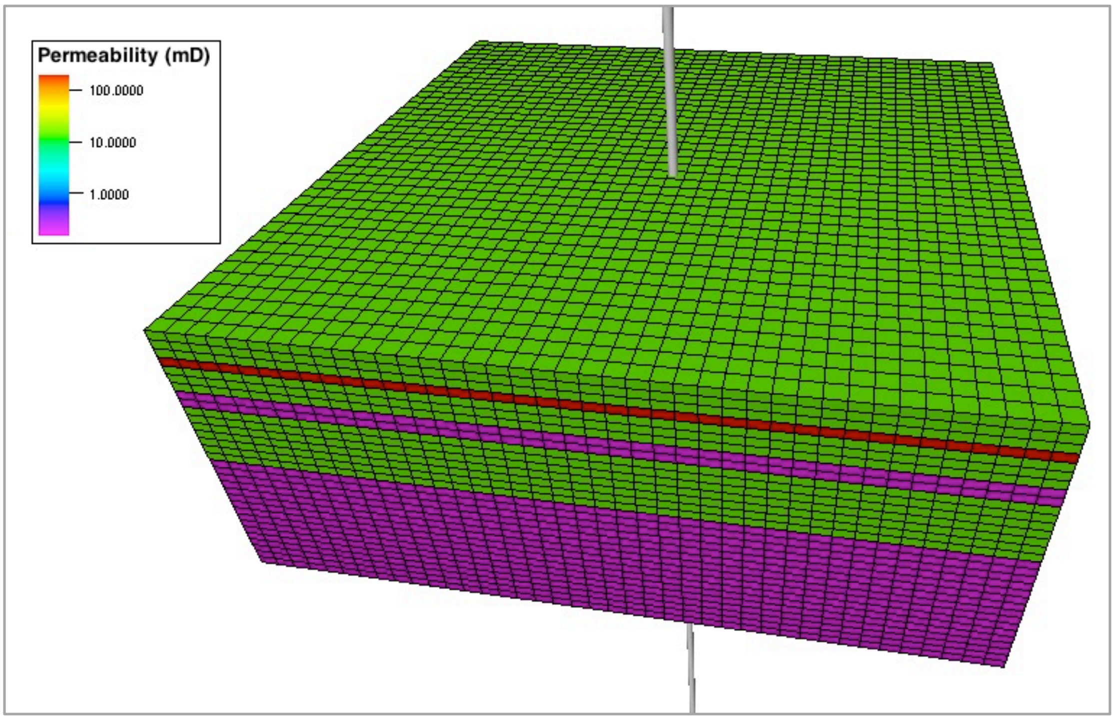


Horizontal box model Homogeneous reservoir with clay layer(HBM3)

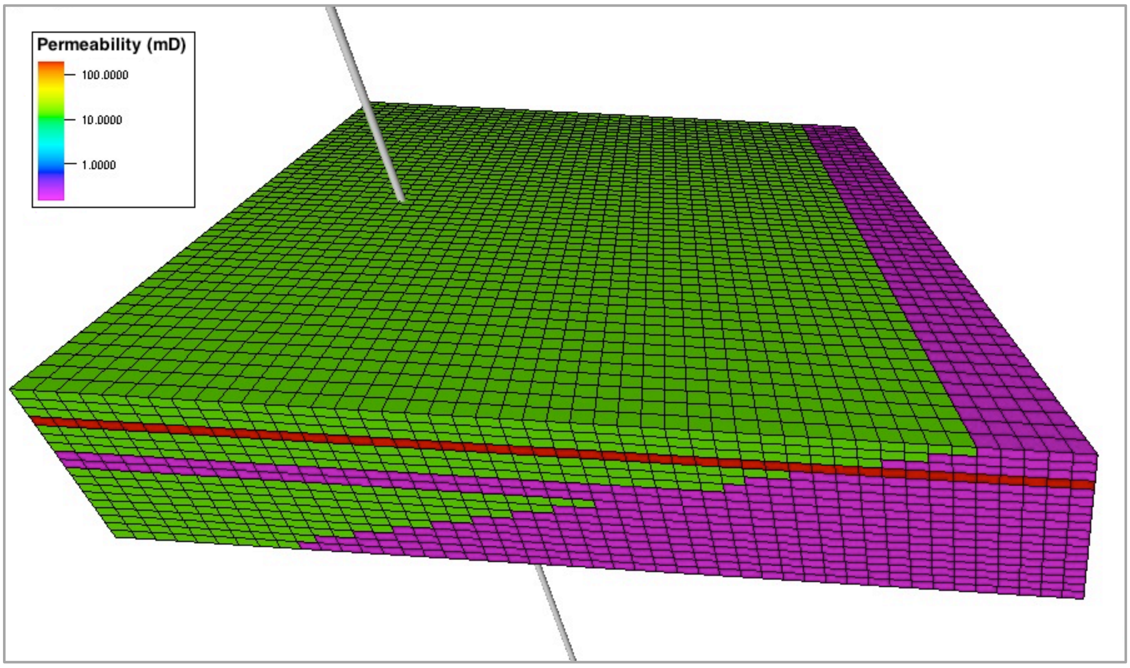


Tilted box model Homogeneous reservoir with clay layer (TBM3)

APPENDIX B4 HORIZONTAL AND TILTED BOX MODEL WITH HIGH-PERMEABILITY STREAK AND A CLAY LAYER



Horizontal box model Homogeneous reservoir with high-permeability streak above clay layer (HBM4)



Tilted box model Homogeneous reservoir with high-permeability streak above clay layer (TBM4)

