Groningen Velocity Model 2017 - Groningen full elastic velocity model September 2017

NAM

Remco Romijn

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General Introduction

The hazard due to induced earthquakes is primarily presented by the ground motion to which buildings and people are subjected. The prediction of ground motion, resulting from the earthquakes in the Groningen area induced by the production of gas, is therefore critical.

This research was started in 2012 and is continuing with ever more ground motion data from Groningen earthquakes being collected. The methodology for Ground Motion Model (GMM) was therefore updated and progress documented regularly (Ref. 1 to 8). The latest update of the Ground Motion Model was used for the Hazard and Risk Assessment of November 2017 (Ref. 9).

For Ground Motion Prediction and for determination of the hypo-centre of an earthquake a model of the rock between the reservoir (and source of the earthquakes) and the surface is necessary. Especially, the velocity of the pressure wave and shear wave are important.

This document describes the geological formations above the reservoir and the Groningen velocity model. This model is used in the determination of hypo-centre locations (Ref. 10 and 11) and ground motion prediction.

References

1 Technical Addendum to the Winningsplan Groningen 2013; Subsidence, Induced Earthquakes and Seismic Hazard Analysis in the Groningen Field, Nederlandse Aardolie Maatschappij BV (Jan van Elk and Dirk Doornhof, eds), November 2013.

2 Development of Version 1 GMPEs for Response Spectral Accelerations and for Strong-Motion Durations, Julian J Bommer, Peter J Stafford, Benjamin Edwards, Michail Ntinalexis, Bernard Dost and Dirk Kraaijpoel, March 2015.

3 Development of Version 2 GMPEs for Response Spectral Accelerations and Significant Durations for Induced Earthquakes in the Groningen field, Julian J Bommer, Bernard Dost, Benjamin Edwards, Adrian Rodriguez-Marek, Pauline P Kruiver, Piet Meijers, Michail Ntinalexis & Peter J Stafford, October 2015

4 Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part I, Deltares, Pauline Kruiver and Ger de Lange.

5 Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part II, Deltares, Pauline Kruiver and Ger de Lange.

6 Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part III, Deltares, Pauline Kruiver and Ger de Lange.

7 Modifications of the Geological model for Site response at the Groningen field, Deltares, Pauline Kruiver, Ger de Lange, Ane Wiersma, Piet Meijers, Mandy Korff, Jan Peeters, Jan Stafleu, Ronald Harting, Roula Dambrink, Freek Busschers, Jan Gunnink

8 V4 Ground-motion Model (GMM) for Response Spectral Accelerations, Peak Ground Velocity and Significant Duration in the Groningen field, Julian Bommer, Bernard Dost, Benjamin Edwards, Pauline Kruiver, Pier Meijers, Michail Ntinalexis, Adrian Rodriguez-Marek, Elmer Ruigrok, Jesper Spetzler and Peter Stafford, Independent Consultants, Deltares and KNMI, June 2017 with Parameter files - V4 Ground-Motion Model (GMM) for Response Spectral Accelerations, Peak Ground Velocity, and Significant Durations in the Groningen Field, Supplement to V4 GMM, Julian Bommer and Peter Stafford, Independent Consultants, June 2017

9 V5 Ground-Motion Model (GMM) for the Groningen Field, Julian J Bommer, Benjamin Edwards, Pauline P Kruiver, Adrian Rodriguez-Marek, Peter J Stafford, Bernard Dost, Michail Ntinalexis, Elmer Ruigrok and Jesper Spetzler, October 2017

10 A re-estimate of the earthquake hypo-centre locations in the Groningen Gas Field, Matt Pickering, March 2015.

11 Special Report on the earthquake density and activity rate following the earthquake in Appingedam (ML=1.8) and Scharmer (ML=1.5) in August 2017, NAM, Jan van Elk and Dirk Doornhof, September 2017

These reports are also available at the study reports page of the website www.namplatform.nl.

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<u>Comment:</u>
The hazard due to induced earthquakes is primarily presented by the ground motion to which buildings and people are subjected. The prediction of ground motion, resulting from the earthquakes in the Groningen area induced by the production of gas, is therefore critical.
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For Ground Motion Prediction and for determination of the hypo-centre of an earthquake a model of the rock between the reservoir (and source of the earthquakes) and the surface is necessary. Especially, the velocity of the pressure wave and shear wave are important.
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<tr><td>Directliy linked research</td><td colspan="4">(1) Hazard Assessment
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Nederlandse Aardolie Maatschappij (NAM)

Groningen Velocity Model 2017

Groningen full elastic velocity model September 2017

Remco Romijn, Team Lead Geophysics, Groningen Asset
9-1-2017

1.0 Introduction

This document describes the updated model for the greater Groningen subsurface. The previous model, called May2015, is hereby superseded. The main differences between the previous and new model are the lateral extent and the number of layers that are used.

This Sept2017 model is extended to the West, the South and the South-East so it now incorporates, besides the Groningen Field, the Grijpskerk and Norg UGS, the Annerveen field and more KNMI borehole stations. The number of layers have been reduced slightly to simplify the model, while still maintaining the key features. The P wave velocities are based on the latest reprocessing and imaging of the seismic data that took place in 2015-2016 over the entire area.

Fig. 1 shows the outline of the Groningen field, the various polygons and geophone networks.

