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TNO report

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VELMOD-4

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Contents

1 Introduction

The velocity model VELMOD-4 is the successor of the VELMOD-1 to -3 models (Van Dalfsen et al, 2007). Contrary to the previous models, VELMOD-4 includes seismic velocity information which is integrated with velocity data from sonic logs and checkshot data for the main lithostratigraphic layers in the Dutch on- and offshore. With this data a layer-cake velocity model is constructed based on V0-k parameterization.
The primary application of the VELMOD-4 model is time-depth conversion for large scale (regional) seismic interpretation and mapping.
The VELMOD-4 project started in February 2017, when TNO and Estimages signed an agreement to cooperate in building this new velocity model. TNO delivered data and geological expertise of the Dutch subsurface and applied previous velocity models. Estimages delivered geostatistical expertise and experience in regional time-depth conversion executed in various regions across the globe.
In this project two velocity models have been produced:

(i) VELMOD-4a is a velocity model integrating the seismic velocities (PSTM) and resulting from a full 3D calibration process to the well TD functions. This model was completed in May 2018.

(ii) VELMOD-4b is a layer cake velocity model integrating the well tops information. For this model the first VELMOD-4a model has been used to “guide” the model far from the wells. The VELMOD-4b model was finalised in December 2019.

2 Data

2.1 Well velocity data

The well velocity dataset consists of sonic logs and checkshot data. Sonic data from various logging tools were available, often expressed in different units like slowness, instantaneous sonic velocity and (calibrated) travel time-depth (TZ) pairs.

The dataset comprises (digitally available) data of well released to the public domain before September 1st 2012. All borehole data files used within this project are listed in VELMOD-3.1 report (see Appendix B of VELMOD3.1, 2017).

All used deviation data were available from DINO (the National Geo-data Centre of the Netherlands), through the 'NL Olie- en Gasportaal' at www.nlog.nl.

The requirements for VELMOD-4a with respect to the use of velocity sources are different than for VELMOD-3.1. Only one velocity source can be used for the whole depth range of a borehole. So for the selection of a velocity source the consideration between coverage and quality of the data had to be done for the whole depth range, for VELMOD-3.1 this was done for the depth range of each individual layer.

In total 1642 wells have been used for VELMOD-3.1 model. For the VELMOD-4a model a total of 577 wells have been selected and for the VELMOD-4b model a total of 1623 wells have been used (Table 1).

Number of wells used for	NU	NM+NL	CK	KN	S+AT	RN+RB	ZE	Total
Velmod-3.1	660	757	1160	122	631	1024	1063	1642
Velmod-4a	375	376	471	478	207	310	244	577
Velmod-4b	902	925	1321	1343	560	869	698	1623
Velmod-4b-s4	535	748	1148	1207	516	802	-	1493
Velmod-4b-s5	863	823	1172	1239	350	694	698	1550
blindset Velmod-4b	1544	1505	1737	1693	503	921	907	2980

Table 1: Used wells for the various velocity models and the lithostratigraphic layers

2.2 Seismic velocity data (PSTM)

A total of 179 3D-velocity datasets and 136 2D-velocity data sets were used for the project. Most of these data were available from DINO, but several 2D-velocity data sets have been digitised by TNO in 2017 (see Figure 1 and Deliverable 1).

2.3 Lithostratigraphic marker data

Borehole lithostratigraphic marker data were retrieved from DINO. These markers are assigned conform the standard stratigraphic nomenclature of the Netherlands

(Van Adrichem Boogaert & Kouwe, 1993-1997). The lithostratigraphic data was aggregated from stratigraphic member level to main stratigraphic (sub) group level (Figure 3).