APPENDIX C1 RESERVOIR MODEL HISTORY MATCH FIELD A

Field A Gas Production History Match

Field A Bottom Hole Pressure History Match

Field A Water Production History Match

APPENDIX C2 RESERVOIR MODEL HISTORY MATCH FIELD B

Field B Gas Production History Match

Field B Bottom Hole Pressure History Match

Field B Water Production History Match

APPENDIX C3 RESERVOIR MODEL HISTORY MATCH FIELD C

Field C Gas Production History Match

Field C Bottom Hole Pressure History Match

Field C Water Production History Match

Appendix C4 Reservoir Model History Match Field D

Field D Gas Production History Match

Field D Bottom Hole Pressure History Match

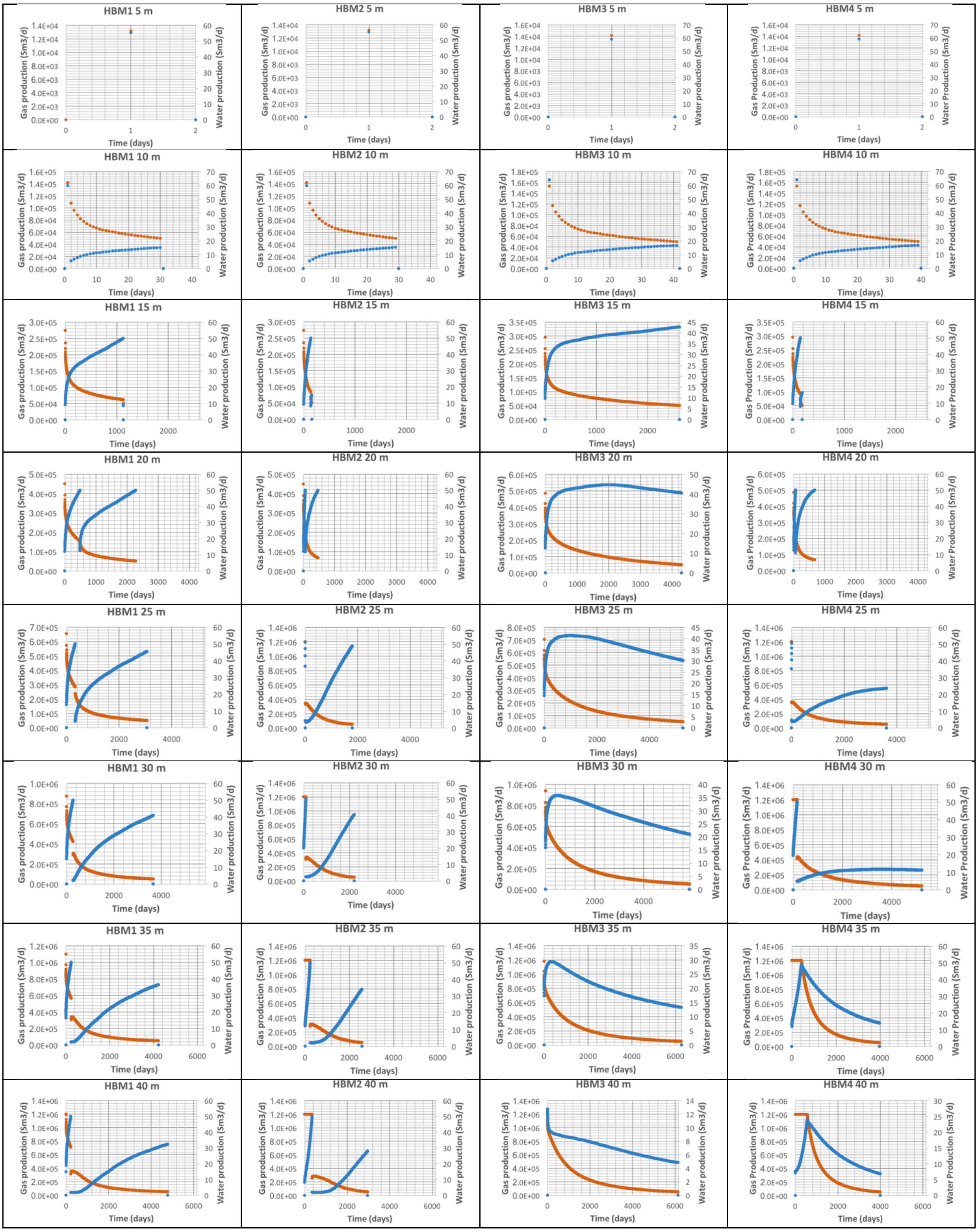
Field D Water Production History Match

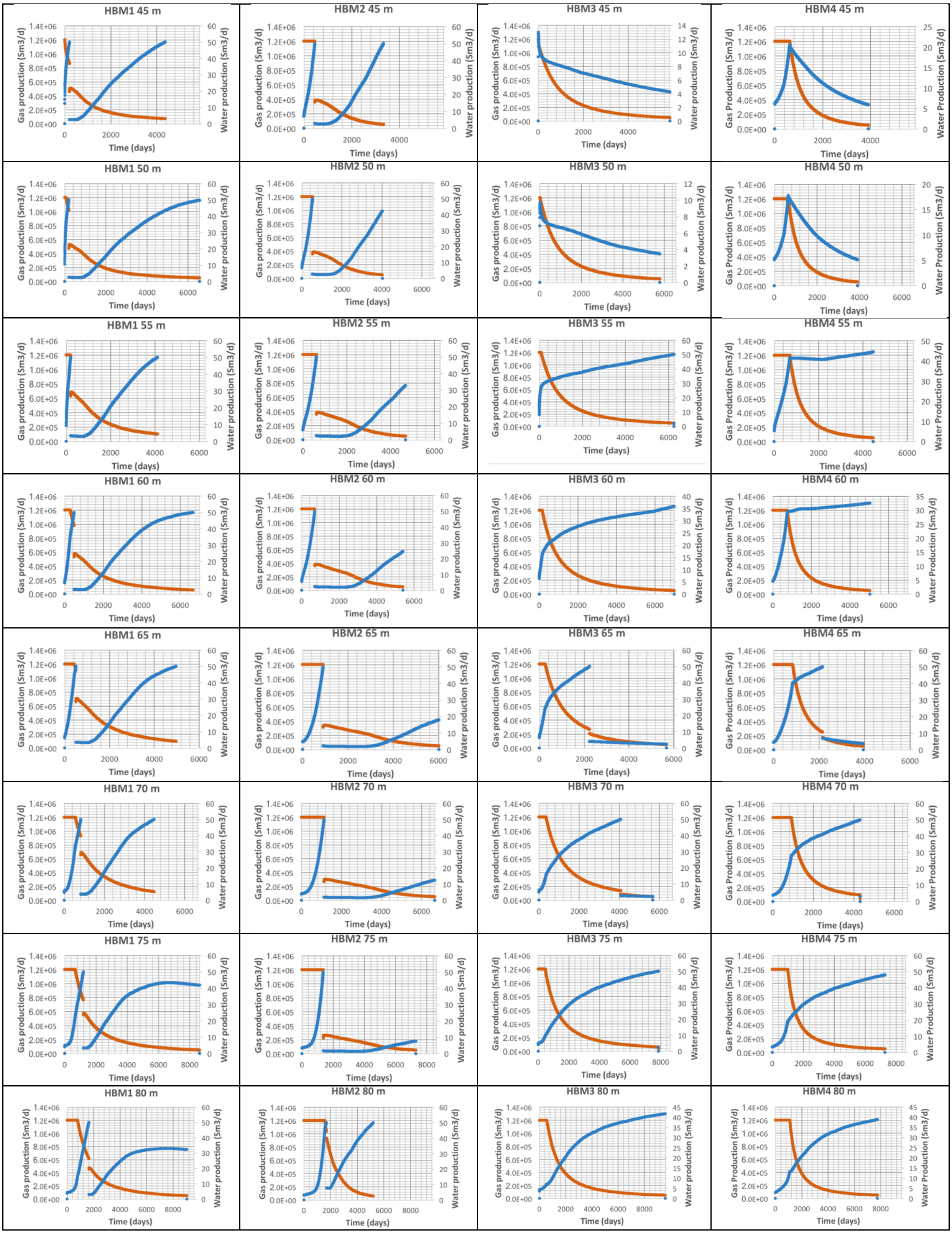
APPENDIX D PERMEABILITY DISTRIBUTION IN RESERVOIR MODEL (CRM1) AFTER HISTORY MATCH

[For confidential reasons this content has been removed]

APPENDIX E PRODUCTION PROFILES OF THE HORIZONTAL BOX MODEL VERSIONS, HBM1-4

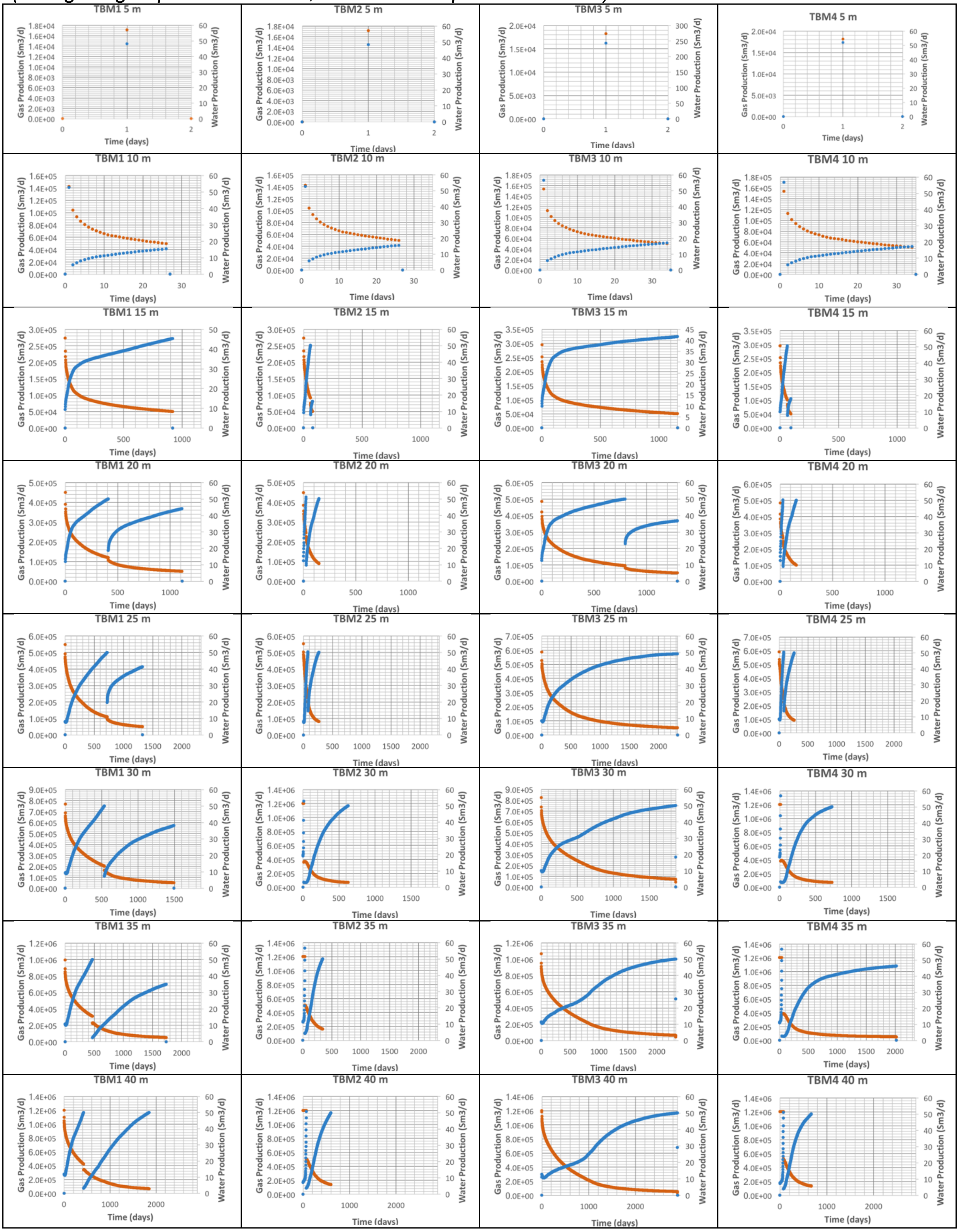
(orange = gas production rate; blue = water production rate)