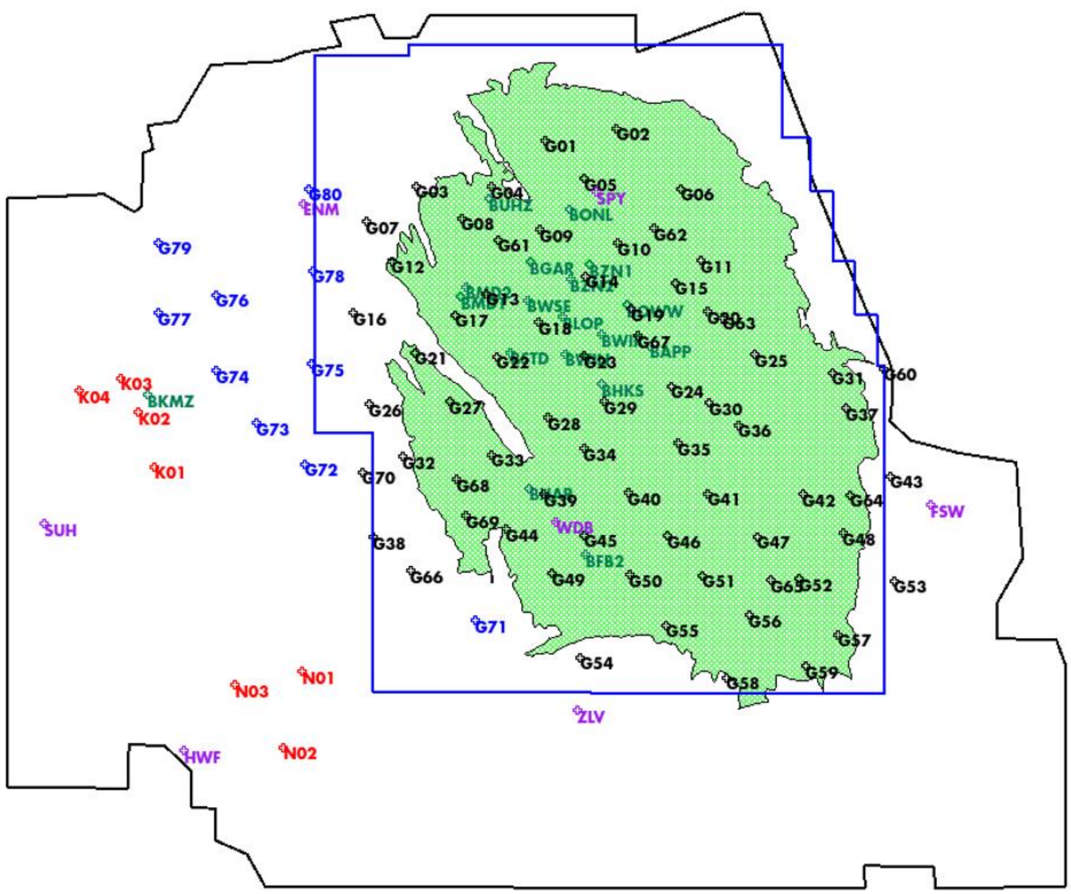

Figure 1: map view of Groningen gas field (green area), the May2015 previous velocity model outline (in blue), the new Sept2017 velocity model outline (in black) and the various network stations:
Purple: the "old" KNMI borehole stations, Green: the B network accelerometers, Black: the new G network borehole stations, Blue: the addition to the B network accelerometers and in Red: the borehole stations at Norg and Grijpskerk UGS.

At the basis of the velocity model are depth-converted time horizons and interval velocities per layer, as derived during Time-to-Depth (called DCAT) conversion projects (Groningen DCAT2016.05, DC_T DCAT2017.09 and Norg DCAT2017.02). For parts outside the DCAT area's, the velocity models for Friesland and Drenthe PreSDM projects (R-3137 and R-3138) were used to convert the time horizons to depth. Once we have the key horizons of the various layers in both time and depth, we can calculate the interval velocity of these layers. Subsequently, these interval velocities are reworked to laterally varying Vo maps by introducing a burial or K factor per layer when appropriate. This way, the velocities are in line with the trends as seen in the sonic logs. See fig. 2 for an example of the velocity model plotted against the actual sonic logs of two wells.

