KEM-24 WP0 Literature review and compilation of input data/parameters for Groningen gas field modelling

Effect of pressure maintenance by fluid injection on seismic risk

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Contents

1. Introduction

Fugro performed a literature review to complete a list of needed data for the fluid injection modelling (list provided by Dynafrax UG, in charge of the modelling). These data should be used to determine the values of entry parameters for the numerical simulations of the effect of pressure maintenance by fluid injection on seismic risk.

The list of data is focussing on the Groningen gas field area. Most part of the literature review integrate reports issued by NAM. Data issue from the NAM 3D Petrel Groningen model were also provided to Dynafrax UG.

A selection of a 10 x 10 km zone within the Groningen gas field was discussed with Dynafrax UG. This zone, with representative fault pattern and seismicity is used for the modelling. The geological and geotechnical parameters selected in this study will correspond mainly to this zone.

This report closes the work of the geological team regarding the WP0 literature review. Only a brief list of the provided data is mentioned. The completed list and corresponding values and references is provided in appendices.

2. Literature review and data collection

Fugro performed a literature review to complete a list of data provided by Dynafrax UG in charge of the modelling. This list covers the following topics:

- Reservoir rock mechanical data.
- Reservoir rock seismic data.
- Reservoir rock hydraulic data.
- Reservoir fault mechanical data.
- Reservoir fault hydraulic data.
- In-situ stress data.
- Groningen field production history data.
- Implementation of reservoir faults in 3D Groningen model.

The completed list of required parameters with corresponding values and references is provided in appendices in the form of an informal internal document.

To facilitate the use of these data list, sources are referred using the pdf naming. This is not the conventional way of referencing, but it facilitates the hyperlink between the data and the source. Correlations between pdf names and references are provided in the table in the reference section of this report.

Data values indicated in the list correspond to "geological" information (from well / core / sample analysis). Values derived from or used in modelling studies are not referenced in the lists. They were defined by Dynafrax using expert criteria.

Additional data were also requested by Dynafrax UG. These data refer to:

- Groningen field in-situ temperature (depth at 3 km);
- Groningen field gas viscosity (for example, water at 20 ºC is 1 cP = 1e-3 Pa.s);
- Groningen field gas bulk modulus (or compressibility) (for example, water at 20 ºCis 2.2 GPa).

Additional references were delivered to Dynafrax UG and added into the reference section of this report.

The provided parameters and data are focussing on the whole Groningen gas field. Discussion took place between Fugro and Dynafrax UG to define a 10 x 10 km zone within the Groningen gas field that will be used by the models (the whole Groningen gas field been too large to be covered by the models). This zone (black square in Figure 1), located in the North-West part of the gas field, was chosen with representative fault patterns and a representative seismic activity.

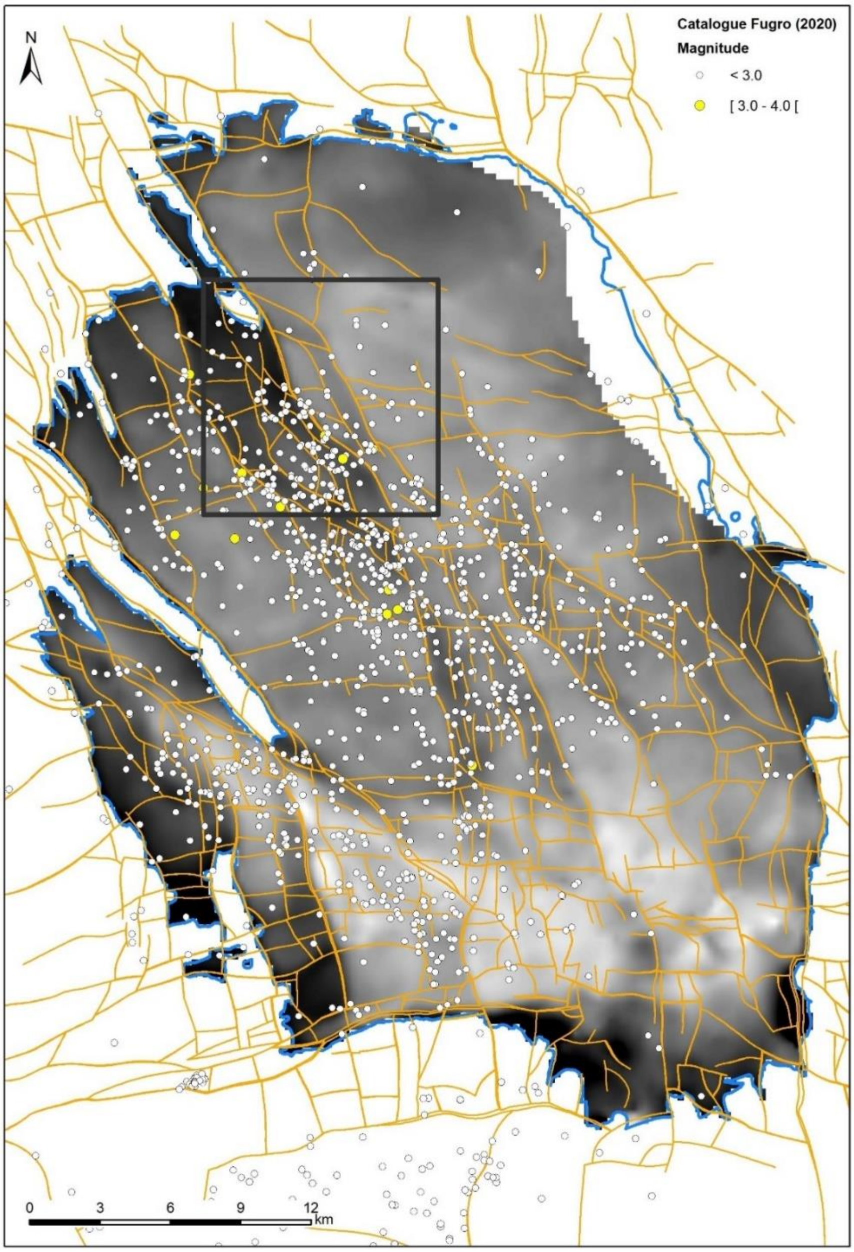


Figure 1: Faults and seismicity at the Groningen gas field. Source: Fault traces are courtesy from C. Visser ; The base Zechstein Group surface applied in the background is from NLOG website (https://www.nlog.nl/en)

Fugro team accessed to the NAM 3D Petrel Groningen model. This model was preferred to the data available from the NLOG website (https://www.nlog.nl/en) to have accurate / up to date structural data input at the scale of the Groningen gas field. The NAM model was accessible in its Petrel format. A data format conversion work was necessary to integrate the fault geometry into the Dynafrax UG model (Figure 2). This work was performed at the scale of the 10 x 10 km zone only. After few tries and interaction between teams, fault planes were delivered in .dbf format to Dynafrax UG.

A thickness map at the scale of the Groningen gas field was also provided to Dynafrax UG. This map was processed from the base of the Zechstein Group surface and the base of the Upper-Rotliegend Group surface, both available from the NLOG website.

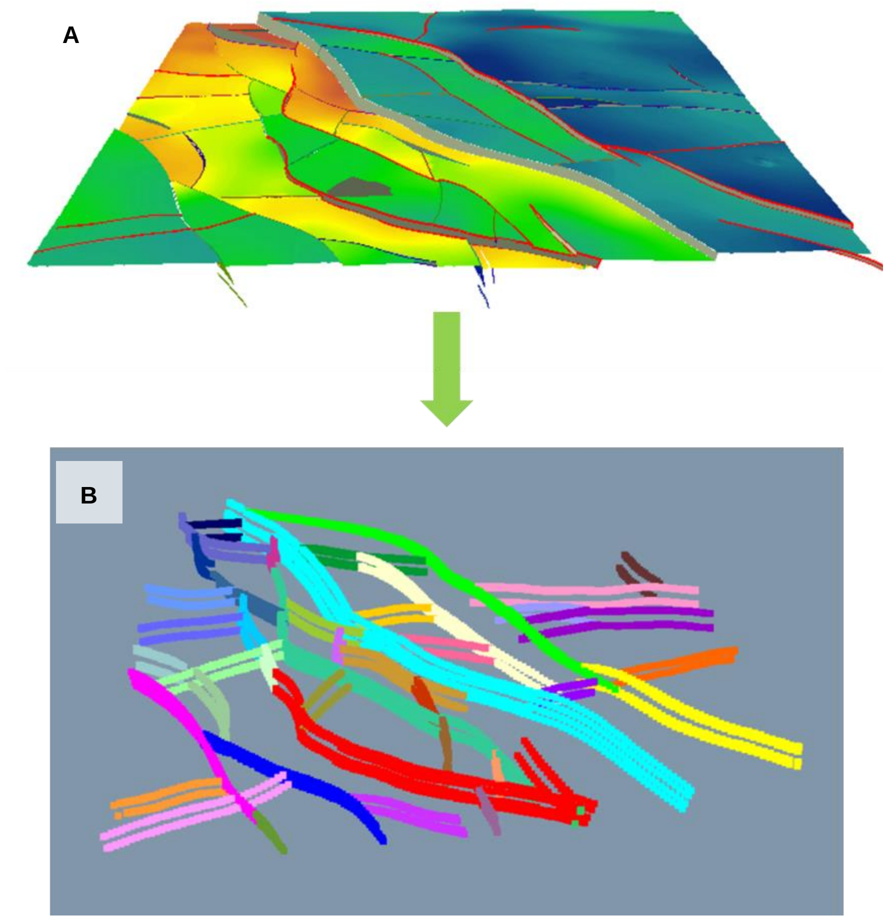


Figure 2: Fault geometry data format conversion work. A) Fault planes converted in ArcGIS after export from Petrel; B) Fault planes plotted by Dynafrax UG for their models.

A seismicity catalogue was provided to Dynafrax UG. This catalogue, in a .txt file format, is the raw unprocessed catalogue from KNMI. It has events up to and including 2019. It includes all the recorded events. No declustering, magnitude homogenization, etc. has been performed. The data were accessed here: https://dataplatform.knmi.nl/open-data-info/index.html.

3. References

List of references used or compiled to complete the KEM24 project data requirements.