HBM1 45 m
HBM2 45 m
HBM3 45 m
HBM4 45 m
HBM1 50 m
HBM2 50 m
HBM3 50 m
HBM4 50 m
HBM1 55 m
HBM2 55 m
HBM3 55 m
HBM4 55 m
HBM1 60 m
HBM2 60 m
HBM3 60 m
HBM4 60 m
HBM1 65 m
HBM2 65 m
HBM3 65 m
HBM4 65 m
HBM1 70 m
HBM2 70 m
HBM3 70 m
HBM4 70 m
HBM1 75 m
HBM2 75 m
HBM3 75 m
HBM4 75 m
HBM1 80 m
HBM2 80 m
HBM3 80 m
HBM4 80 m
Gas production (Sm3/d)
Water production (Sm3/d)
Time (days)

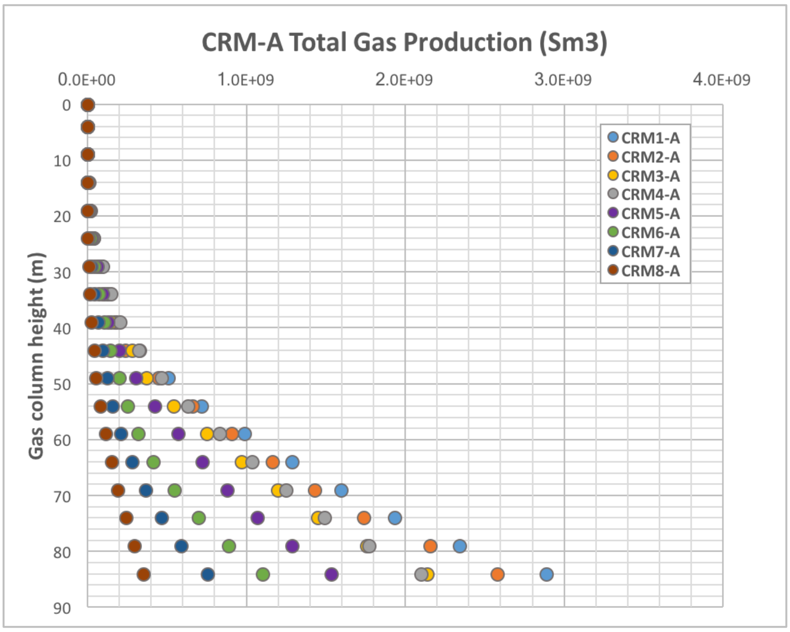
Appendix F Production profiles of the tilted box model versions 1-4

(orange = gas production rate; blue = water production rate)

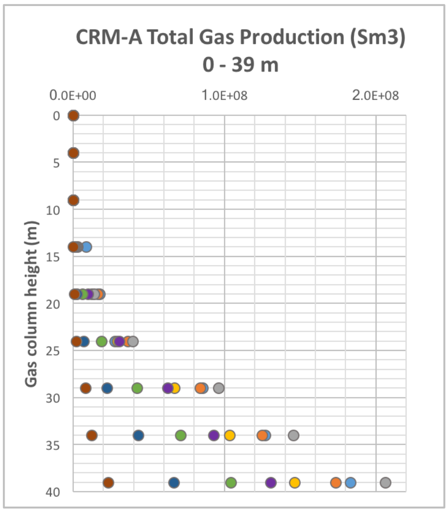



TBM1 45 m
TBM2 45 m
TBM3 45 m
TBM4 45 m
TBM1 50 m
TBM2 50 m
TBM3 50 m
TBM4 50 m
TBM1 55 m
TBM2 55 m
TBM3 55 m
TBM4 55 m
TBM1 60 m
TBM2 60 m
TBM3 60 m
TBM4 60 m
TBM1 65 m
TBM2 65 m
TBM3 65 m
TBM4 65 m
TBM1 70 m
TBM2 70 m
TBM3 70 m
TBM4 70 m
TBM1 75 m
TBM2 75 m
TBM3 75 m
TBM4 75 m
TBM1 80 m
TBM2 80 m
TBM3 80 m
TBM4 80 m
TBM1 85 m
TBM2 85 m
TBM3 85 m
TBM4 85 m
Gas Production (Sm3/d)
Water Production (Sm3/d)
Time (days)