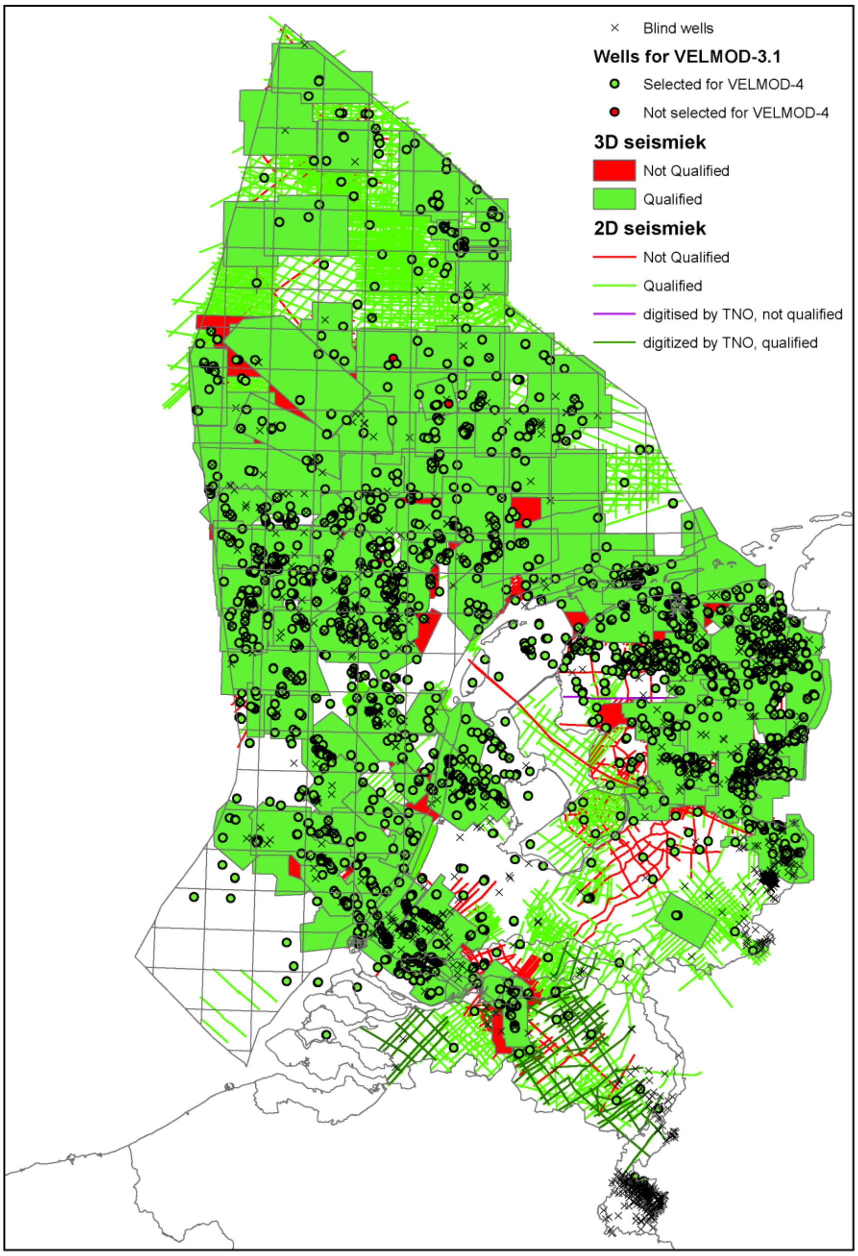

Figure 1: Wells and seismic surveys, containing velocity data which have been used in VELMOD-4

2.4 Twt horizon data

For this project time grids for the 7 main horizons (Figure 3) have been made by combining the time grids that have been produced for the DGM-deep V3 (offshore, 2012) and -V4 (onshore, 2012) models (see https://www.nlog.nl/en/geological-maps). In the meantime a new on- and offshore model DGM-deep V5 has been finalized in 2019, but was not used in this project, because the whole process was based on the combined DGM-deep V3 and V4 time grids.

2.5 Data quality control and normalization

1) Seismic velocity data:

For each seismic 3D velocity volume a geostatistical QC study is carried out. Velocity anomalies corresponding to acquisition and processing artefacts (footprint, random noise, picking effects, outliers…) are highlighted and, if necessary, corrected by 3D Factorial Kriging technique. M-GS (Moving-GeoStatistics®) models are used to filter out non-stationary artefacts. As it leads to getting spatially coherent seismic velocity volumes, this geostatistical QC and filtering step is essential for ensuring consistent results for the merge process.

For each 2D velocity data set a geostatistical QC study is carried out. In particular each velocity sample is qualified by a spatial Coherency Index (CI). Anomalous velocity samples, with a high CI, are removed from the data base before entering the merge process. A cross-coherency analysis of the seismic velocity data sets is realized. Anomalous velocity data sets are reported

Each horizon is divided into a trend and a residual part. The residuals part is inspected in order to track potential picking artefacts. If there are any, the artefacts are filtered out by factorial kriging technique.