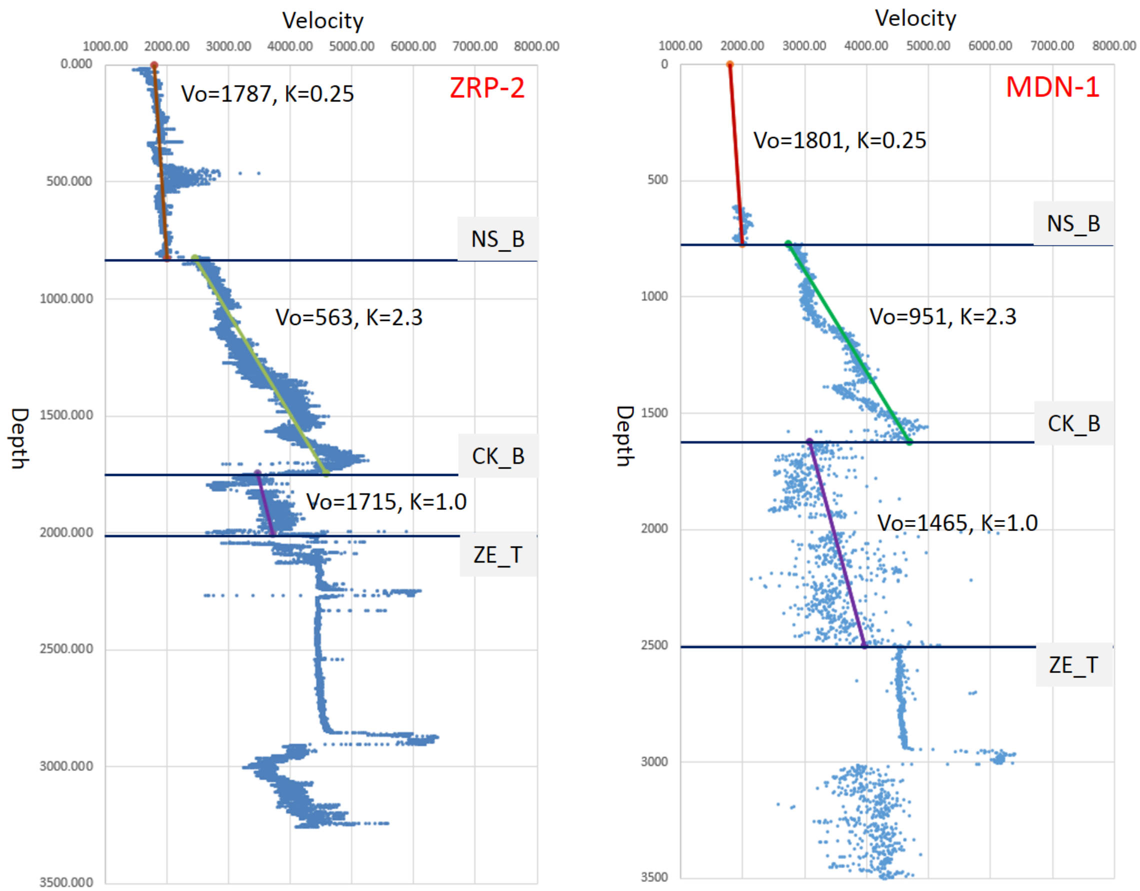

Figure 2: the velocity model of the Cenozoic and Mesozoic overburden until top Zechstein, plotted against the actual sonic logs of the wells ZRP-2 (on the left) and MDN-1 (on the right). Notice how well the velocity model captures the strong velocity increase at the NS_B and the velocity inversion at the CK_B, as well as the strong velocity increase in the Chalk layer, as expressed by the large K value of 2.3

In the next three chapters the various layers that build the model will be discussed, from top to bottom, divided into Cenozoic and Mesozoic overburden layers, the Zechstein section and the Slochteren reservoir and Carboniferous part.

2.0 Description of the Cenozoic and Mesozoic overburden layers

2.1 North Sea formation

The North Sea formation is subdivided into an upper part, Upper NS (NU) and a lower part, Middle + Lower NS (NM+NL). There are only two wells (ZRP-2 and BRW-5) that have P and S wave sonic logs and density logs all the way from surface to TD. These two wells are therefore used to derive the K factor and the Vp-Vs relations that will be used for the whole NS formation.

There is a clear distinction seen in the S wave velocities in the upper NS, as compared to the lower NS. This distinction is not seen for the P wave velocities. Therefore we can use *one* Vo map for the P wave velocities for the *entire* NS formation, in combination with a K factor of 0.25 a shown in fig. 3, left.

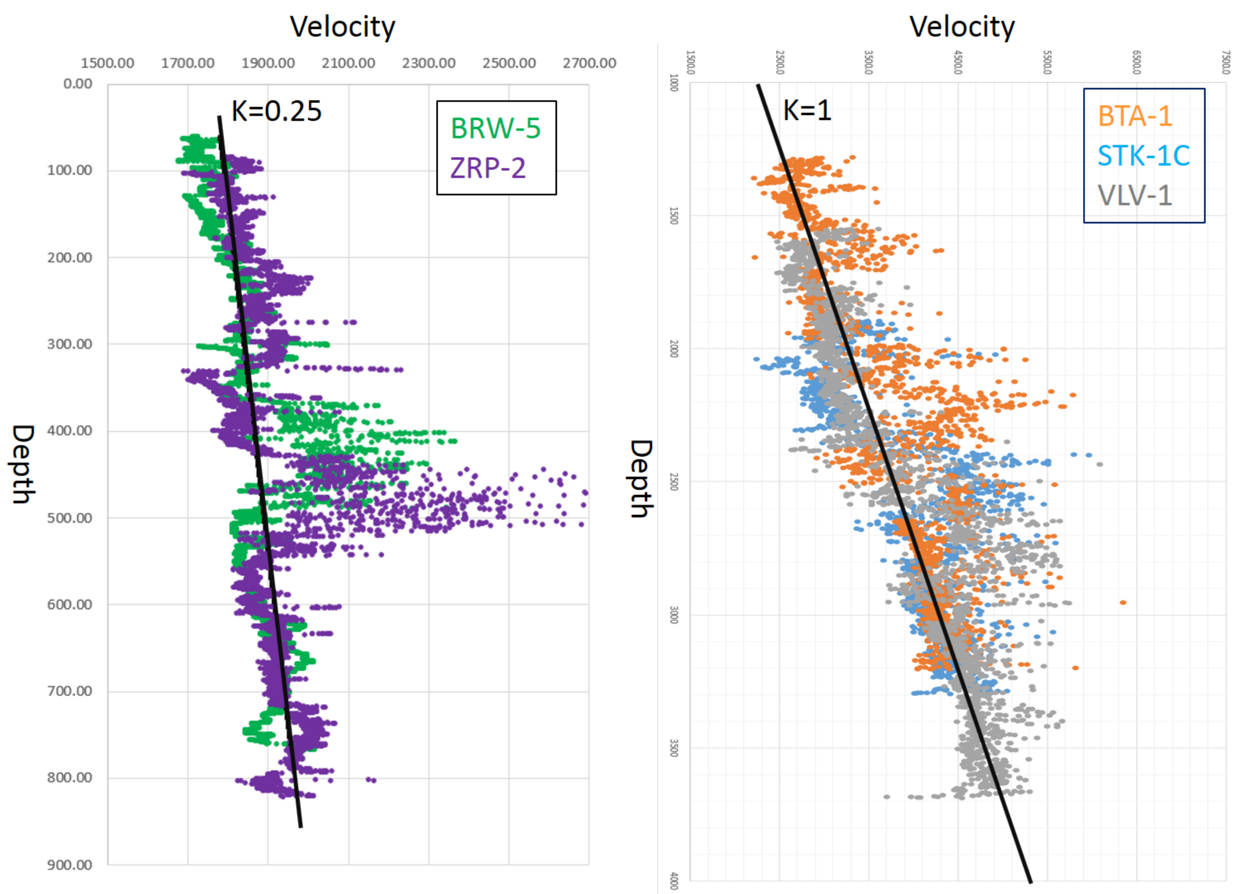

Figure 3: determining the K factor for the NS formation, based on the wells BRW-5 and ZRP-2, and for the Rijnland+Jurassic+Triassic formations, based on the wells BTA-1, STK-1C and VLV-1.