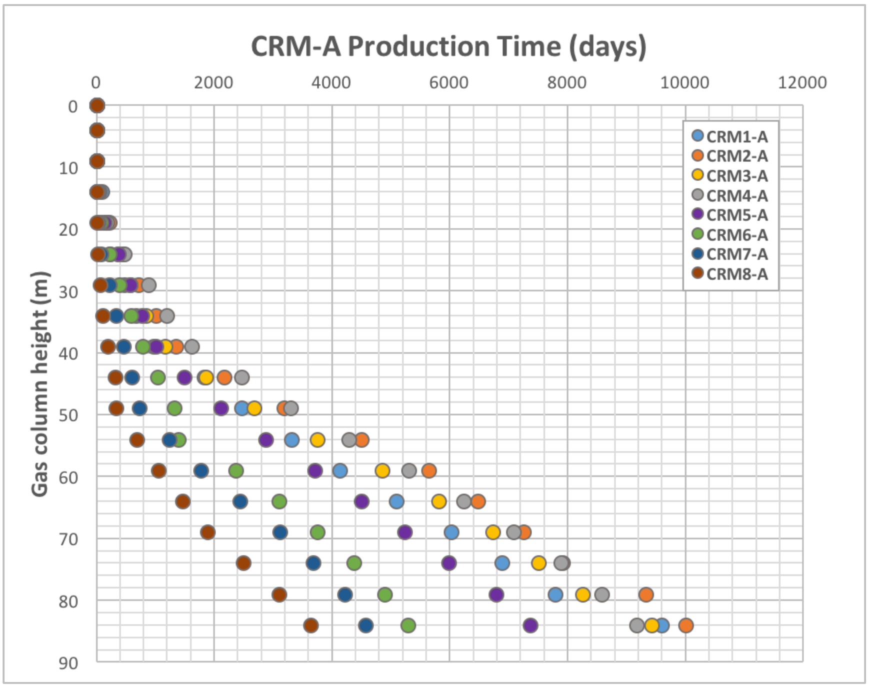
APPENDIX G1 CRM-A TOTAL GAS PRODUCTION AND PRODUCTION TIME



CRM-A Total gas production 0 – 84 m

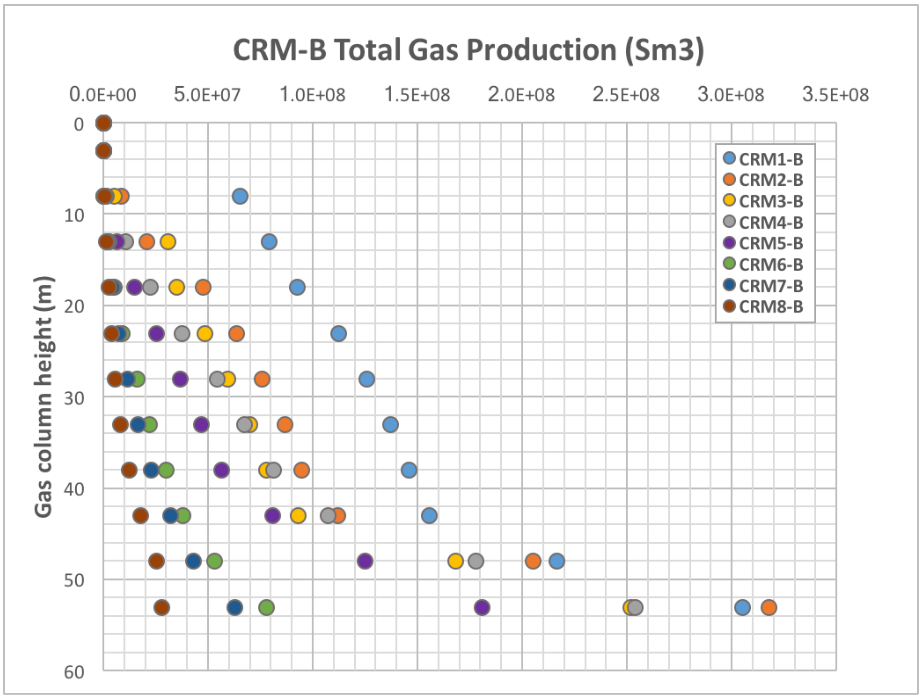


CRM-A Total production 0 – 39 m

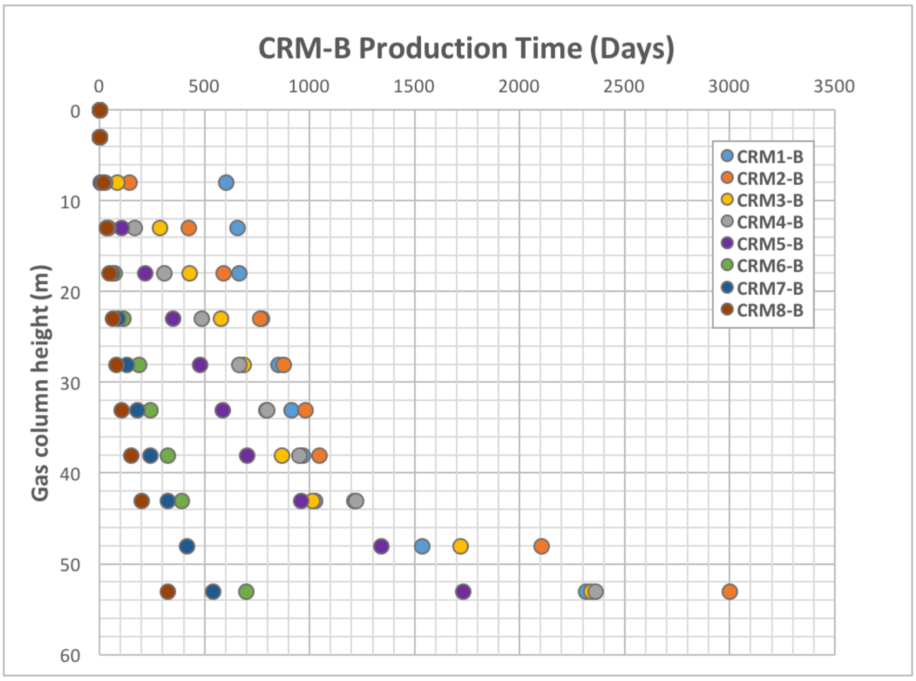


CRM-A Production Time

APPENDIX G2 CRM-B TOTAL GAS PRODUCTION AND PRODUCTION TIME

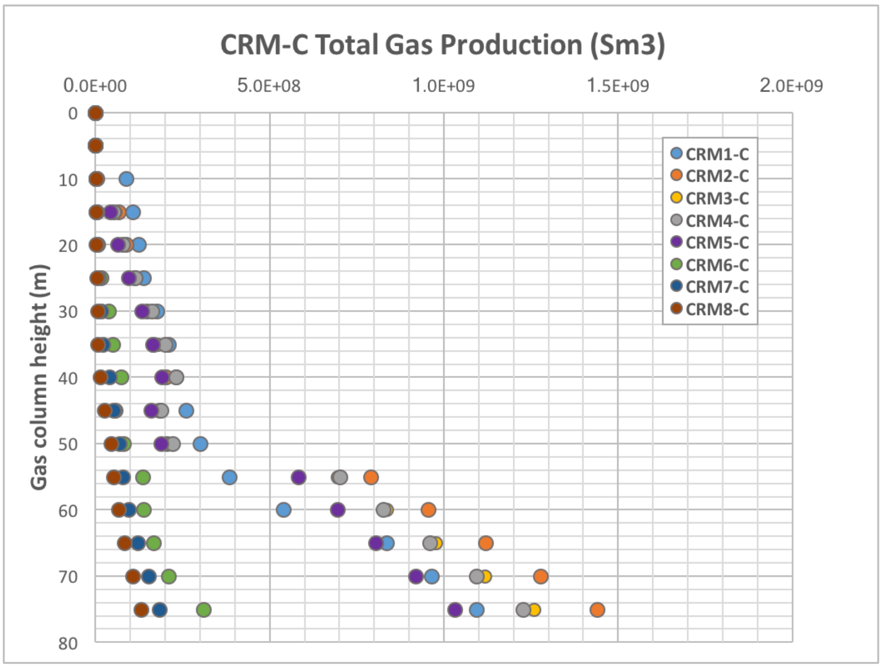


CRM-B Total gas production 0 – 53 m

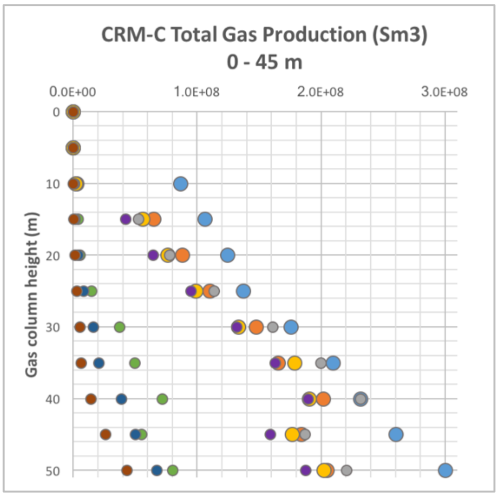


CRM-B Production Time

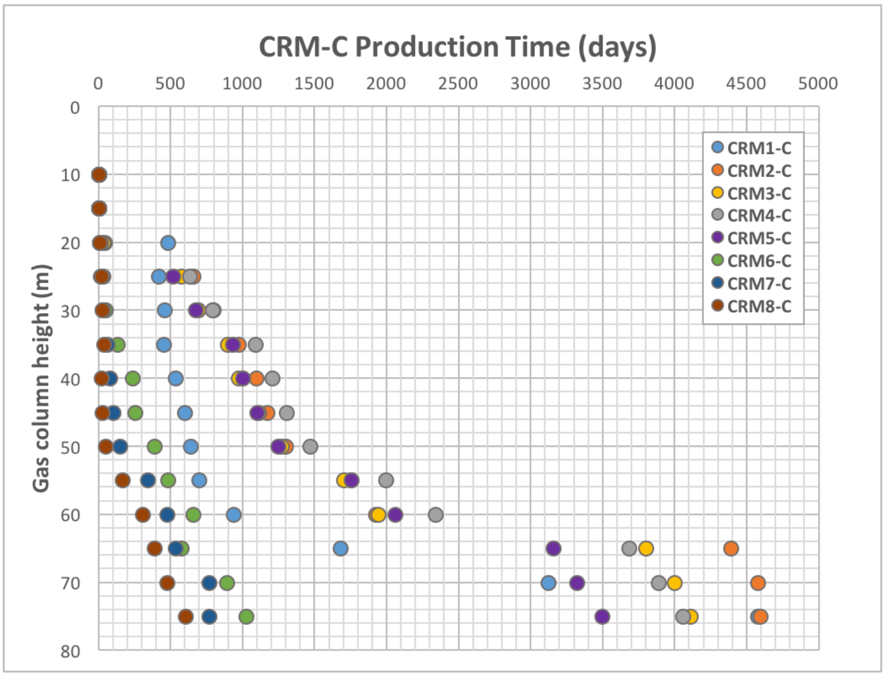
APPENDIX G3 CRM-C TOTAL GAS PRODUCTION AND PRODUCTION TIME