2) Well velocity data:

All raw well velocity data was subject to quality control in terms of (velocity) data type and accompanying data unit. Per well the dataset was checked on completeness. Wells without stratigraphic information were discarded. Wells without deviation data were considered to be vertical (in general a correct assumption, because per well the dataset was checked on completeness: see above). The aggregated stratigraphic data was QC-ed on completeness and updated when necessary.

All well velocity datasets were normalized to TVDSS (m), time (s), velocity (m/s). Duplicate depth/time values were removed. Datasets wit depth and/or time reversals (mainly checkshot data) were discarded from analysis. All normalized velocity data was stored in a database together with metadata, deviation data and stratigraphic data from the wells.

The well data processing and QC is summarized in Figure 2.

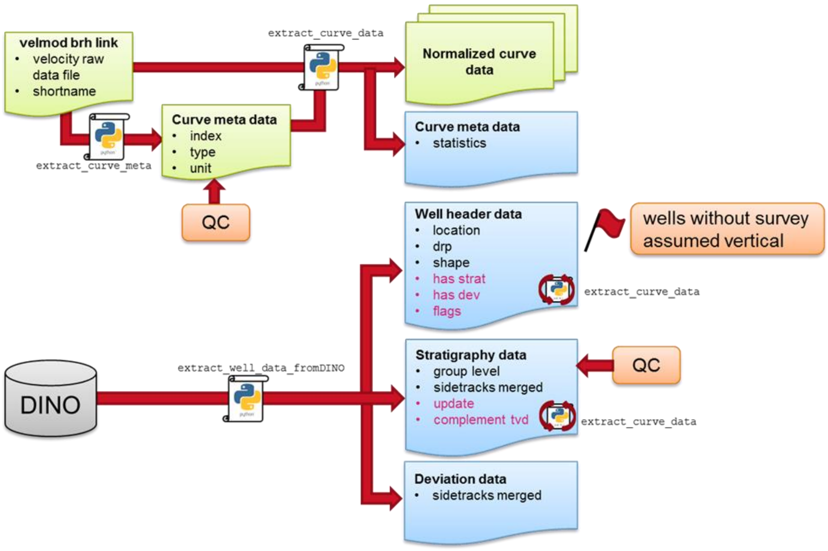

Figure 2 Overview of well data processing workflow

3 VELMOD-4 velocity model

3.1 Use of the seismic velocities

Seismic velocities are used to build the VELMOD-4 velocity model. They contribute to decrease depth estimation errors, especially in areas of poor wells density.

3.2 Layer cake model

Within this project a 'layer cake' type velocity model is used. For seven stratigraphic layers the velocity is modelled: NU, NM+NL, CK, KN, S+AT, RN+RB and ZE (Figure 3). Only the Zechstein Group (layer 7 in Figure 3) was modelled with a different method (see 3.5).