The Vp-Vs relation is different for the upper part and the lower part of the NS formation. For the upper part, the Vp/Vs ratio decreases with depth, from 5 at surface, down to 3 at NU_B, see fig. 4 left. For the lower NS, the Vp/Vs ratio is about constant, see fig. 4 right.

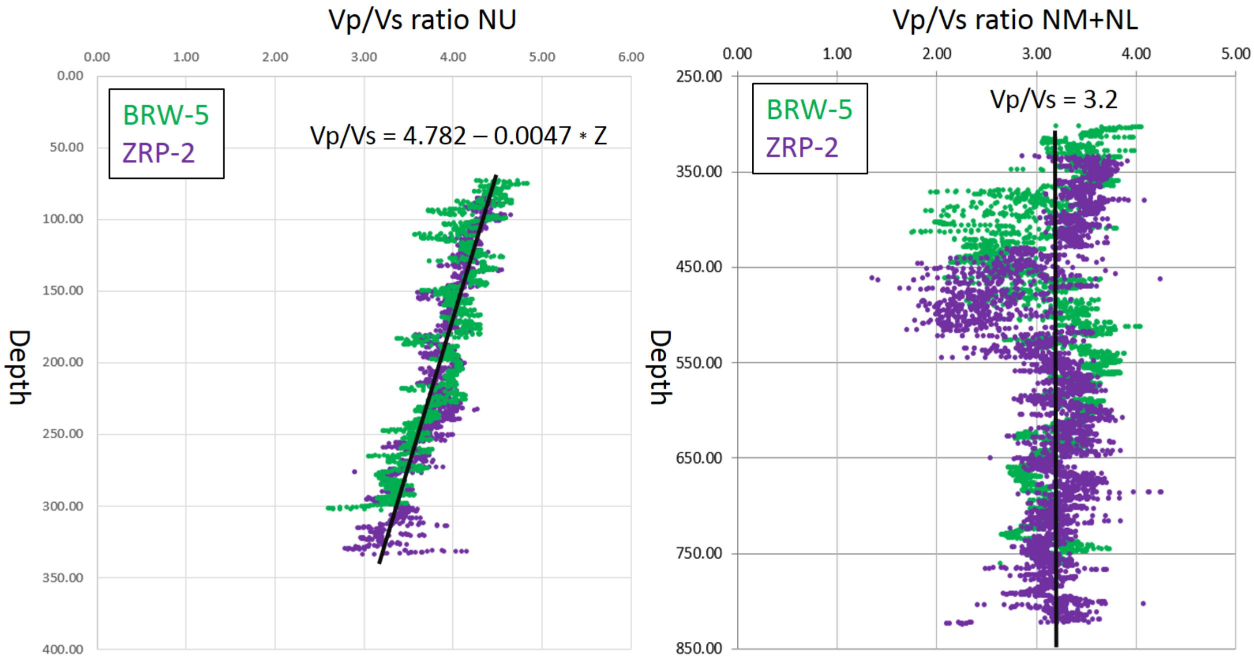

Figure 4: deriving the Vp/Vs ratios for the upper NS (left) and the lower NS (right) formations, based on the wells BRW-5 and ZRP-2. Note the depth dependency of the Vp/Vs ratio for the NU, as expressed by the formula, whereby Z stands for depth from surface.

The velocity model (Vp and Vs) for the NS formation is a relative smooth one, to be used in conjunction with earthquake event location workflows or forward modeling of travel times. There is a much more detailed NS velocity model available, but only for S waves and only for the Groningen field outline. This detailed S wave model is used for the GMPE work. See ref. [1]. Since this S wave model comes in a gridded form, it is incompatible with the velocity model described in this paper.

The density model for the NS formation is also split into two parts: one for the upper NS and one for the lower NS. For the upper NS formation, using the two wells BRW-5 and ZRP-2, we see no strong correlation with velocity. See fig. 5. Therefore, we choose a constant value of 2.04 gr/cm^3. For the lower NS formation, we use the available density log information from multiple wells to derive at a relation between slowness (in us/ft) versus density, see fig. 6.

Formation	Vp model	Vs model	Density
Upper NS	Vo map, k=0.25	Vp/Vs = 4.782-0.0047*Z	2.04
Lower NS	idem	Vp/Vs = 3.2	-0.00285*Slown+2.452