CRM-C Total gas production 0 – 75 m

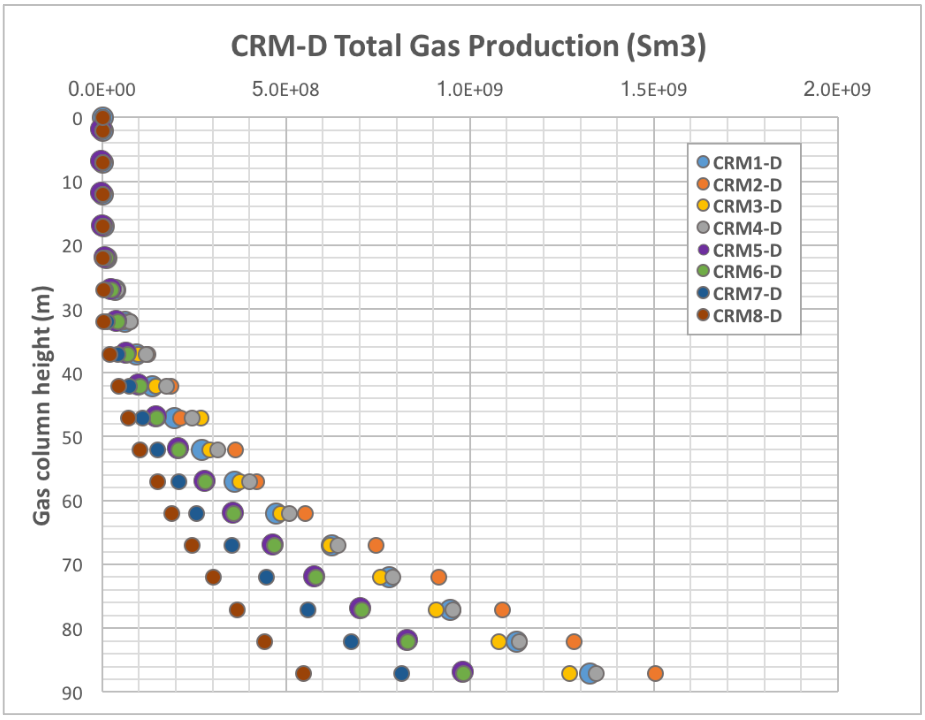


CRM-C Total gas production 0 – 45 m

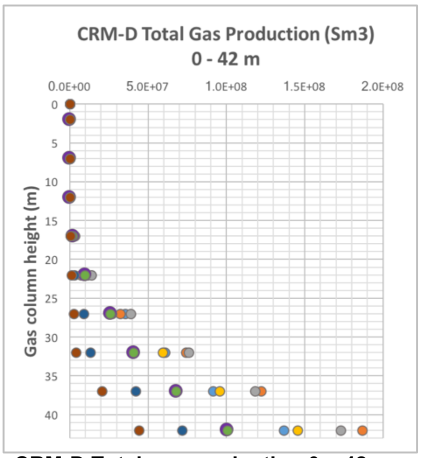


CRM-C Production Time

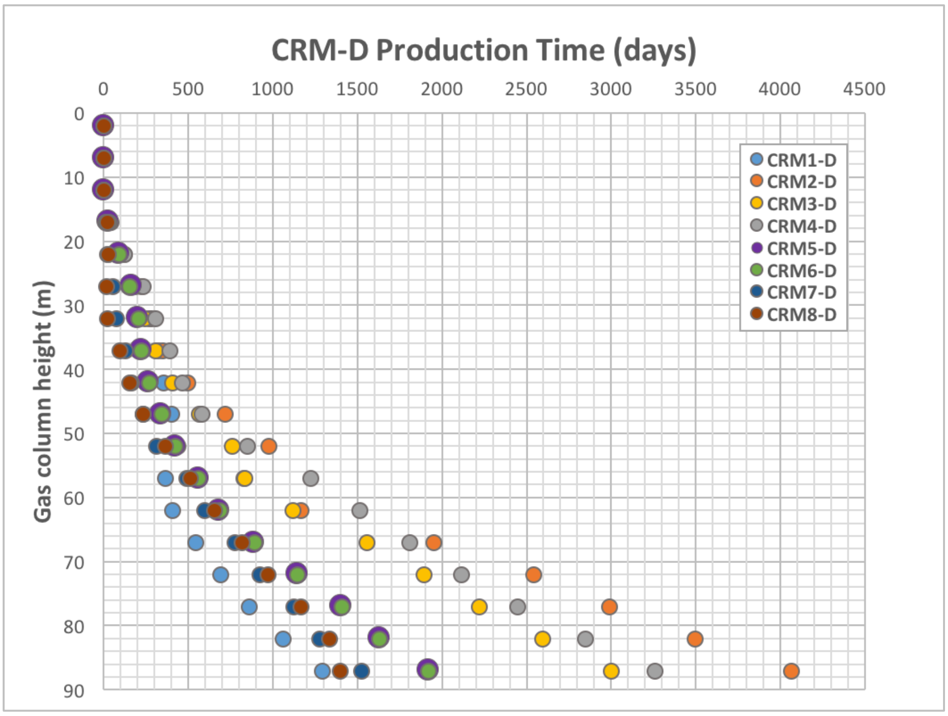
APPENDIX G4 FIELD D TOTAL GAS PRODUCTION AND PRODUCTION TIME



CRM-D Total gas production 0 – 87 m

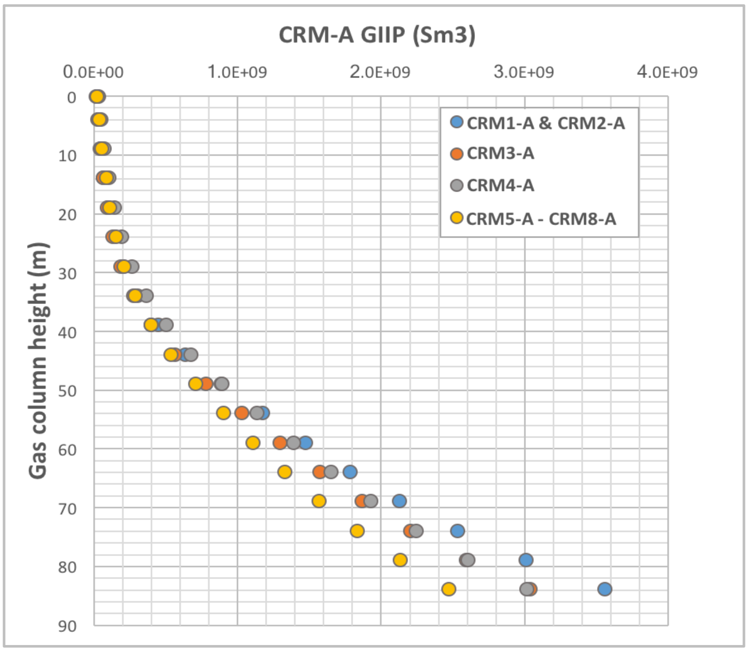


CRM-D Total gas production 0 – 42 m

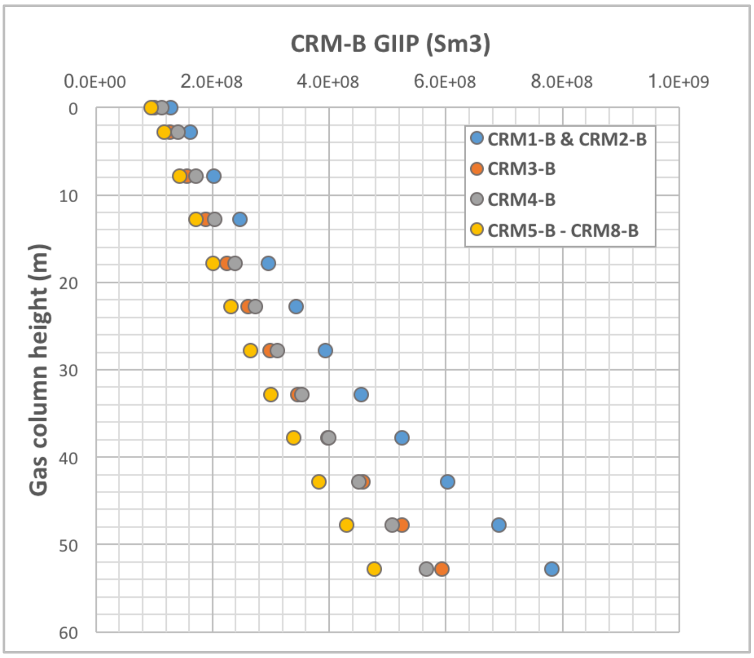


CRM-D Production Time

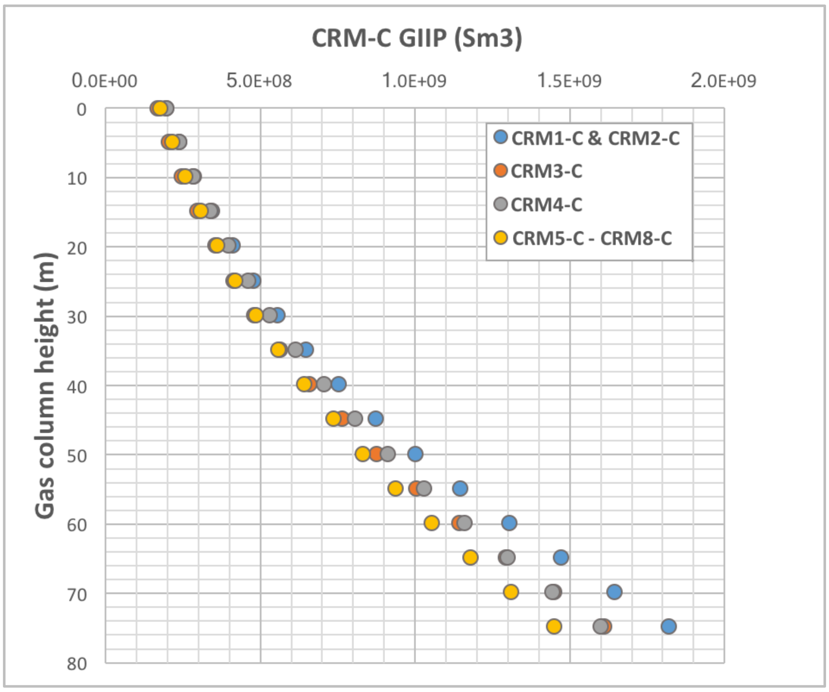
APPENDIX H FIELD A - D GAS INITIALLY IN PLACE PER GAS COLUMN