.pdf file name	Reference
NAM_2015_Groningen 2015 Geomechanical Analysis.pdf	Suvrat P. Lele, Jorge L. Garzon, Sheng-Yuan Hsu, Nora L. DeDontney, Kevin H. Searles and Pablo F. Sanz (ExxonMobil Upstream Research Company, Spring, TX). (November 2015) Groningen 2015 Geomechanical Analysis. *NAM report, Editors Jan van Elk & Dirk Doornhof*
NAM_2015_Dynamic Geomechanical Modelling Risk Fault Slip Groningen.pdf	Baker RDS - Romain Guises, Jean-Michel Embry and Colleen Barton (June 2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field - Part 1: 1D Geomechanical Model - Part 2: 3D Geomechanical Model. *NAM report, Editors Jan van Elk & Dirk Doornhof*
NAM_2017_Groningen Velocity Model 2017 - Groningen full elastic velocity model.pdf	NAM – Remco Romijn (September 2017) Groningen Velocity Model 2017 - Groningen full elastic velocity model September 2017. *NAM report, Editors Jan van Elk & Dirk Doornhof*
NAM_Groningen Dynamic Model Update 2019.pdf	NAM - Quint de Zeeuw and Leendert Geurtsen (October 218) Groningen Dynamic Model Update 2019. *NAM report, Editors Jan van Elk & Dirk Doornhof*
NAM_2016_Groningen Pressure Maintenance.pdf	Richard A Hofmann, Tjerk E Hassing, Peter Schutjens, Casper Buitendijk, Joop van der Steen and Jeanine CM van Leeuwen (2016) Groningen Pressure Maintenance (GPM) Study Progress Report, February 2016. *NAM report, Editors Richard Hofmann, Jan van Elk Dirk Doornhof*
NAM_2019_Groningen Geomechanical Lab Testing Zeerijp-3A Compact Study.pdf	Aletta Filippidou (January 2019) Groningen Geomechanical Laboratory Testing of the Zeerijp-3A Compaction Study - An overview of the experimental compaction measurements. *NAM report, Editors Jan van Elk & Dirk Doornhof*
Technical Addendum to the Winningsplan and suporting documents- Groningen 2013.pdf	Jan van Elk, Dirk Doornhof, Stephen Bourne, Steve Oates, Julian Bommer, Clemens Visser, Rob van Eijs and Peter van den Bogert (November 2013) Technical Addendum to the Winningsplan Groningen 2013 Subsidence, Induced Earthquakes and Seismic Hazard Analysis in the Groningen Field. *NAM report, Editors Jan van Elk & Dirk Doornhof*
NAM_2015_Neotectonic Stresses in the Permian Slochteren Formation of the Groningen Field.pdf	Rob van Eijs (November 2015) Neotectonic Stresses in the Permian Slochteren Formation of the Groningen Field. *NAM report, Editors Jan van Elk & Dirk Doornhof*
NAM_2017_Fault Interpretation of the Groningen area supra-Zechstein Overburden.pdf	NAM - Thomas Logeman (March 2017) Fault Interpretation of the Groningen area supra-Zechstein Overburden. *NAM report, Editors Richard Hofmann, Jan van Elk Dirk Doornhof*
NAM_Groningen Dynamic Model Update 2018.pdf	NAM - Quint de Zeeuw and Leendert Geurtsen (June 2018) Groningen Dynamic Model Update 2018. *NAM report, Editors Richard Hofmann, Jan van Elk Dirk Doornhof*
Jager & Visser_2017_geology_of_the_groningen_field.pdf	Jan de Jager and Clemens Visser (2017) Geology of the Groningen field – an overview. *Netherlands Journal of Geosciences — Geologie en Mijnbouw, 96 – 5, s3–s15, 2017*
MSc_thesis_Eelco_Mechelse_External.pdf	Eelco Mechelse. (2017) The in-situ stress field in the Netherlands: Regional trends, local deviations and an analysis of the stress regimes in the northeast of the Netherlands *MSc Thesis – TU Delft, Delft University of Technology, Department of Geoscience & Engineering*

Kortekaas & Jaarsma_2017_faults_in_the_groningen_field_using_seismic_attributes.pdf	Marloes Kortekaas and Bastiaan Jaarsma (2017) Improved definitio of faults in the Groningen fiel usingseismic attributes. *Netherlands Journal of Geosciences — Geologie en Mijnbouw, 96 – 5, s71–s85, 2017*
an-empirical-relationship-for-the-seismic-activity-rate-of-the-groningen-gas-field.pdf	Marc H.H. Hettema, Bastiaan Jaarsma, Barthold M. Schroot and Guido C.N. van Yperen (2017) An empirical relationship for the seismic activity rate of theGroningen gas feld. *Netherlands Journal of Geosciences — Geologie en Mijnbouw, 96 – 5, s149–s161, 2017*
geology_of_the_groningen_field_an_overview.pdf	1988. Physical properties of natural gases. Published by N.V. Nederlandse Gasunie. Book. P. 255
tle34060664.1.pdf	K. van Thienen-Visser and J. N. Breunese (2015) Induced seismicity of the Groningen gas field: History and recent developments. *THE LEADING EDGE - Special Section: Injection-induced seismicity*

Appendices – Input data required

A.1. Data requested by Dynafrax UG

This section presents the description of the data required for Groningen reservoir fluid injection induced seismicity modelling using Particle Flow Code

This document summarizes the plan/idea of hydro-mechanical coupled PFC modelling of fluid injection induced seismicity in Groningen reservoir, and also lists the data required for generation of Groningen reservoir geological model. DynaFrax asked the project partners to provide relevant data and references that might help model generation and planning the injection scenarios.

The final look of the 2D Groningen reservoir fault model should be similar to Figure 1, where the fault traces are modelled using PFC smooth joint contact model and the reservoir rock mass is modelled using PFC parallel bond (or flat joint contact) model. Such approach has been already tested and applied to TM (thermo-mechanical) coupled modelling for long-term safety assessment of an underground nuclear waste repository at Forsmark Sweden (2D modelling in Yoon et al. 2017; 3D modelling in Yoon & Zang 2019).

In order to construct the 2D Groningen reservoir fault model, data/information are required and they are listed below, in the following section A.2.

A.2. Data compiled by Fugro in the bibliography

Fugro completed the data tables provided by Dynafrax and presented in the following sections.

Most of the data requested has been completed, however some requested data remain outstanding and Dynafrax estimated these data using expert criteria.

A.2.1. Reservoir rock mechanical data

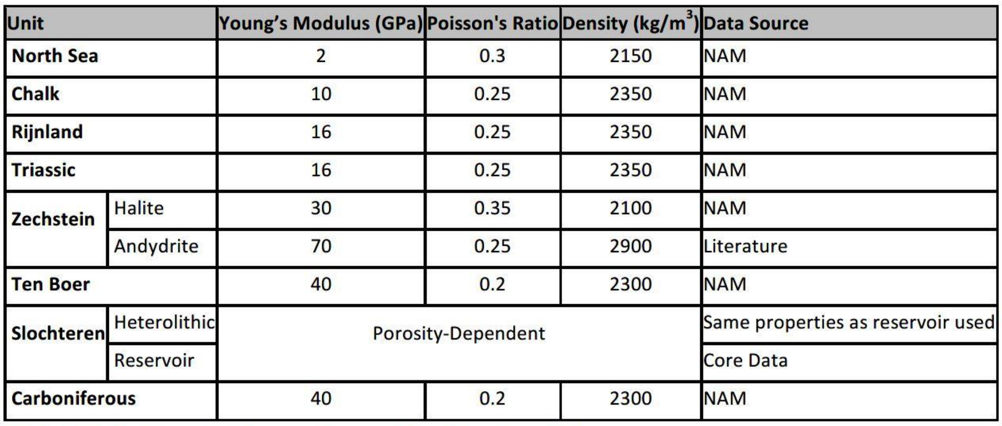
For most of these parameters, a detailed description is provided in section 2.3 of NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field.

Composite diagrams of rock mechanical properties are provided in Appendix 2 "UCS and Rock Properties" of the previously mentioned report.

Properties (unit)	Value	Description
Young's modulus (Pa)	See estimated values from EKL-12 and ZPD-12 wells (Figure 0.2)	"Across the reservoir formation, the Young's modulus has been estimated using the relationship derived from laboratory tests of young's modulus and porosity carried out in the wells Eemskanaal-12 and Zuiderpolder-12." *Source: NAM (2015) Groningen 2015 Geomechanical Analysis*
	Porosity-Dependent	Values for stratigraphic intervals above and below the reservoir are presented in Figure 0.1 below *Source: NAM (2015) Groningen 2015 Geomechanical Analysis*
Poisson ratio (-)	See values derived from data from 13 wells across Groningen field (Figure 0.5)	Figure 0.5 - Details for the equations used to calculate the Poisson ratio are presented in section 2.3.2. of *NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*
	Porosity-Dependent	Values for stratigraphic intervals above and below the reservoir are presented in Figure 0.1 *Source: NAM (2015) Groningen 2015 Geomechanical Analysis*
Uniaxial compressive strength (Pa)	9 – 10 MPa	"the average rock strength across the sand was estimated to be around 9 – 10 MPa." See values from the Uiterburen-10 well in Figure 0.3.

Uniaxial Compressive Strength also known as the Unconfined Compressive Strength (UCS)		*Source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*
	15 – 26 MPa	"the average rock strength for the Slochteren formation is around 15 – 26 MPa in the Loppersum area." Values from ZND-12 well. *Source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*
	See other values from acoustic logs data from 13 wells across Groningen field (Figure 0.4)	*Source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*
	See values from additional 3 wells (FRB-8, ZND-12 and ZDV-6) in Figure 0.6	*Source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*
Tensile strength (Pa)	Not defined at the time of the compilation of data because the parameters were not found in the bibliography reviewed	During the modelling tests, the permeability was defined using expert criteria and discussions with the internal and external experts.
Cohesion (Pa)	See values from 3 wells (FRB-8, ZND-12 and ZDV-6) in Figure 0.6	*Source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*
Internal friction angle (Deg.)	See values from 3 wells (FRB-8, ZND-12 and ZDV-6) in Figure 0.6	*Source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*
Friction coefficient (-)	See values derived from data from 13 wells across Groningen field (Figure 0.5)	Figure 0.5 - Details for the equations used to calculate the Poisson ratio are presented in section 2.3.2. of *NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*
Density (kg/m^3)	2460 kg/m^3	2.46 gr/cm^3 is the value provided in tables for the Rotliegend Formation.

		Source: NAM (2017) Groningen Velocity Model 2017 – Groningen full elactic velocity model September 2017
	Porosity-Dependent	Values for stratigraphic intervals above and below the reservoir are presented in Figure 0.1 *Source: NAM (2015) Groningen 2015 Geomechanical Analysis*



Unit		Young's Modulus (GPa)	Poisson's Ratio	Density (kg/m^3)	Data Source
North Sea		2	0.3	2150	NAM
Chalk		10	0.25	2350	NAM
Rijnland		16	0.25	2350	NAM
Triassic		16	0.25	2350	NAM
Zechstein	Halite	30	0.35	2100	NAM
	Andydrite	70	0.25	2900	Literature
Ten Boer		40	0.2	2300	NAM
Slochteren	Heterolithic	Porosity-Dependent			Same properties as reservoir used
	Reservoir				Core Data
Carboniferous		40	0.2	2300	NAM

Table 1.1. Elastic material properties and densities for rock layers.