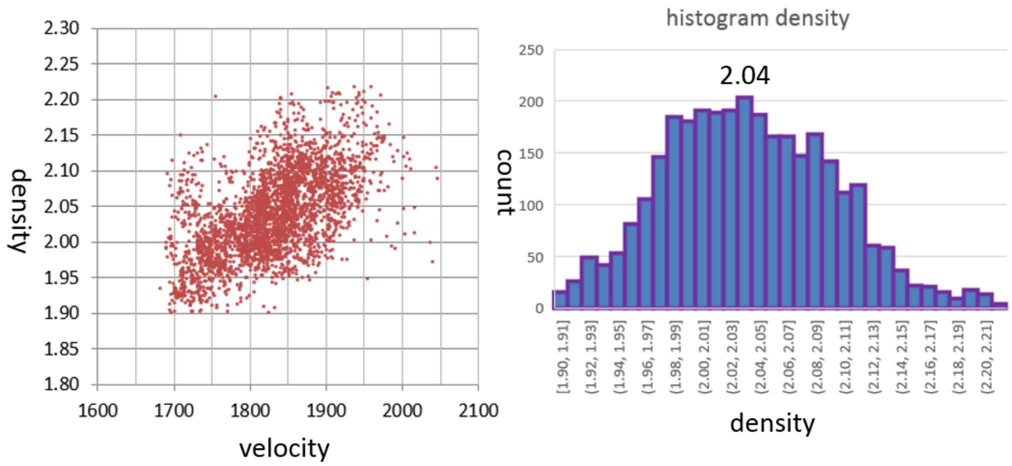

Figure 5: finding the density for the upper NS formation, using the information from logs from BRW-5 and ZRP-2. Since no clear relation exists between density and velocity, we take the value of 2.04 gr/cm^3

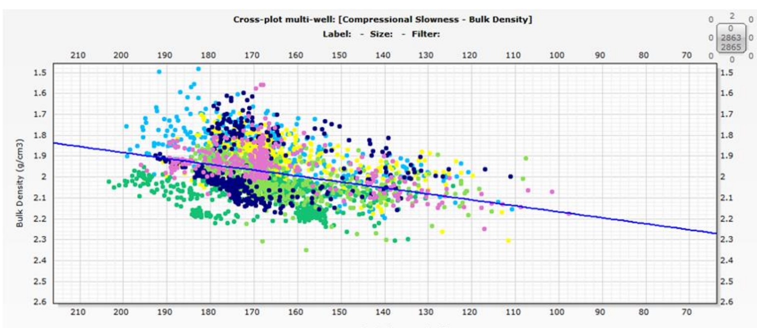

Figure 6: relation between density and P wave slowness for the lower NS formation. Multiple well logs were used, as indicated by the different colors.

2.2 Chalk formation

The Chalk velocity gradient or K value is set at 2.3 This value was used before, for the time-to-depth conversion of the W2827 PreSDM dataset in 2010. See ref [2]. This K value was actually derived during the PreSDM project R-826, as can be read in ref [3]. Although this K factor seems rather high, it does fit the actual P wave sonic logs well, as can be seen in fig. 2.

For the Vp-Vs relation, we make use of multiple P and S sonic logs that are available over the Chalk interval (see fig. 7, left).

For the Chalk formation, we use the available density log information from multiple wells to derive at a relation between P wave slowness (in us/ft) versus density (see fig. 7, right).

Formation	**Vp model**	**Vs model**	**Density**
Chalk	Vo map, k=2.3	Vs = 0.6045 * Vp – 415.6	-0.01076*Slown+3.305

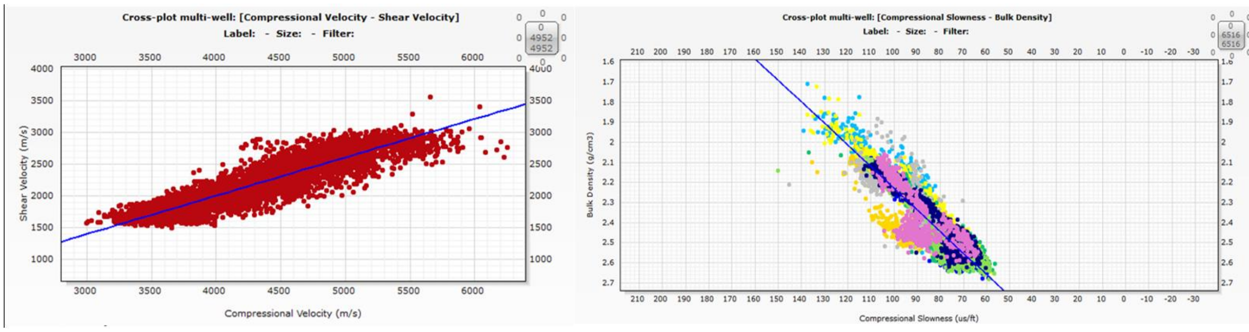

Figure 7: Vp-Vs relation (left) and P wave slowness – density relation (right) for the Chalk formation

2.3 Rijnland + Jurassic + Triassic formations

The part between base Chalk (CK_B) and top Zechstein (ZE_T) is considered as one section. The sonic logs over this section do not show any abrupt changes, reflecting the predominantly sandstone and claystone lithology of the Mesozoic. We do see a trend of velocity with depth, with a K factor of 1.0, as can be seen in fig. 3, right. This K factor fits the actual logs quite nicely, as shown in fig. 2.

For the Vp-Vs relation, we make use of the P and S sonic logs that are available over the interval, see fig. 8, left.

For the Rijnland+Jurassic+Triassic formations, we use the available density log information from multiple wells to derive a relation between P wave slowness (in us/ft) versus density, see fig. 8, right.

Formation	Vp model	Vs model	Density
KN+JW+TR	Vo map, k=1.0	Vs = 0.7423 * Vp - 745.003	-0.01*Slown+3.3

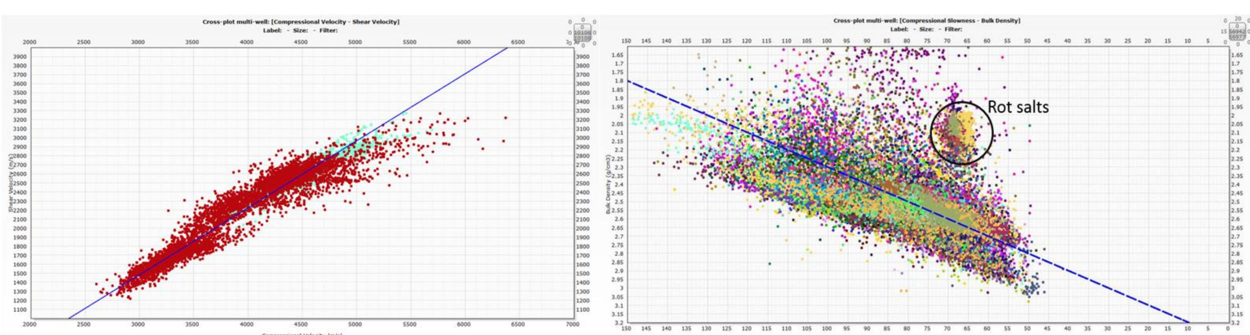

Figure 8: Vp-Vs relation (left) and P wave slowness – density relation (right) for the Rijnland + Jurassic + Triassic section