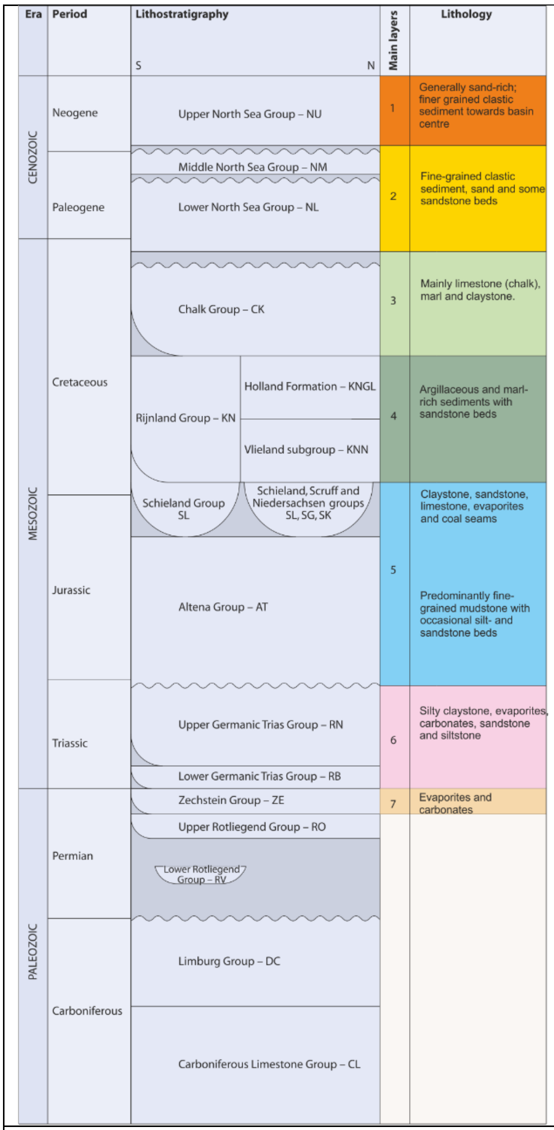

Figure 3 Layer cake model of VELMOD-4 based on lithostratigraphy after Van Adrichem Boogaert and Kouwe (1993-1997)

Except the layer of the Zechstein Group (layer 7 in Figure 3) all layers have been subject to considerable compaction due to sediment loading during burial phases. This compaction resulted in an increase of compressional wave velocity of layer sediments with burial depth.

For the compacting layers, we adopt model velocities that increase linearly with depth. A velocity model of this type is completely described by:

$$V = V_0 + k\, Z$$

Where V [m/s] is the instantaneous velocity, V_0 [m/s] the velocity at surface (depth=0 m), k [m/s/m] the velocity-depth gradient and Z [m] the depth.

3.3 Model parameterization

The workflow used during the project has been displayed in Figure 4. In the following the five main steps of this workflow will be described.

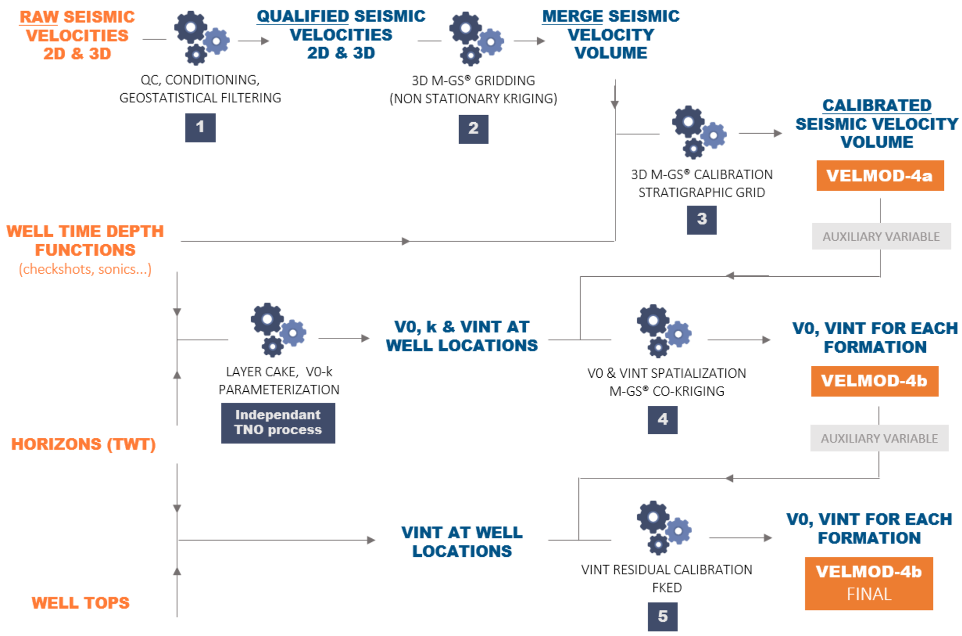

Figure 4 Workflow used during VELMOD-4 project. The M-GS® technology is a technology developed by ESTIMAGES, dedicated to the local optimization of variographic parameters.

3.3.1 *STEP 1 – Seismic velocity conditioning*

The seismic velocity datasets are qualified through a geostatistical QC process (see also 2.4). If necessary, acquisition and processing artefacts are filtered out by 3D factorial kriging.

RMS vs. DIX vs. average velocities

The seismic velocity is usually expressed in 3 different forms: RMS velocity (quadratic mean of instantaneous velocity - the most frequently received form coming from seismic processing), average velocity (arithmetic mean of instantaneous velocity) and an interval velocity calculated with DIX formula from rms velocities (similar to instantaneous velocity when the computation support tends to 0).