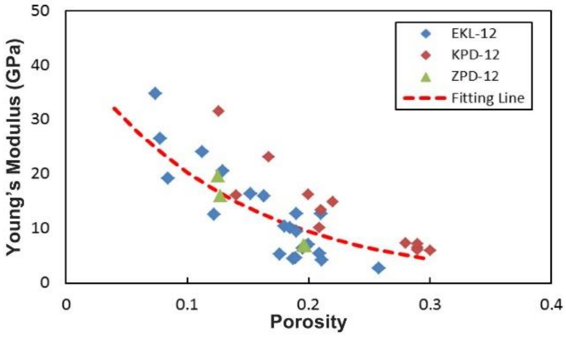


Fig. 1.2. Young's modulus vs. porosity of the reservoir rock.

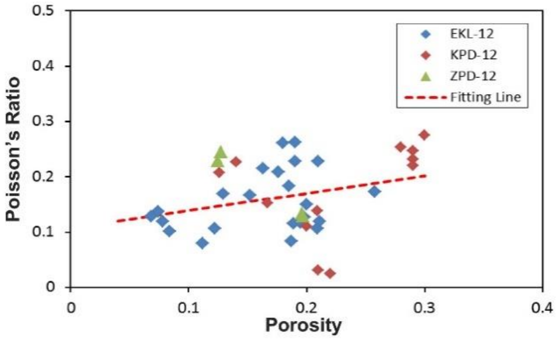


Fig. 1.3. Poisson's ratio vs. porosity of the reservoir rock.

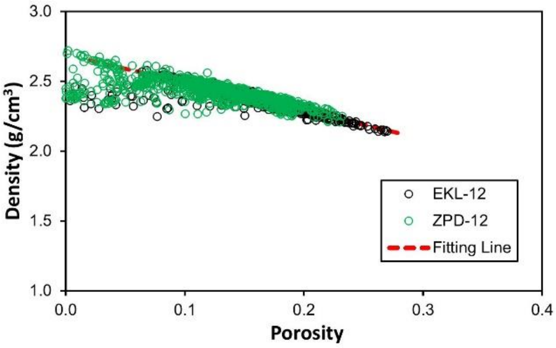


Fig. 1.4. Density vs. porosity of the reservoir rock.

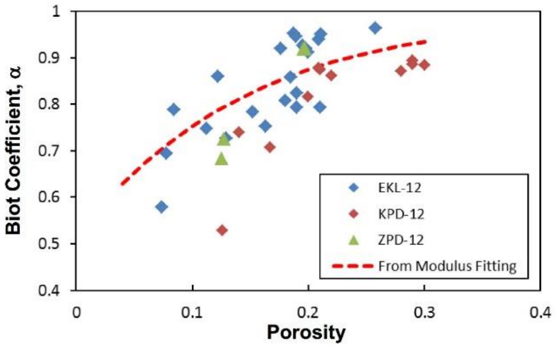


Fig 1.5. Biot coefficient vs. porosity for the reservoir rock.

Figure 0.1 : *(source: NAM (2015) Groningen 2015 Geomechanical Analysis)*

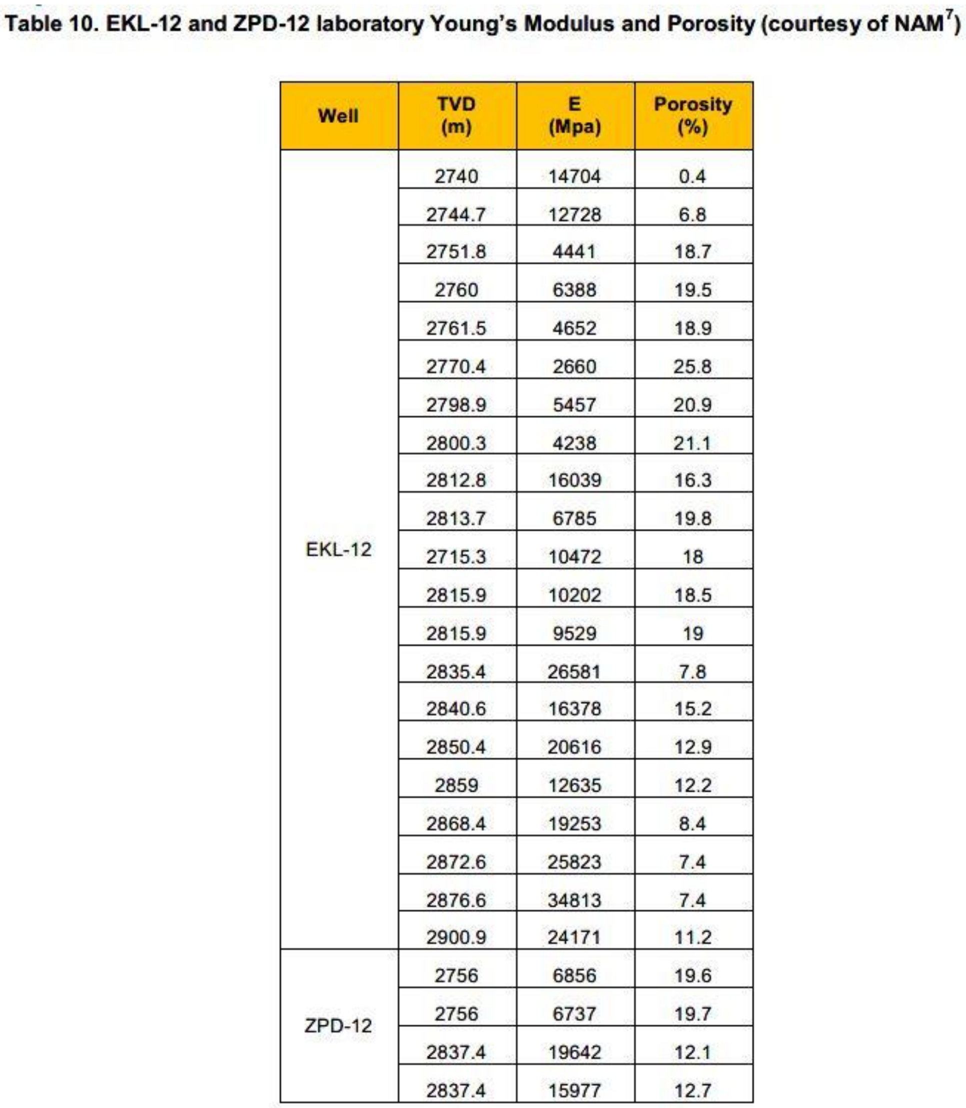


Table 10. EKL-12 and ZPD-12 laboratory Young's Modulus and Porosity (courtesy of NAM[7])

Well	TVD (m)	E (Mpa)	Porosity (%)
EKL-12	2740	14704	0.4
	2744.7	12728	6.8
	2751.8	4441	18.7
	2760	6388	19.5
	2761.5	4652	18.9
	2770.4	2660	25.8
	2798.9	5457	20.9
	2800.3	4238	21.1
	2812.8	16039	16.3
	2813.7	6785	19.8
	2715.3	10472	18
	2815.9	10202	18.5
	2815.9	9529	19
	2835.4	26581	7.8
	2840.6	16378	15.2
	2850.4	20616	12.9
	2859	12635	12.2
	2868.4	19253	8.4
	2872.6	25823	7.4
	2876.6	34813	7.4
	2900.9	24171	11.2
ZPD-12	2756	6856	19.6
	2756	6737	19.7
	2837.4	19642	12.1
	2837.4	15977	12.7

Figure 0.2 : *(source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field)*

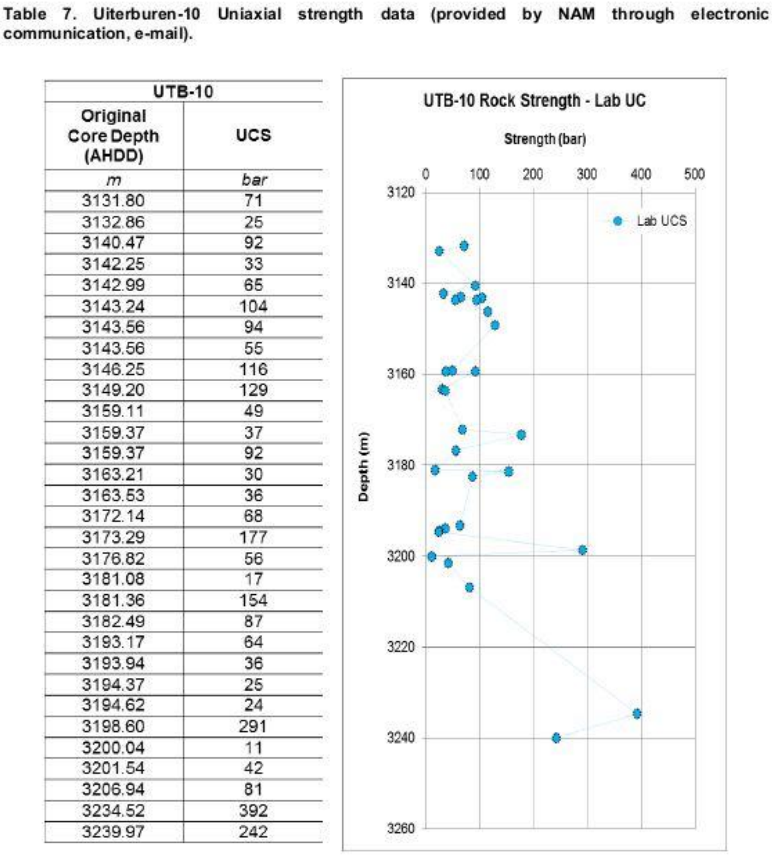


Table 7. Uiterburen-10 Uniaxial strength data (provided by NAM through electronic communication, e-mail).