3.0 Zechstein section

The Zechstein section is characterized by Halite salts as a 'background', in which high velocity/density anhydrite/carbonate floaters (ZEZ3A/C) are present. These floaters are absent in the south-east part of the area, but in the rest of the area, where they are present, they have a variable thickness. Sometimes there are discontinuities in the floaters, sometimes the thickness is doubled, and sometimes the floaters are very much broken up. Examples of all these styles are shown in fig. 9.

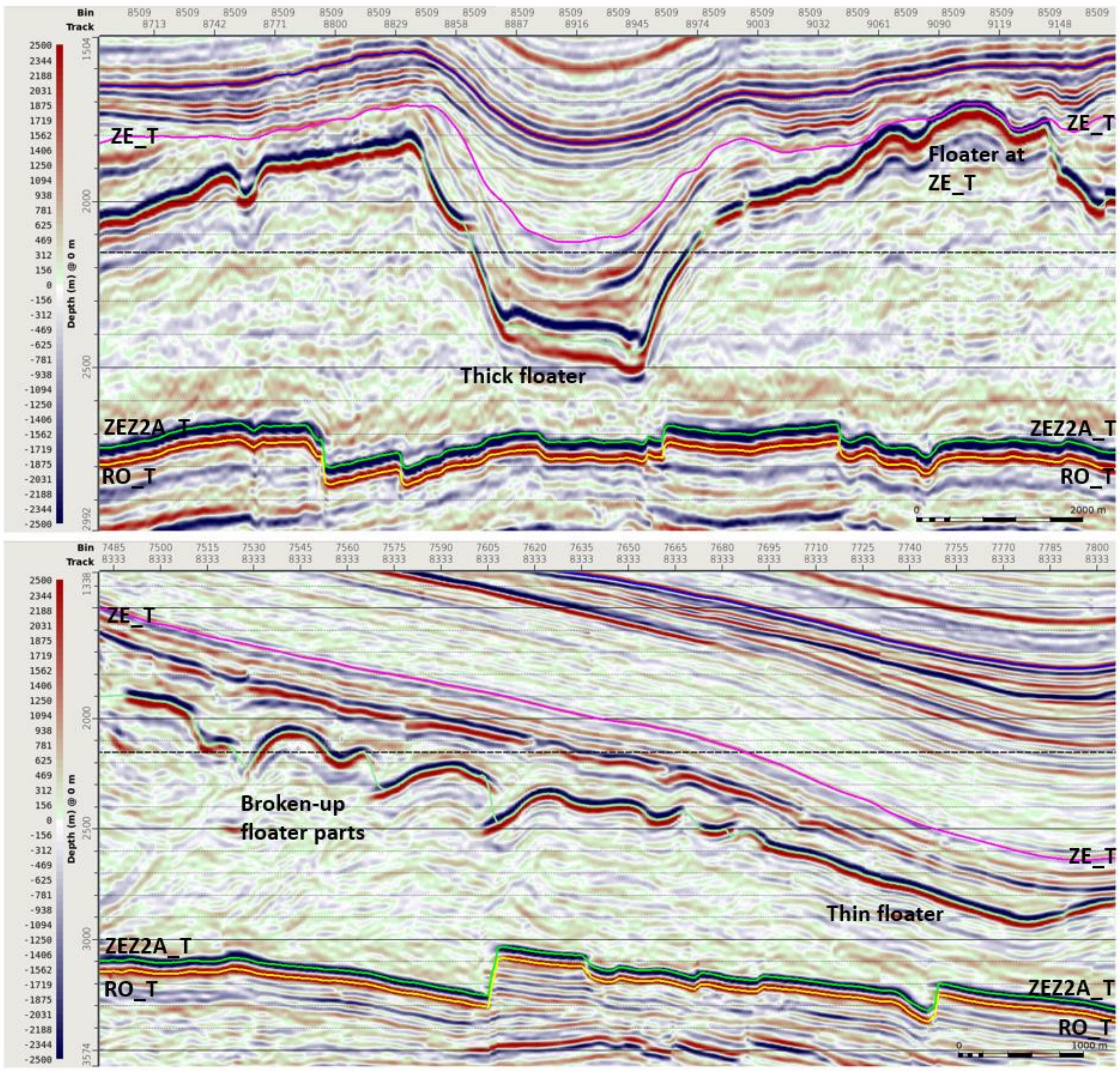

Figure 9: Various expressions of anhydrite/carbonate floaters in the Zechstein. Also shown is the 50 m thick basal anhydrite (ZEZ2A_T) directly overlying the Rotliegend reservoir (RO_T).

The top and base horizon of the floaters are present and defined over the entire area, but where the floaters are absent or where they exhibit discontinuities, the top and bottom horizons have the same depth value, effectively expressing a zero thickness.

At the base of the salt, and thus directly overlying the Rotliegend reservoir, is the so called basal anhydrite layer (ZEZ2A). It has a relative constant thickness over the entire area of about 50 m.