Conversion can be done anytime between one and the others forms. All the velocities that we handle in the project are vertical velocities. The raw DIX velocities are the velocities computed from the raw RMS velocities using the DIX formula. No other treatment was performed. DIX velocities are interesting because they can be compared to instantaneous velocities.

Spatial analysis and filtering

If there are any, artefacts are filtered out by factorial kriging. Factorial kriging is a variogram-based filtering technique. It relies on a simple additive model where the spatial variable under study (such as the seismic velocity) is modeled by a random function V(x), which is parted in terms of independent factors:

$V(x) = V1(x) + V2(x) + \dots$

Noise attenuation issues can be easily handled in the framework of this model, as far as the noise can be considered independent of the signal:

$V(x) = V_{NOISE}(x) + V_{SIGNAL}(x)$

$\Gamma V(hx) = \Gamma_{NOISE}(hx) + \Gamma_{SIGNAL}(hx)$, where Γ refers to variogram

In such a way, factorial kriging, by estimating $V_{SIGNAL}(x)$, allows to filter out the noisy component of a data set. More information about each factorial kriging run, including parameters description, can be found in in each seismic velocity QC report (Deliverable 2).

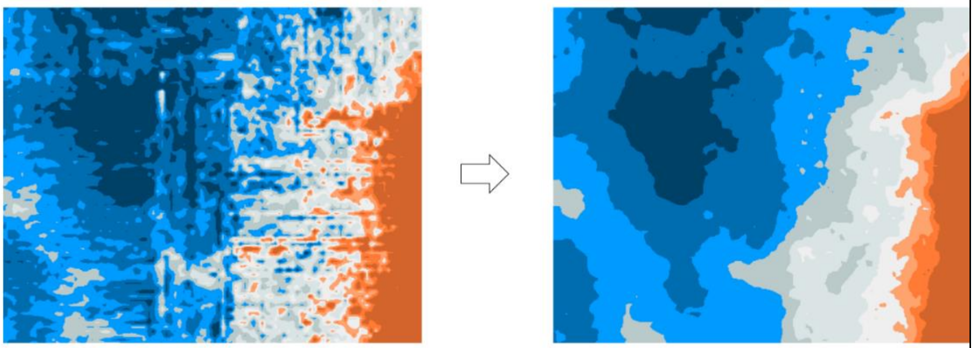

Figure 5: QC and conditioning of the seismic velocities by using 3D geostatistical filtering

More precisely, regarding the methodology for 3D seismic velocity data sets, we compute a velocity trend from the RMS velocities. Removing that trend from the raw velocities, we obtain stationary velocity residuals. We then perform a structural analysis of the residuals by computing an experimental variogram. The experimental variogram is interpreted in terms of geological and artefact structures. Based on that interpretation a variogram model is fitted to the experimental variogram. Artefact structures are filtered out by factorial kriging. Filtered velocity residuals are finally added back to the velocity trend, leading to a filtered velocity volume.

The QC step is done independently for each velocity volume (Figure 5). The aim of the filtering step is to have a clean input for the calibration step (see 3.3.3).

3.3.2 *STEP 2 – Merge of the seismic velocity data sets*

The seismic velocity data sets are merged in 3D by a local least square polynomial technique adapted to the local density of the seismic information. The algorithm ensures a stable gridding while preserving as much as possible short scale geological heterogeneities (Figure 6). The gridding process is driven by the horizons.