UTB-10	
Original Core Depth (AHDD)	UCS
m	*bar*
3131.80	71
3132.86	25
3140.47	92
3142.25	33
3142.99	65
3143.24	104
3143.56	94
3143.56	55
3146.25	116
3149.20	129
3159.11	49
3159.37	37
3159.37	92
3163.21	30
3163.53	36
3172.14	68
3173.29	177
3176.82	56
3181.08	17
3181.36	154
3182.49	87
3193.17	64
3193.94	36
3194.37	25
3194.62	24
3198.60	291
3200.04	11
3201.54	42
3206.94	81
3234.52	392
3239.97	242

Figure 0.3 : *(source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field)*

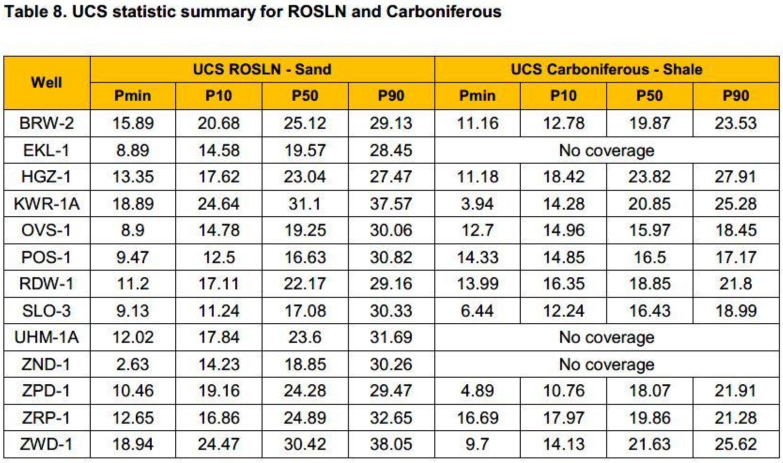
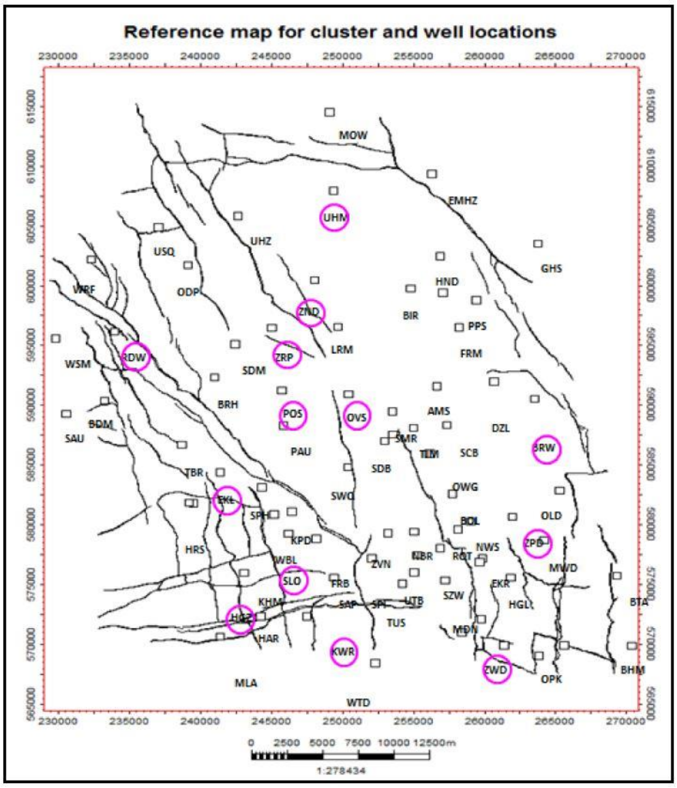


Table 8. UCS statistic summary for ROSLN and Carboniferous

Well	UCS ROSLN - Sand				UCS Carboniferous - Shale			
	Pmin	P10	P50	P90	Pmin	P10	P50	P90
BRW-2	15.89	20.68	25.12	29.13	11.16	12.78	19.87	23.53
EKL-1	8.89	14.58	19.57	28.45	No coverage			
HGZ-1	13.35	17.62	23.04	27.47	11.18	18.42	23.82	27.91
KWR-1A	18.89	24.64	31.1	37.57	3.94	14.28	20.85	25.28
OVS-1	8.9	14.78	19.25	30.06	12.7	14.96	15.97	18.45
POS-1	9.47	12.5	16.63	30.82	14.33	14.85	16.5	17.17
RDW-1	11.2	17.11	22.17	29.16	13.99	16.35	18.85	21.8
SLO-3	9.13	11.24	17.08	30.33	6.44	12.24	16.43	18.99
UHM-1A	12.02	17.84	23.6	31.69	No coverage			
ZND-1	2.63	14.23	18.85	30.26	No coverage			
ZPD-1	10.46	19.16	24.28	29.47	4.89	10.76	18.07	21.91
ZRP-1	12.65	16.86	24.89	32.65	16.69	17.97	19.86	21.28
ZWD-1	18.94	24.47	30.42	38.05	9.7	14.13	21.63	25.62



Wells location map

Borgsweer (BRW-2), Eemskanaal (EKL-1)
Hoogezand (HGZ-1), Kielwindeweer (KWR-1A)
Overschild (OVS-1), Ten Post (POS-1)
Rodewolt (RDW-1), Slochteren (SLO-3)
Uithuizermeeden (UHM-1A), T Zand (ZND-1)
Zuiderpolder (ZPD-1), Zeerijp (ZRP-1)
Zuidwending (ZWD-1)

Figure 0.4 : ***(source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field)***

ROSLN = Rotliegend Group / Slochteren Formation
The results of Pmin, P10, P50 and P90 indicate respectively the minimum, 10%, 50% and 90% of the rock strength, commonly presented in probabilistic analysis.

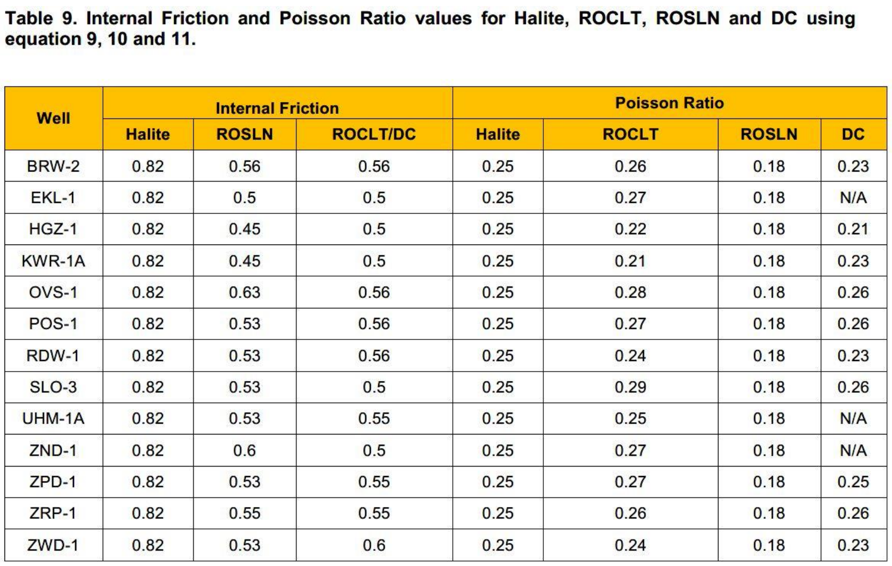


Table 9. Internal Friction and Poisson Ratio values for Halite, ROCLT, ROSLN and DC using equation 9, 10 and 11.

Well	Internal Friction			Poisson Ratio			
	Halite	ROSLN	ROCLT/DC	Halite	ROCLT	ROSLN	DC
BRW-2	0.82	0.56	0.56	0.25	0.26	0.18	0.23
EKL-1	0.82	0.5	0.5	0.25	0.27	0.18	N/A
HGZ-1	0.82	0.45	0.5	0.25	0.22	0.18	0.21
KWR-1A	0.82	0.45	0.5	0.25	0.21	0.18	0.23
OVS-1	0.82	0.63	0.56	0.25	0.28	0.18	0.26
POS-1	0.82	0.53	0.56	0.25	0.27	0.18	0.26
RDW-1	0.82	0.53	0.56	0.25	0.24	0.18	0.23
SLO-3	0.82	0.53	0.5	0.25	0.29	0.18	0.26
UHM-1A	0.82	0.53	0.55	0.25	0.25	0.18	N/A
ZND-1	0.82	0.6	0.5	0.25	0.27	0.18	N/A
ZPD-1	0.82	0.53	0.55	0.25	0.27	0.18	0.25
ZRP-1	0.82	0.55	0.55	0.25	0.26	0.18	0.26
ZWD-1	0.82	0.53	0.6	0.25	0.24	0.18	0.23

Figure 0.5 : *(source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field)*

ROSLN = Rotliegend Group / Slochteren Formation; ROCLT = Rotliegend Group / Ten Boer Member; DC = Carboniferous.
See wells location map in Figure C.

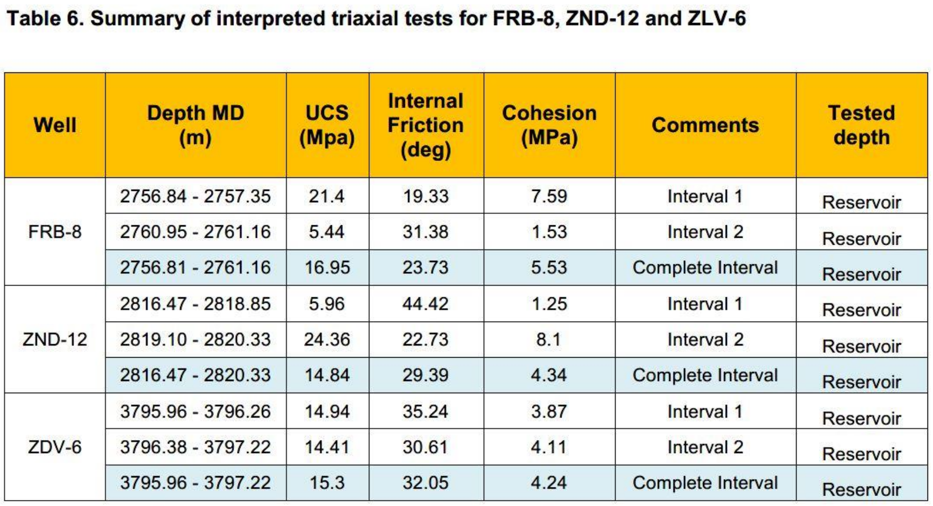


Table 6. Summary of interpreted triaxial tests for FRB-8, ZND-12 and ZLV-6

Well	Depth MD (m)	UCS (Mpa)	Internal Friction (deg)	Cohesion (MPa)	Comments	Tested depth
FRB-8	2756.84 - 2757.35	21.4	19.33	7.59	Interval 1	Reservoir
	2760.95 - 2761.16	5.44	31.38	1.53	Interval 2	Reservoir
	2756.81 - 2761.16	16.95	23.73	5.53	Complete Interval	Reservoir
ZND-12	2816.47 - 2818.85	5.96	44.42	1.25	Interval 1	Reservoir
	2819.10 - 2820.33	24.36	22.73	8.1	Interval 2	Reservoir
	2816.47 - 2820.33	14.84	29.39	4.34	Complete Interval	Reservoir
ZDV-6	3795.96 - 3796.26	14.94	35.24	3.87	Interval 1	Reservoir
	3796.38 - 3797.22	14.41	30.61	4.11	Interval 2	Reservoir
	3795.96 - 3797.22	15.3	32.05	4.24	Complete Interval	Reservoir

Figure 0.6 : *(source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field)*

A.2.2. Reservoir rock seismic data

Properties (unit)	Value	Description
P-wave velocity (km/s)	3.9 km/s	"The reservoir (between top Rotliegend and top Carboniferous) has an interval P wave velocity that loosely correlates with the thickness of the reservoir. This is concluded from considering 344 sonic logs. The thinner the reservoir, the higher the velocities are. But also inside the reservoir, the velocities can vary from top to bottom: higher at the top and bottom of the reservoir, lower in the middle part. The average velocity in the reservoir and over the entire area is roughly 3900 m/s." *Source: NAM (2017) Groningen Velocity Model 2017 – Groningen full elactic velocity model September 2017*
S-wave velocity (km/s)	2.286 km/s	Vs = 2286 m/s: value provided for the Rotliegend Formation. *Source: NAM (2017) Groningen Velocity Model 2017 – Groningen full elactic velocity model September 2017*
Seismic quality factor, Q (-)	200	200 is the value provided for the Rotliegend Formation. The Q values are best guess estimates, based on work by several groups (NAM, Shell, KNMI, Norsar, J. Bommer). *Source: NAM (2017) Groningen Velocity Model 2017 – Groningen full elactic velocity model September 2017*