Vp-Vs relation is shown in fig. 10, left, P wave slowness-density relation in fig. 10, right

Formation	**Vp model**	**Vs model**	**Density**
Zechstein	n.a.	Vs = 0.50092 * Vp + 282.23	-0.04068*Slown+4.912
Halite	4400	2486	2.09
Anhydrite	5900	3238	2.81

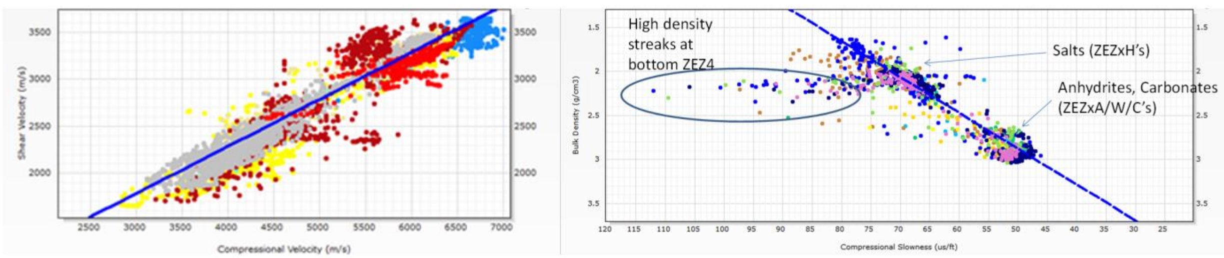

Figure 10: Vp-Vs relation (left) and P wave slowness – density relation (right) of the Zechstein section

4.0 Reservoir and Carboniferous

4.1 Rotliegend reservoir

The reservoir section, between top Rotliegend (RO_T) and top Carboniferous (DC_T) 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

The Vp-Vs relation is shown in fig. 11, left, while the P wave slowness-density relation is shown in fig. 11, right.

Formation	**Vp model**	**Vs model**	**Density**
Rotliegend	n.a.	Vs = 0.5364 * Vp + 193.96	-0.01109*Slown+3.324
Rotliegend	3900	2286	2.46

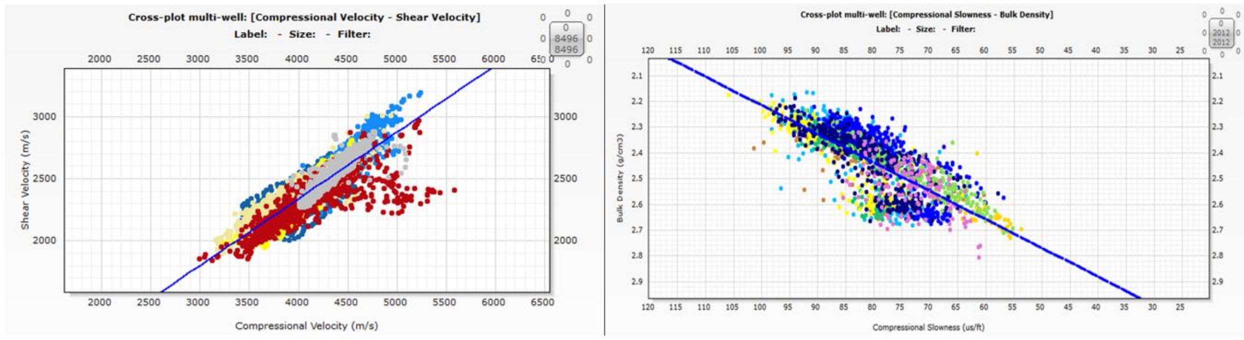

Figure 11: Vp-Vs relation (left) and P wave slowness – density relation (right) for Rotliegend reservoir section

4.2 Carboniferous

The P wave velocities of the Carboniferous underburden are increasing with depth, according to fig. 12, left. Based on various logs, each of which penetrates the Carboniferous only a couple of hundreds of meters at most, we do see a clear depth dependent trend. The maximum depth to which this trend is valid is probably around 4500 m, for which a velocity of 5000 m/s holds.

The Vp-Vs relation is based on only two wells which have S wave sonic logs, BRW-5 and WIT-3. See fig. 12, right, top.

The density velocity relation is not so clear, so we take the maximum of the Vp/dens cross plot, which is shown in fig. 12 right, bottom.

Formation	**Vp model**	**Vs model**	**Density**
Carboniferous	Vp=0.541*Z + 2572.3	Vs = 0.927 * Vp - 1547.313	2.65