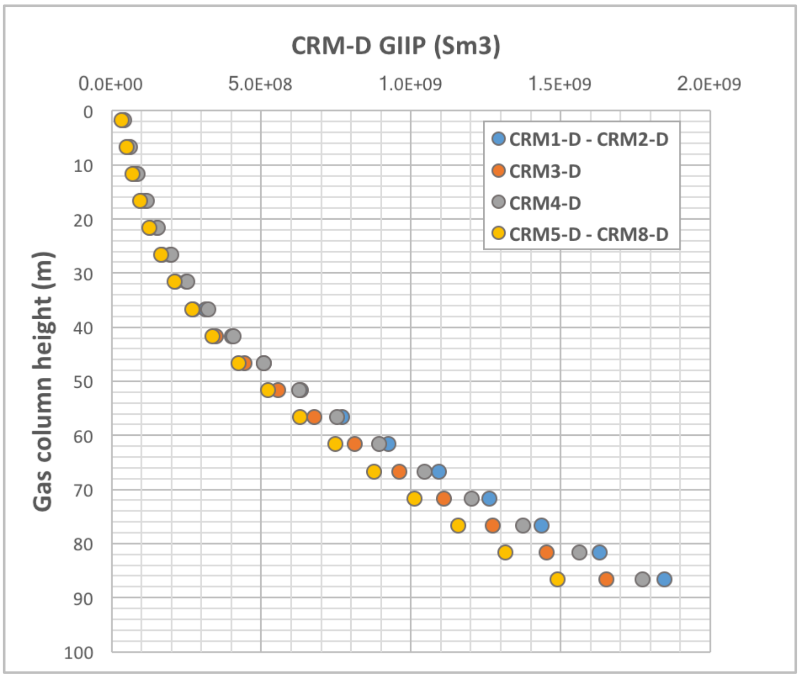
CRM-A GIIP



CRM-B GIIP



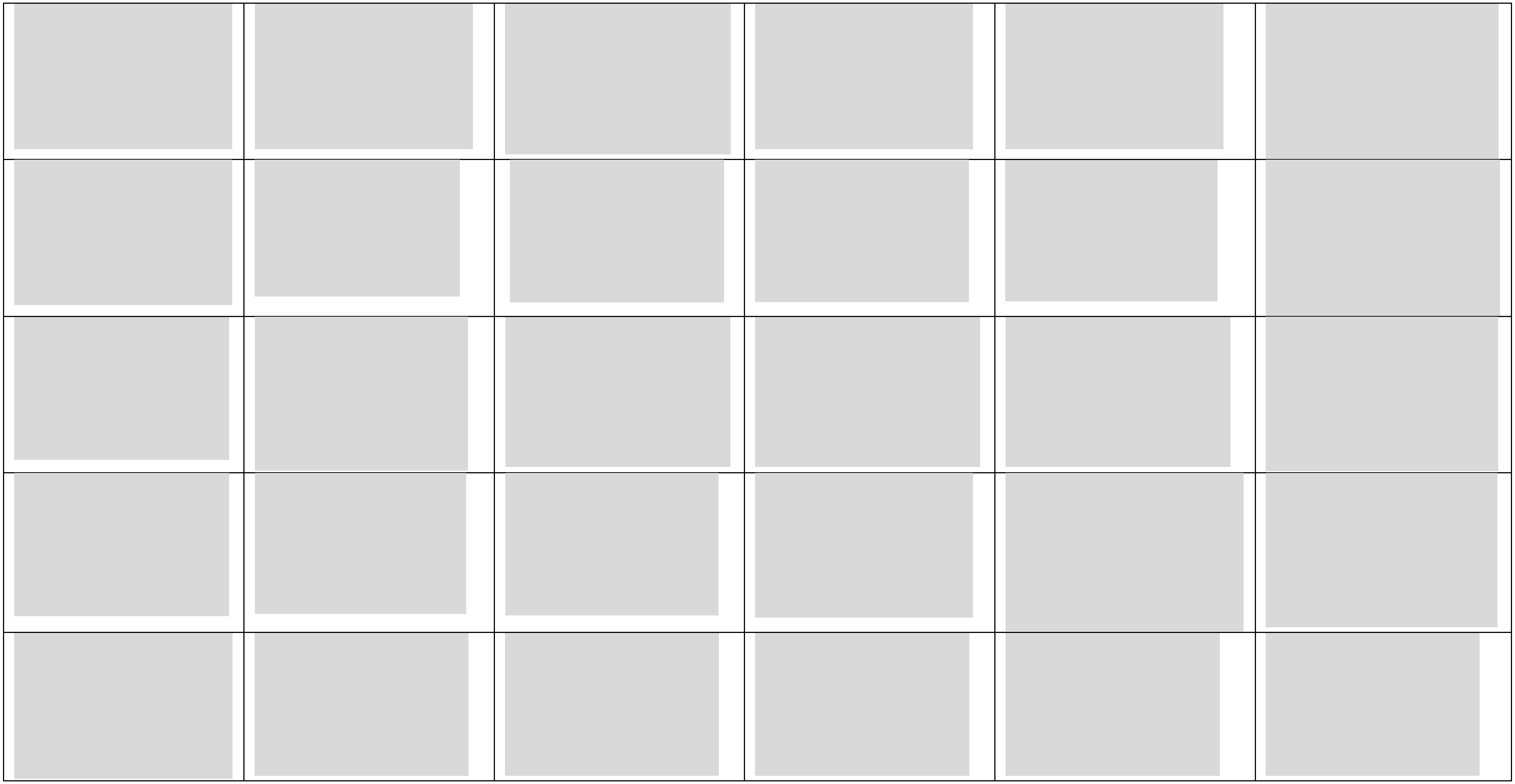
CRM-C GIIP



CRM-D GIIP

APPENDIX I1 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM1-CRM6 – A

(ORANGE = GAS PRODUCTION RATE; BLUE = WATER PRODUCTION RATE)

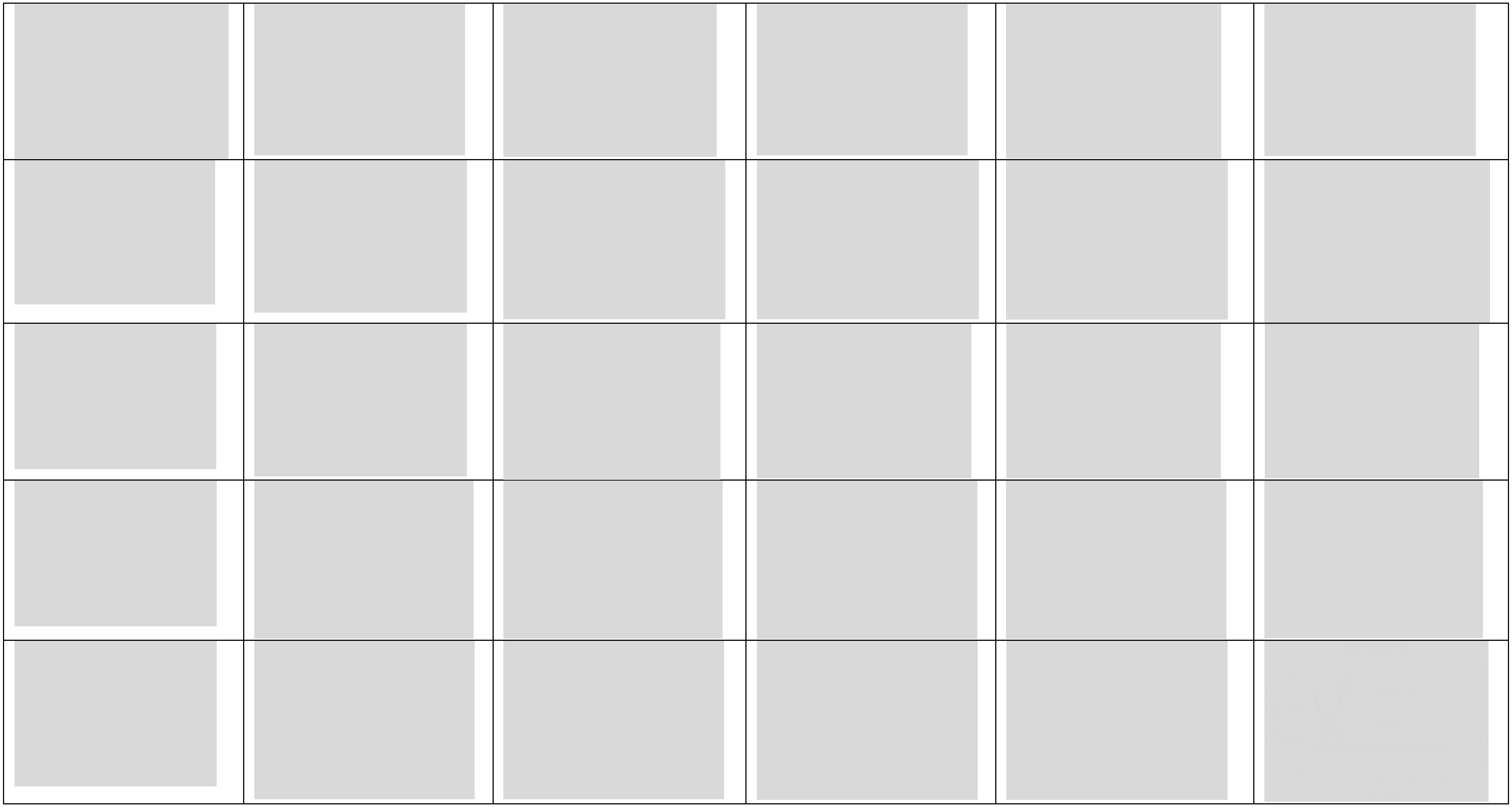


The production profiles of the simulation cases which only run 1-3 days are left out.

The production profiles of the simulation cases which only run 1-3 days are left out.

APPENDIX I2 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM1-CRM6 – B