A.2.3. Reservoir rock hydraulic data

Properties (unit)	Value	Description
Permeability (m^2) Common unit for permeability is Darcy (D) *Note the range of values found in the literature does not look coherent.*	1 to 1000 mD	"The reservoir quality of Rotliegend sediments from the Groningen field has been measured on thousands of core plugs. Porosity typically ranges from 10 to 24% and permeability from 1 to1000 mD, but lower and higher values have also been measured (Visser, 2012)." *Source: Jager and Visser (2017) – Geology of the Groningen field – an overview*
	0.01 mD < k_h < 1 mD 0.01 < kv/kh multiplier < 1	Horizontal permeability: "Based on the core data, a range in permeability values within the Carboniferous porosity range deemed acceptable is: 0.01 mD < k_h < 1 mD. The high case value was selected relatively aggressively to include a scenario that will drain the full Carboniferous." Vertical permeability: "The vertical permeability in the Carboniferous is implemented using a k_v/k_h multiplier, ranging from: 0.01 < kv/kh multiplier < 1. No extremely low values are used since the Carboniferous grid is concordant with the Slochteren grid, whereas in reality the angular unconformity could locally give some more vertical connectivity. *Source: NAM (2018) Groningen Dynamic Model Update 2019*
	3 D	"The main reservoir is the Lower Permian, Rotliegend Sloch-teren mainly aeoliean sandstone, which has good properties with porosities in the range of 15-20% and permeabilities of up to 3D." *Source: NAM (2016) Groningen Pressure Maintenance (GPM) Study*
Biot coefficient	Ranged from 0.7 to 0.9 See graph Figure 0.1	"The Biot coefficient is generally stress insensitive and ranged from 0.7 – 0.9 for most samples. A few high porosity samples displayed decreasing Biot

		coefficients with stress and were also much lower, with value range 0.4 – 0.7.” *Source: NAM (2019) Groningen Geomechanical Laboratory Testing of the Zeerijp-3A Compaction study*
	Porosity-Dependent	Values for stratigraphic intervals above and below the reservoir are presented in Figure 0.1 *Source: NAM (2015) Groningen 2015 Geomechanical Analysis*

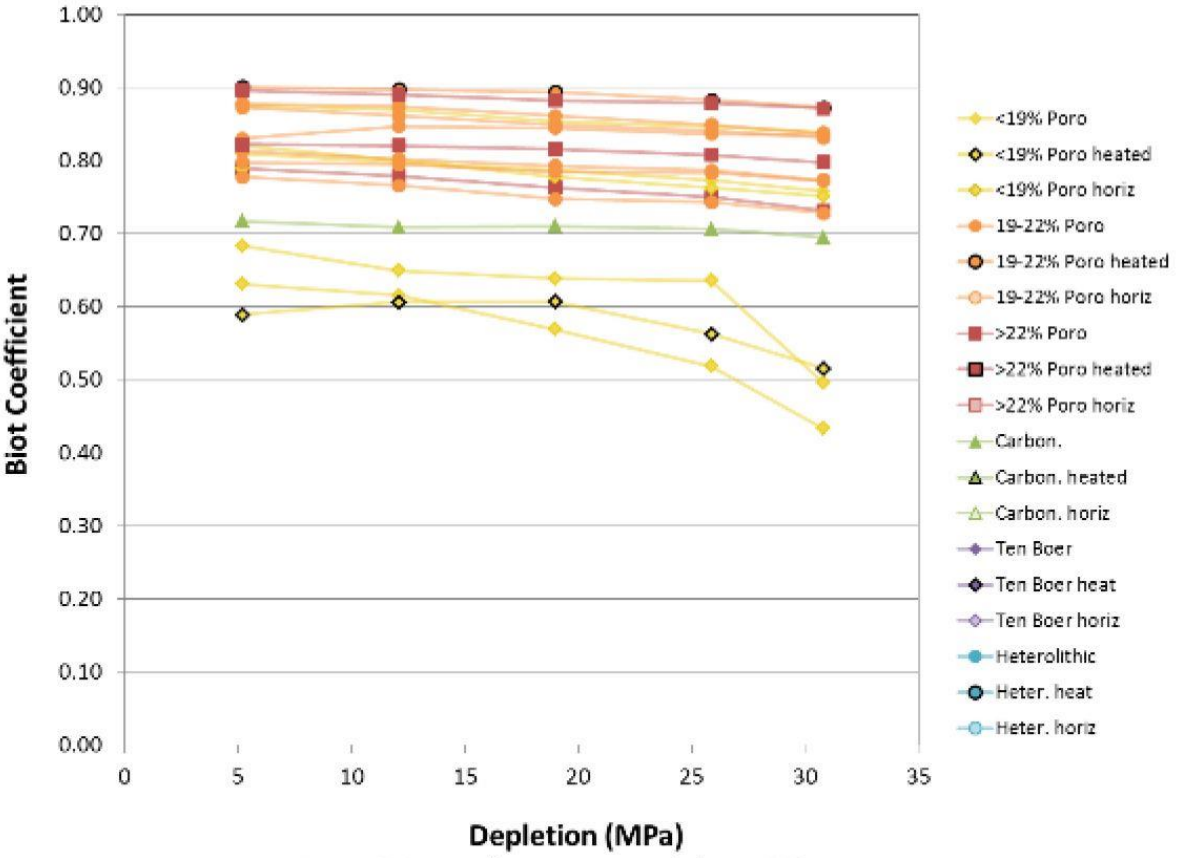


Figure 5. Biot coefficient measurend during UXS testing.

Figure 0.1 : ***(source: NAM (2019) Groningen Geomechanical Laboratory Testing of the Zeerijp-3A Compaction study)***

A.2.4. Reservoir fault mechanical data

Information regarding faults is found in Chapter 9 ("The role of faults" of: *NAM (2013) Technical Addendum to the Winningsplan Groningen 2013 – Subsidence, induced Earthquakes and Seismic Hazard Analysis in the Groningen Field*(.

Properties (unit)	Value	Description
Young's modulus (Pa)	Not defined at the time of the compilation of data because the parameters were not found in the bibliography reviewed	During the modelling tests, the permeability was defined using expert criteria and discussions with the internal and external experts.
Poisson's ratio (-)	Not defined at the time of the compilation of data because the parameters were not found in the bibliography reviewed	During the modelling tests, the permeability was defined using expert criteria and discussions with the internal and external experts.
Normal stiffness (Pa/m)	Not defined at the time of the compilation of data because the parameters were not found in the bibliography reviewed	During the modelling tests, the permeability was defined using expert criteria and discussions with the internal and external experts.
Shear stiffness (Pa/m)	Not defined at the time of the compilation of data because the parameters were not found in the bibliography reviewed	During the modelling tests, the permeability was defined using expert criteria and discussions with the internal and external experts.
Tensile strength (Pa)	Not defined at the time of the compilation of data because the parameters were not found in the bibliography reviewed	During the modelling tests, the permeability was defined using expert criteria and discussions with the internal and external experts.
Cohesion (Pa)	7 MPa	"… the analysis show a better consistency with the recorded seismic events when using a cohesion of 7 MPa and a sliding friction angle of 13° (sliding friction coefficient = 0.23)" *Source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*

Dilation angle (Deg.)	Not defined at the time of the compilation of data because the parameters were not found in the bibliography reviewed	During the modelling tests, the permeability was defined using expert criteria and discussions with the internal and external experts.
Friction coefficient (-)	0.23	"… the analysis shows a better consistency with the recorded seismic events when using a cohesion of 7 MPa and a sliding friction angle of 13° (sliding friction coefficient = 0.23)" *Source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field*

A.2.5. Reservoir fault hydraulic data

Properties (unit)	Value	Description
Permeability (m^2)	Not defined at the time of the compilation of data because the parameters were not found in the bibliography reviewed	During the modelling tests, the permeability was defined using expert criteria and discussions with the internal and external experts.
Fault seal factor		See Fig. 2 "In total 48 fault seal factors were assigned, out of over 600 faults in the dynamic grid. Figure 7-12 (Figure 0.1) provides an overview of the faults which have fault seal factors assigned in the final V6 model, chapter 8 provides a more detailed overview per region. It is recommended to review whether the deterministic choices made can be captured in a more holistic framework." *Source: NAM (2018) Groningen Dynamic Model Update 2019*