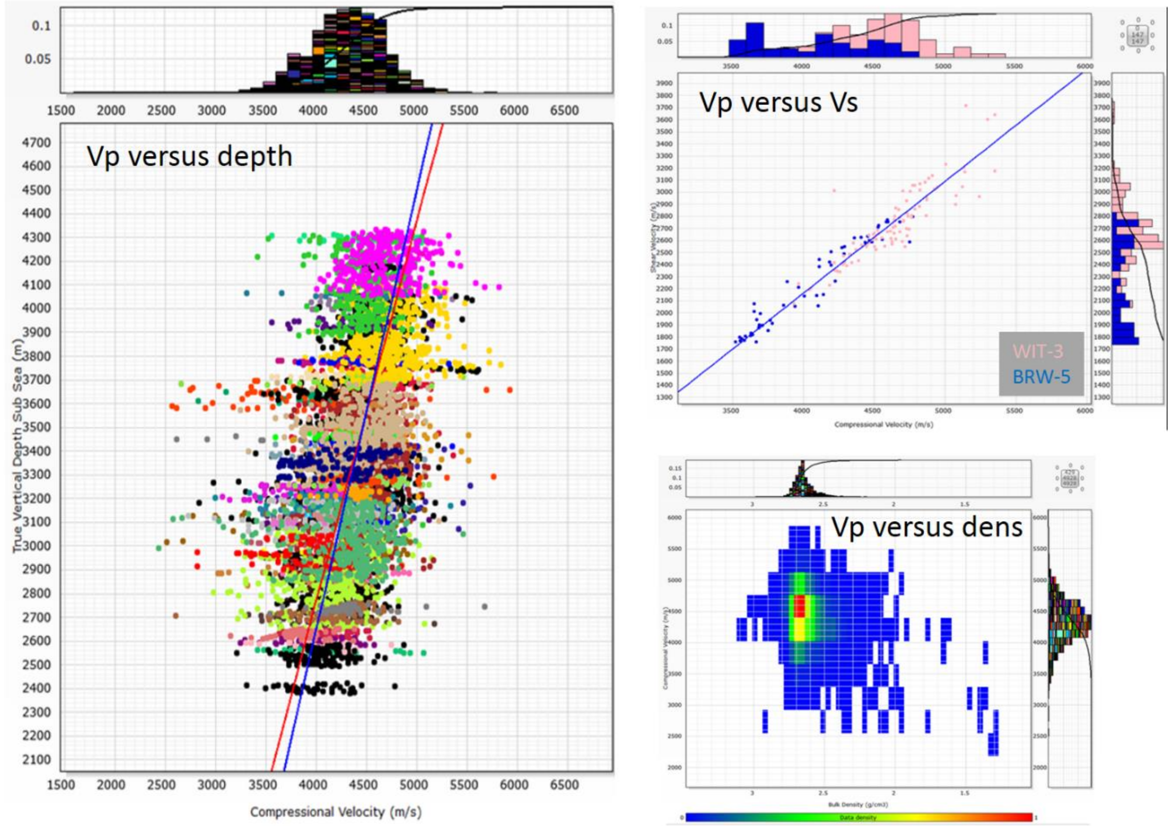

Figure 12: Carboniferous underburden. Left: Vp versus depth using multiple well logs, each indicated with a different color. The blue trendline is without outliers, the red one with outliers included. Top right: Vp-Vs relation. Bottom right: Vp versus density crossplot. The highest coexistence of density / velocity values, the red spot, at 2.65 gr/cm^3

5.0 Anisotropy and attenuation

As measure of anisotropy, we take the Vh/Vv ratio's, as determined during the Pre-SDM project over Groningen, see ref [4] and table below:

Formation	Vh/Vv ratio	Q factor
Upper NS	0.9608	50
Lower NS	1.0394	150
Chalk	1.0086	200
Rijnl + Jurassic +Triassic	1.0256	200
Zechstein	1.0	200
Rotliegend	1.0	200
Carboniferous	1.0	200

The Q values are best guess estimates, based on work by several groups (NAM, Shell, KNMI, Norsar, J. Bommer)

7.0 Velocity Model description

Horizon	Formation	Vp model	Vs model	Density
Z=0				
	Upper NS	Vo map, k=0.25	Vp/Vs = 4.782 - 0.0047 * Z	2.04
NU_B				
	Lower NS	idem	Vp/Vs = 3.2	-0.00285*Slown+2.452
NS_B				
	Chalk	Vo map, k=2.3	Vs = 0.6045 * Vp – 415.6	-0.01076*Slown+3.305
CK_B				
	KN+JW+TR	Vo map, k=1.0	Vs = 0.7423 * Vp - 745.003	-0.01*Slown+3.3
ZE_T				
	ZE Halite	4400	2486	2.09
Floater_T				
	ZE Anhydrite	5900	3238	2.81
Floater_B				
	ZE Halite	4400	2486	2.09
ZEZ2A_T				
	ZE Anhydrite	5900	3238	2.81
RO_T				
	Rotliegend	3900	2286	2.46
DC_T				
	Carboniferous	Vp=0.541*Z + 2572.3	Vs = 0.927 * Vp - 1547.313	2.65
Z=4500				

Velocities are in m/s, Depth in m from surface (Z=0), Density in gr/cm^3, Slowness in us/ft.

6.0 Deliverables

The following files constitute the complete model:

Horizons in depth: NU_B, NS_B, CK_B, ZE_T, floater_T, floater_B, ZEZ2A_T, RO_T, DC_T
File: horizons.txt, 13 columns, 1401851 lines, 194 Mb in size.

Vo maps: NS_Vo for Upper + Lower NS, CK_Vo for Chalk section, ME_Vo for KN+JW+TR section.
Note: because of the high K value for the Chalk, negative values in the Vo map do occur!
File: Vo_maps.txt, 7 columns, 1401851 lines, 90 Mb in size.

X,Y coordinates are in the Dutch Amersfoort/RD-New system (EPSG 28992), sampling grid: 50x50 m. Track and bin numbers are also provided, they are based on the (original) 25x25 m grid the seismic data was in.

7.0 References

Ref [1]: Kruiver, P. P., E. van Dedem, R. Romijn, G. de Lange, M. Korff, J. Stafleu, J. L. Gunnink, A. Rodriguez-Marek, J. J. Bommer, J. van Elk. (2017): An integrated shear-wave velocity model for the Groningen gas field, the Netherlands, *Bulletin of Earthquake Engineering,* pp. 1–26.

Ref [2]: DCAT2010.07 by M. van Dongen on W-2827 seismics for GFR2012 geological model.

Ref [3]: Groningen 3D Pre-Stack Depth Migration Processing Report (R-826) by F.M. Hindriks and J.D.C. van der Toorn, October 2002, Nam Document nr 200203000600.

Ref [4]: Groningen Pre_SDM Report (R-3136) by R. Wervelman, S. Michelet and K.D. Nguyen, October 2015, EP Document nr EP201601206642.

8.0 Acknowledgements

Rob Wervelman and his (former) team members are thanked for the PreSDM P-wave velocity models that ultimately were at the basis of this velocity model. Pepijn Kole is thanked for providing all the petrophysical relations between Vp-Vs-density.