(orange = gas production rate; blue = water production rate)

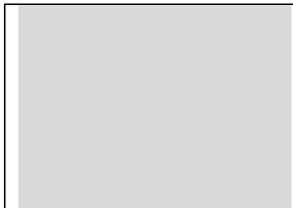
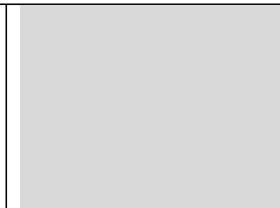
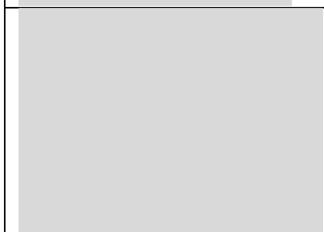
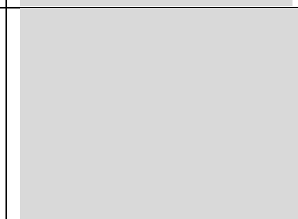
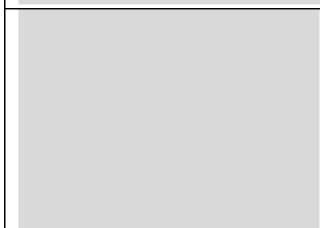
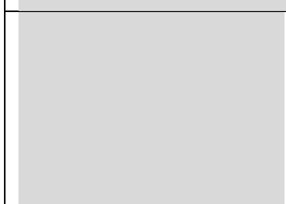
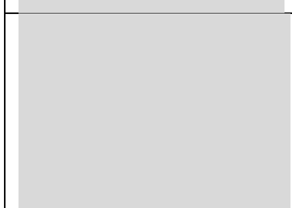
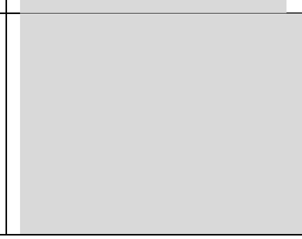


The production profiles of the simulation cases which only run 1-3 days are left out.

The production profiles of the simulation cases which only run 1-3 days are left out.