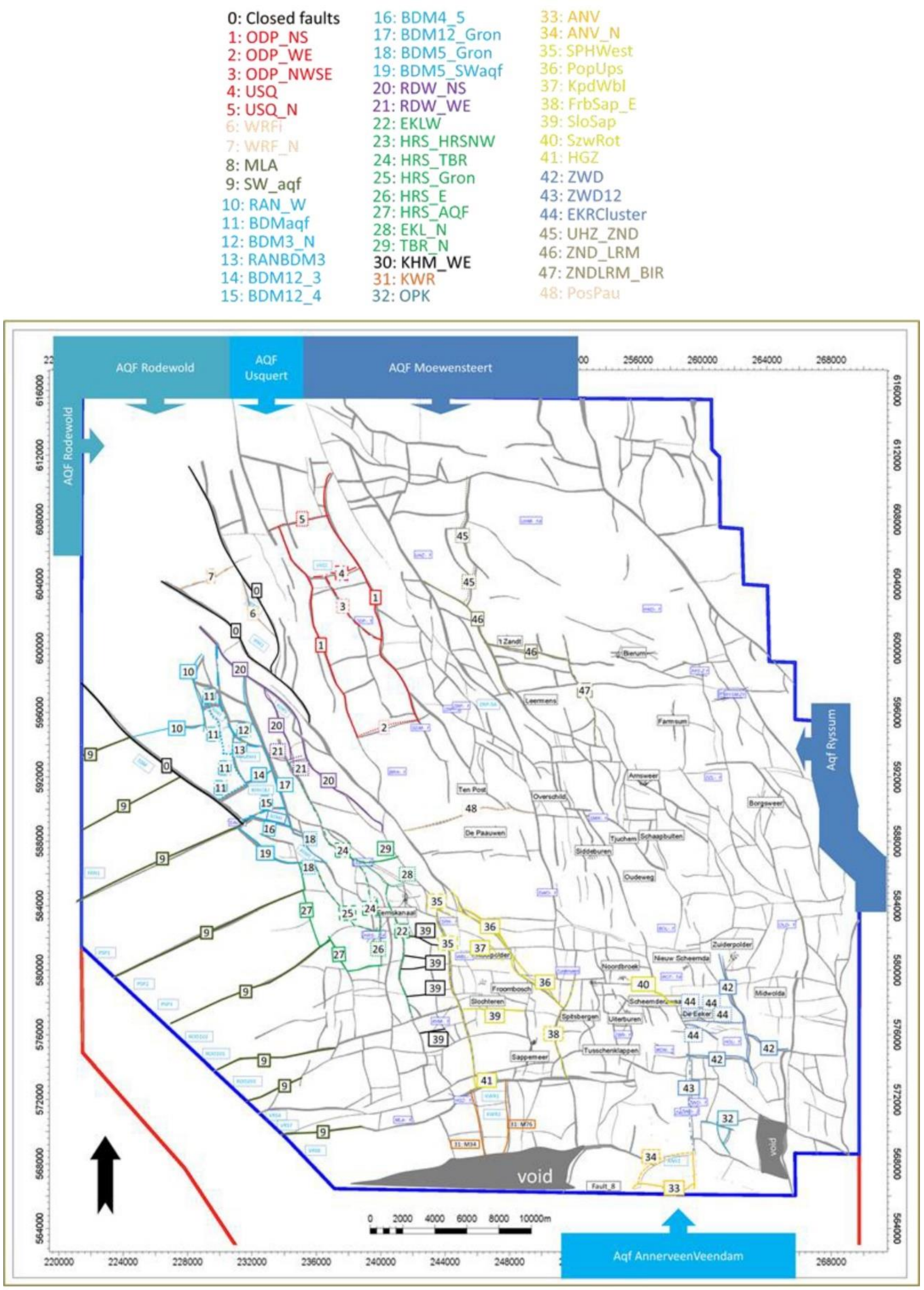


Figure 7-12 Faults with seal factors applied in the V6 model.

Figure 0.1 : ***(source: NAM (2018) Groningen Dynamic Model Update 2019)***

A.2.6. In-situ stress data

Newly, some values listed in the following table are not provided and they were defined by Dynafrax using expert criteria (coming from similar projects). For the stress field to be used as initial model conditions, the following parameters are needed:

- Maximum horizontal stress (SH) magnitude & orientation at the reservoir depth:
  The predicted SH gradient in Groningen varies between 1.73 and 1.82 SG (500 – 560 bars) at the top of the Slochteren formation.
  The orientation of SH is following and average azimuth between N156°E - N160°E ± 10°.
  (source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field)
- Minimum horizontal stress (Sh) magnitude & orientation at the reservoir depth
  Sh = 1.54 and 1.67 SG (420-520 bars) at the top of the reservoir.
  The orientation is 90° from the SH so N066°E – N070°E ± 10°.
  (source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field)
- Vertical stress (Sv) magnitude at the reservoir depth
  Sv = Smax = between 2.19 and 2.35 SG at a reference level of 3000m TVDGL (ground level).
  This difference in vertical stress gradients is mainly caused by Zechstein salt thickness variations.
  (source: NAM (2015) Neotectonic Stresses in the Permian Slochteren Formation of the Groningen Field).
- If available, stress magnitudes as a function of depth, is recommended (e.g. see Fig.3, from Mechelse 2017)

See Figure 0.1 and Figure 0.2 below.

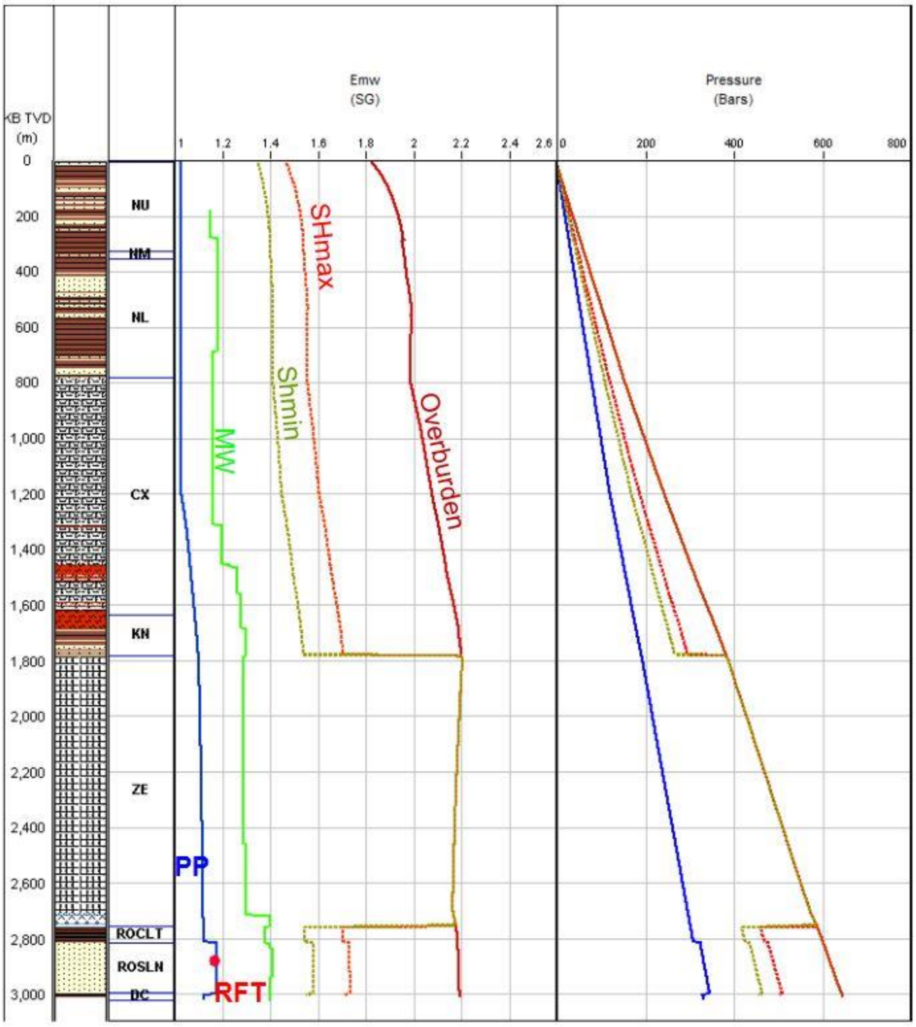


Figure 22. Summary of the principal stress magnitudes and the pore pressure as function of depth (example from well POS-1). S_v in dark red, S_{hmin} in dashed green, S_{Hmax} in dashed red and pore pressure in blue. Here is also displayed the MW used to drill this well (bright green) and the formation pressure measurements.

Figure 0.1: *(source: NAM (2015) Dynamic Geomechanical Modelling to Assess and Minimize the Risk for Fault Slip during Reservoir Depletion of the Groningen Field)*

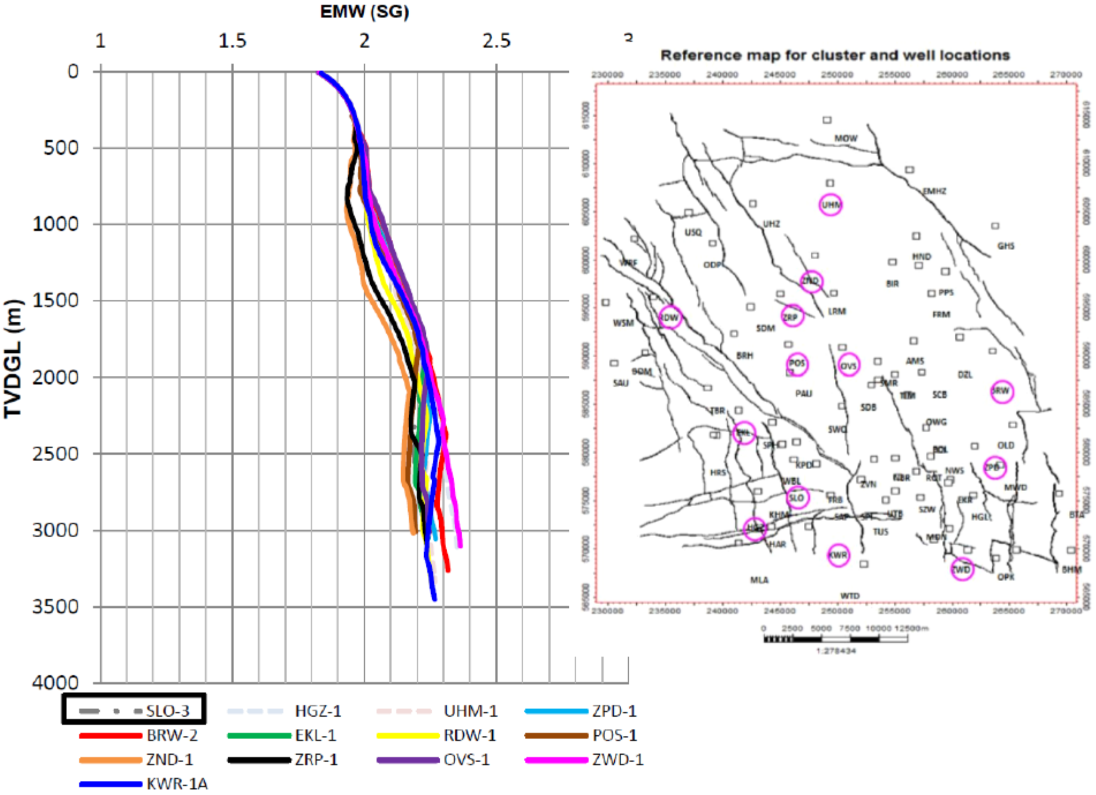


Figure 1 Vertical stress gradients (SG) for thirteen wells in the Groningen area. The overburden gradient varies from 2.19-2.35 SG at 3000m TVDGL (from Yan and Guises, 2013). To the right a map of the Groningen field showing the locations of the wells.

Figure 0.2 : *(source: NAM (2015) Neotectonic Stresses in the Permian Slochteren Formation of the Groningen Field).*

A.2.7. Groningen field production history data

For WPi (Modelling of production-induced seismicity in Groningen gas field), we need information of:

- Initial reservoir formation pressure and its spatial distribution
    - “Initial reservoir pressures of 346 bar (at reference depth of2875 m) were hydrostatic and virtually constant across the field. The Groningen field is produced primarily under gas expansion drive (Burkitov et al., 2016), which has led to a very significant pressure reduction. Extensive aquifers are connected to the field, which could possibly provide some pressure support. In addition, volume reduction as a result of compaction also gives minor pressure support. In the first decade of production, most gas was produced from clusters in the southern half of the field, leading to an imbalance in pressures, with most pressure reduction in the south. After drilling of the northern clusters in the 1970s, production from the northern sectors of the field was preferred to reduce these imbalances. Since 2014, production caps have been imposed on some of the northern clusters, which have led again to an increase in the imbalance. Reservoir pressures in 2015 mainly range from some 65 bar in the south to 85–90 bar in the north. The highest pressures are currently measured in the southwestern periphery.” *(source: de Jager and Visser (2017) Geology of the Groningen field – an overview).*
    - Chapter 8 of *NAM (2018 - Groningen Dynamic Model Update 2019)* provides a detailed overview per region of the pressure.