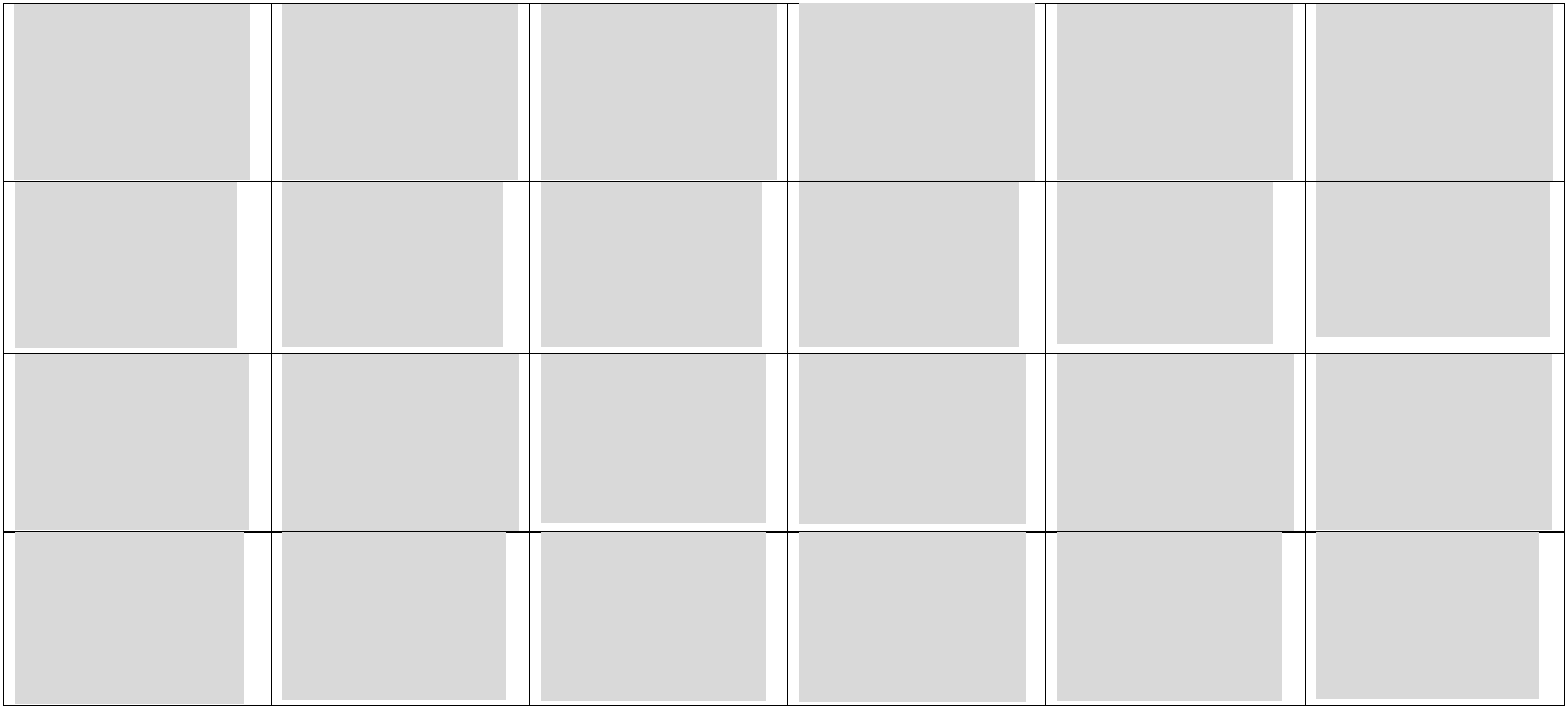
APPENDIX I3 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM1-CRM6 – C

(orange = gas production rate; blue = water production rate)

The production profiles of the simulation cases which only run 1-3 days are left out.

The production profiles of the simulation cases which only run 1-3 days are left out.



The production profiles of the simulation cases which only run 1-3 days are left out.

APPENDIX I4 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM1-CRM6 – D

(orange = gas production rate; blue = water production rate)

The production profiles of the simulation cases which only run 1-3 days are left out.

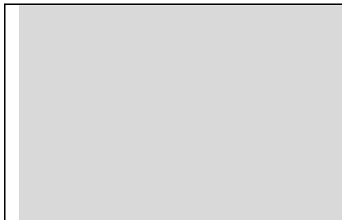
The production profiles of the simulation cases which only run 1-3 days are left out.

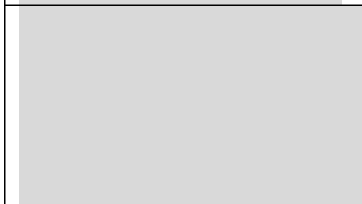
The production profiles of the simulation cases which only run 1-3 days are left out.

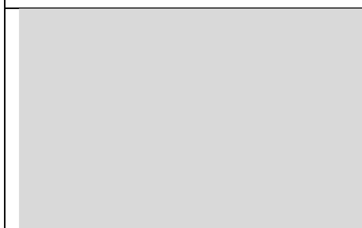
APPENDIX I5 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM7 & CRM8 – A & B

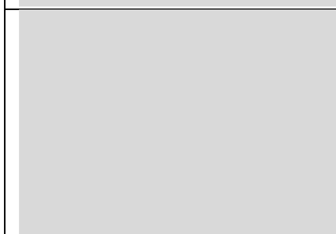
The production profiles of the simulation cases which only run 1-3 days are left out.

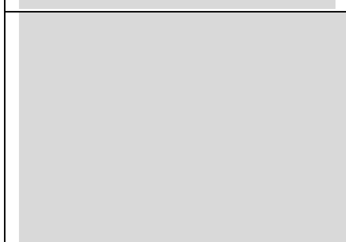
The production profiles of the simulation cases which only run 1-3 days are left out.





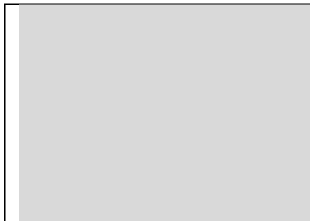
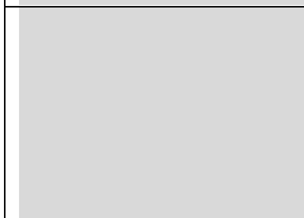
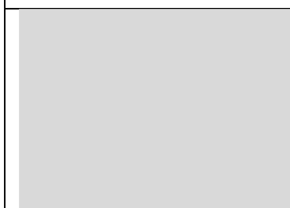
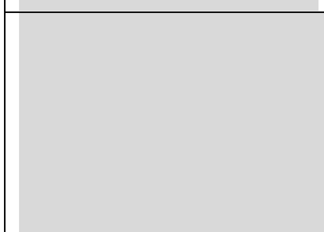


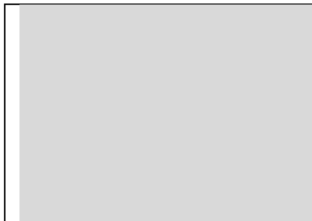
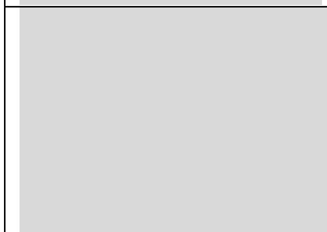
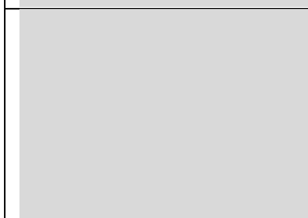
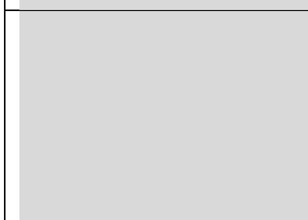
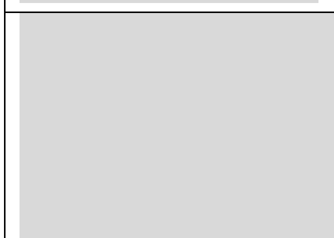




The production profiles of the simulation cases which only run 1-3 days are left out.

APPENDIX I6 PRODUCTION PROFILES OF THE RESERVOIR MODEL VERSIONS CRM7 & CRM8 – C & D

The production profiles of the simulation cases which only run 1-3 days are left out.

The production profiles of the simulation cases which only run 1-3 days are left out.

The production profiles of the simulation cases which only run 1-3 days are left out.