  The source of data is: NAM (2018) Groningen Dynamic Model Update 2019

- Production locations

  “The Groningen field is currently (spring 2016) being produced by means of 258 wells at 22 production locations. Treatment facilities are present at twenty of these production locations, and the gas of the other two well sites is transported by pipeline to the nearest gas-treatment location. There are also 28 observation wells for reservoir management and a number of injection wells to inject the produced water back into the reservoir.”

  The source of data is: NLOG website: https://www.nlog.nl/en/groningen-gasfield). Location of observations wells and clusters is provided by Figure 0.1.

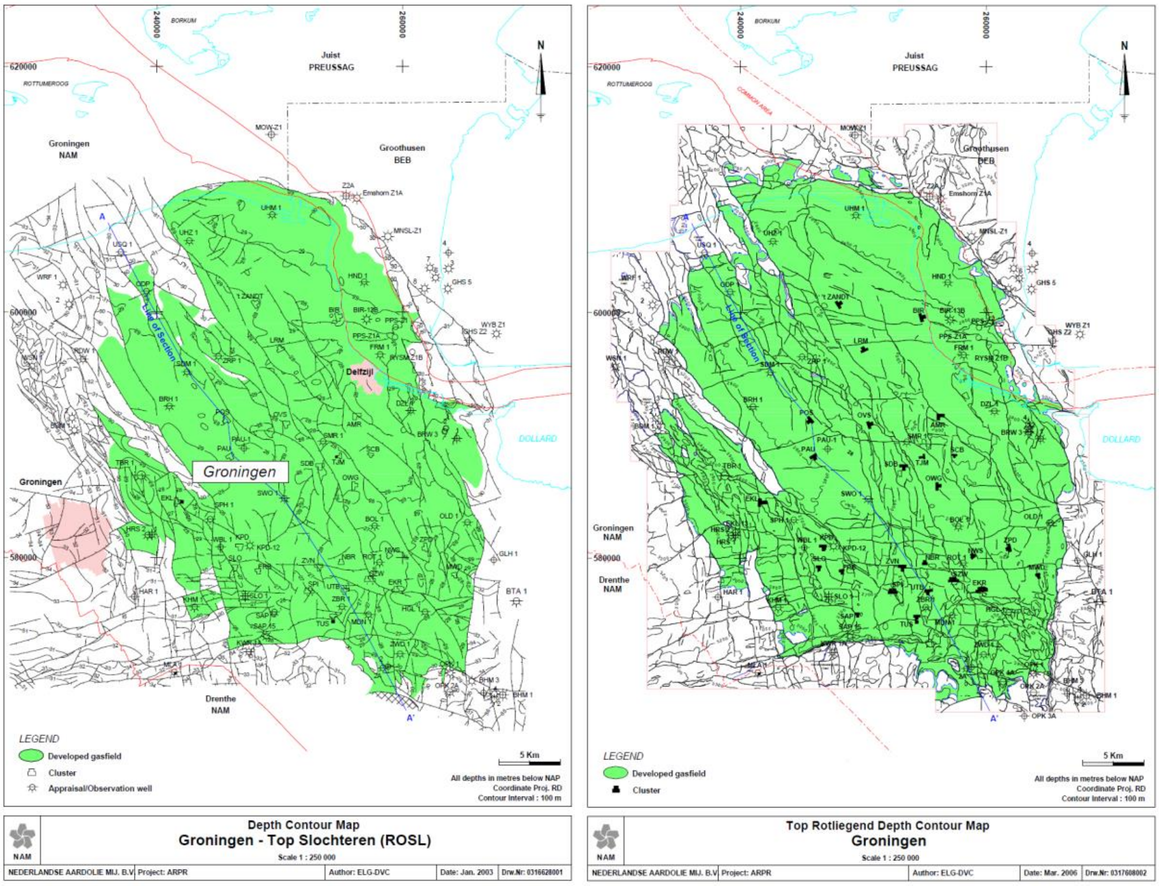
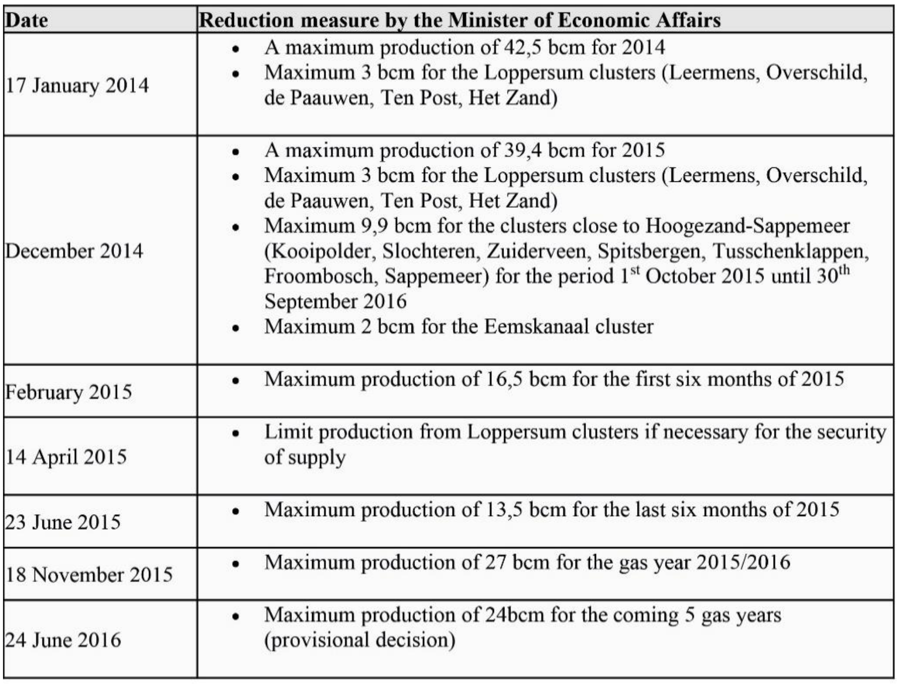


Figure 0.1: *source: NLOG website: https://www.nlog.nl/en/groningen-gasfield*

- Production rates

In view of the increased induced seismicity, the volume of gas to be produced from the Groningen gas field has, since 2014, been determined by the Minister of Economic Affairs in a decree on the Groningen production plan. For the 2015-2016 gas year, the maximum production has been set at 27 billion Nm3. The preliminary decree of July 2016 proposed a further reduction to 24 billion Nm3 per year for the next five gas years, with extra gas being allowed to be produced only in the event of very cold winters in the Netherlands. The Dutch government also publishes news on the decision-making process on its website (https://www.rijksoverheid.nl/). The following table lists the various production-limiting measures taken by the Minister of Economic Affairs since 2014

The source of data is: NLOG website: https://www.nlog.nl/en/groningen-gasfield.



Date	Reduction measure by the Minister of Economic Affairs
17 January 2014	• A maximum production of 42,5 bcm for 2014 • Maximum 3 bcm for the Loppersum clusters (Leermens, Overschild, de Paauwen, Ten Post, Het Zand)
December 2014	• A maximum production of 39,4 bcm for 2015 • Maximum 3 bcm for the Loppersum clusters (Leermens, Overschild, de Paauwen, Ten Post, Het Zand) • Maximum 9,9 bcm for the clusters close to Hoogezand-Sappemeer (Kooipolder, Slochteren, Zuiderveen, Spitsbergen, Tusschenklappen, Froombosch, Sappemeer) for the period 1st October 2015 until 30th September 2016 • Maximum 2 bcm for the Eemskanaal cluster
February 2015	• Maximum production of 16,5 bcm for the first six months of 2015
14 April 2015	• Limit production from Loppersum clusters if necessary for the security of supply
23 June 2015	• Maximum production of 13,5 bcm for the last six months of 2015
18 November 2015	• Maximum production of 27 bcm for the gas year 2015/2016
24 June 2016	• Maximum production of 24bcm for the coming 5 gas years (provisional decision)

- Seismicity catalogues (hypocenter depth, location, magnitude)

The catalogue, included as an accompanying txt file [knmi_cat_with_date_time.txt], is the raw unprocessed catalogue from KNMI. It has events up to and including 2019. It includes all of the recorded events. No declustering, magnitude homogenization, etc. has been performed.

The data were accessed here: https://dataplatform.knmi.nl/open-data-info/index.html. Area of catalogue shown on Figure 0.2.

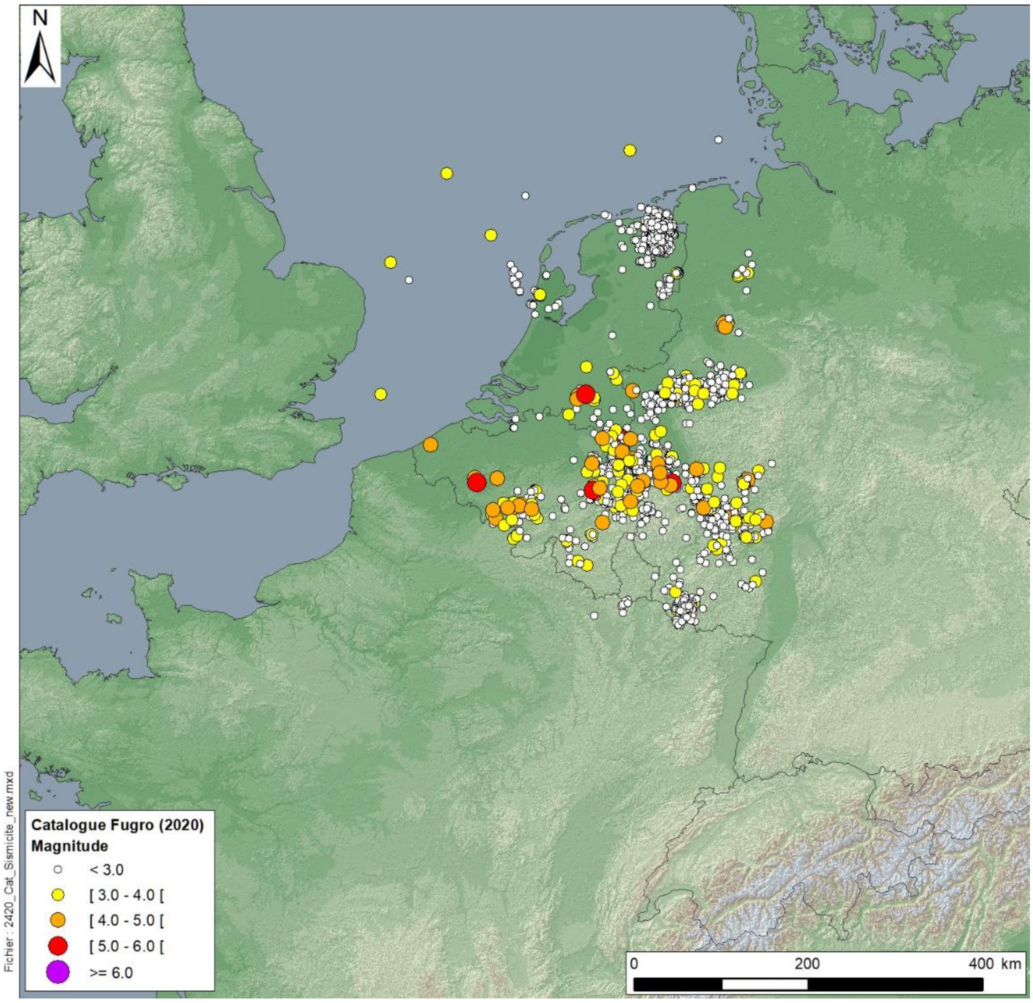


Figure 0.2: KNMI seismicity catalogue

A.2.8. Implementation of reservoir faults in 3D Groningen model

For WP3 (Modelling of gas injection using TOUGH) and WP4 (Modelling of fluid injection induced seismicity in PFC3D model), the aim is to investigate near-wellbore induced seismicity. Therefore, more detailed 3D fault structure will be implemented in the model. In order to do so, fault structure data (e.g. see Fig.4) are required and should be pre-processed. We suggest the format of such fault structure data be dxf. The source of data are the following:

- NAM (2013) Technical Addendum to the Winningsplan Groningen 2013 – Subsidence, Induced Earthquakes and Seismic Hazard Analysis in the Groningen Field: It is indicated that "More than 1700 faults have been interpreted in the Groningen field, of which 707 have been used to construct the static and dynamic reservoir model. Currently, geomechanical evaluation of all 707 faults in a single geomechanical model cannot be conducted realistically. Therefore, simplifications are incorporated in ongoing 3D modeling efforts, and dedicated studies are being conducted to reduce the modeling uncertainties").
- NAM (2017 – Fault interpretation of the Groningen area supra-Zechstein Overburden: It is indicated that: "The fault interpretation project is stored in the following location: \\europe.shell.com\tcs\ams\ui.nam\data\petrel03\epe land\groningen\nl groningen\petrel final\2016 GFR Thomas Logeman Structural OverburdenFaultInterpretation EP201703226971 " , although the provided link seems to be no longer active.

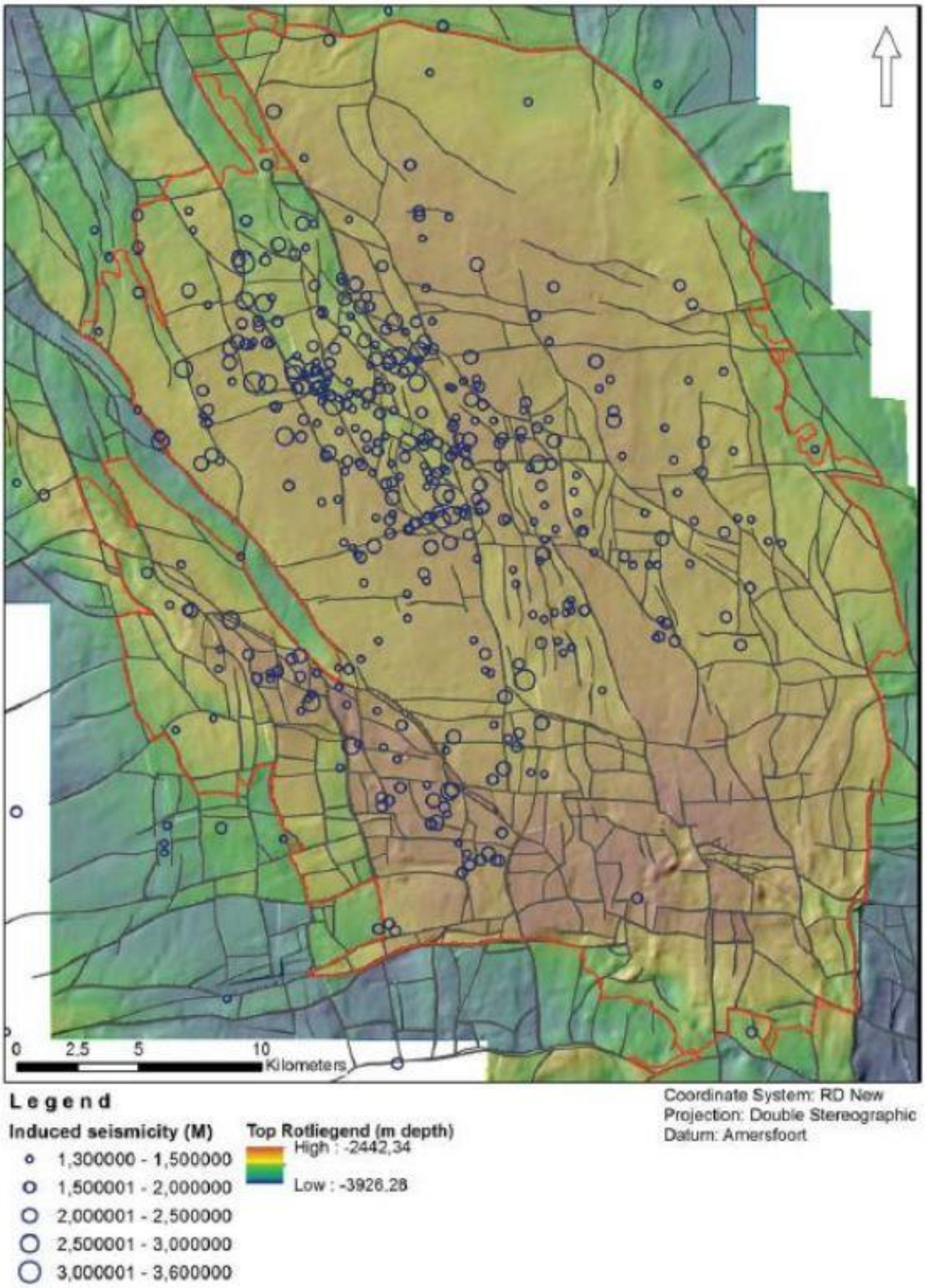


Figure 1. Example of 2D geological fault map of Groningen. PFC2D model with similar level of fault complexity will be generated using the Groningen fault map.

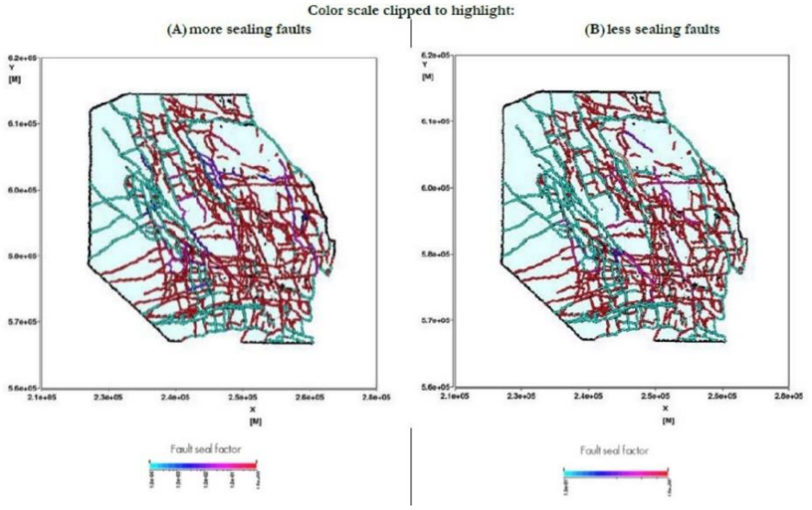


Figure 2. Fault seal factors in the Groningen V5 dynamic model (warm colors indicate more open faults, cold colors indicate more sealing faults) (from NAM, Groningen Dynamic Model Update 2018).

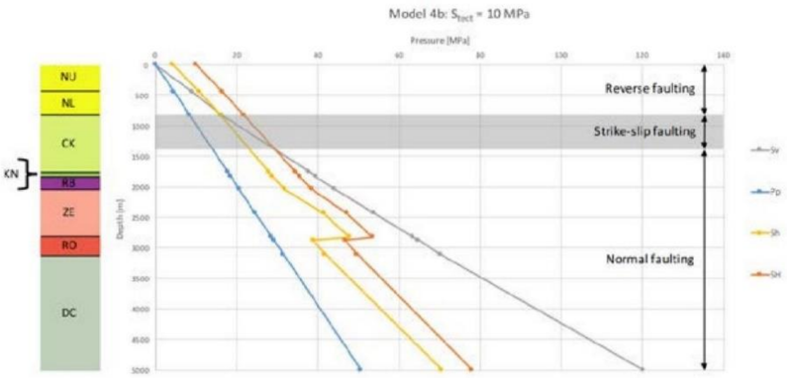


Figure 3. Stress profiles and pore pressure as function of depth (from Mechelse 2017).

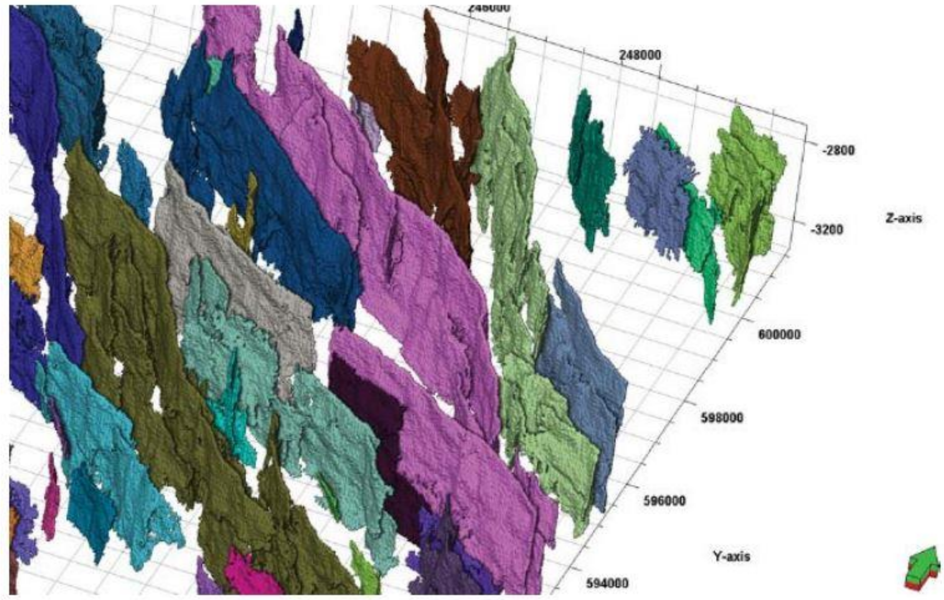


Figure 4. Example of 3D fault structure (from Kortekaas & Jaarsma 2017).