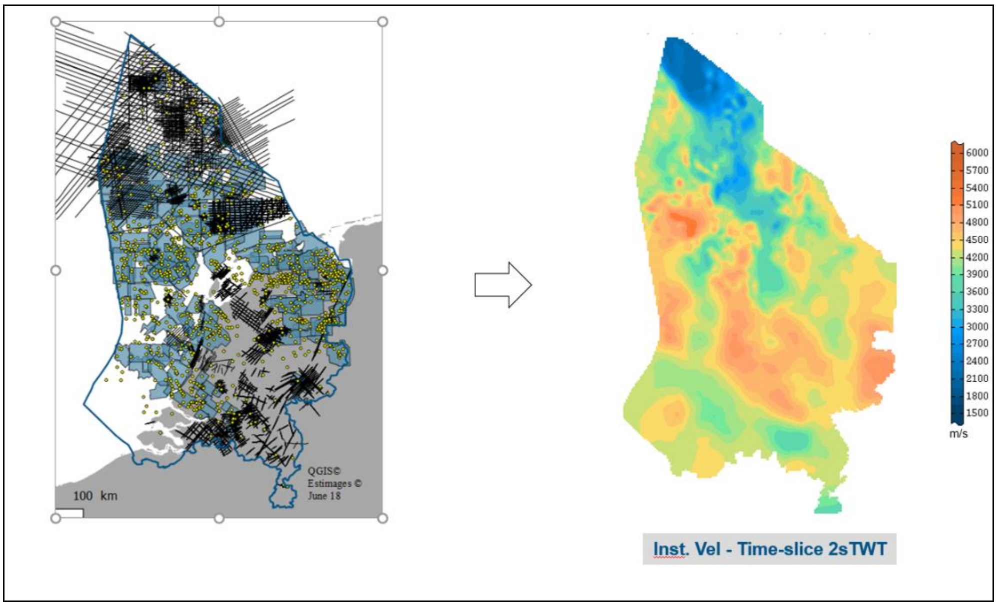

Figure 6: 3D merge of the seismic velocities

3.3.3 *STEP 3 – 3D calibration of the merge seismic velocity volume*

The merge velocity volume is transformed into a depth volume (vertical integration of the seismic velocities). The seismic depth is extracted at the well locations. The depth residuals are computed. They correspond to the difference between the seismic depth and the well's True Vertical Depth. The following step of the workflow consists in the analysis of the spatial correlation of these depth residuals. We have performed a 3D variographic analysis of that variable, and come to a variographic model composed of 2 structures: a long-scale structure (mainly related to the vertical anisotropy effect) and a short-scale structure corresponding to the difference of spatial resolution between well and seismic data (Figures 7 and 8).

Based on the above determined variographic parameters, the seismic velocities are calibrated to the well velocities through a 3D factorial kriging with external drift process. As the kriging process is made on a stratigraphic grid, it leads to a 3D consistent velocity model with minimized errors far from the wells.

The short scale structure (S) is filtered out during the calibration. It means that the very short scale variations observed at the wells are not reproduced in the 3D model. It is impossible to have a spatial control of these variations far from the wells.

Results STEP 3: A regional 3D velocity model VELMOD-4a as merged velocity cube (VAVG, VINST), a calibrated velocity cube (VAVG, VINST) and a depth uncertainty cube (all cubes: 1000m x 1000m x 40mstwt).

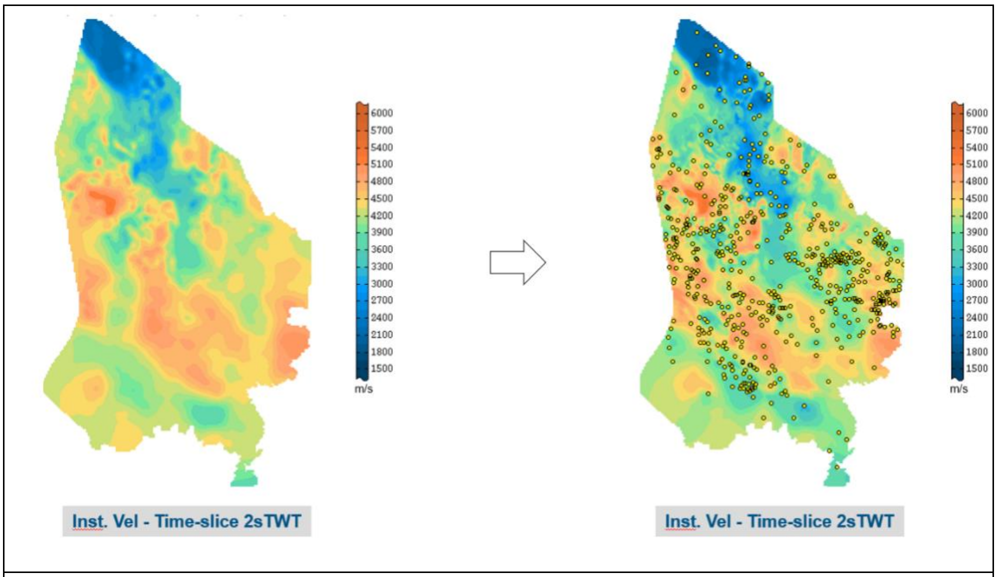

Figure 7: 3D calibration of the seismic velocities

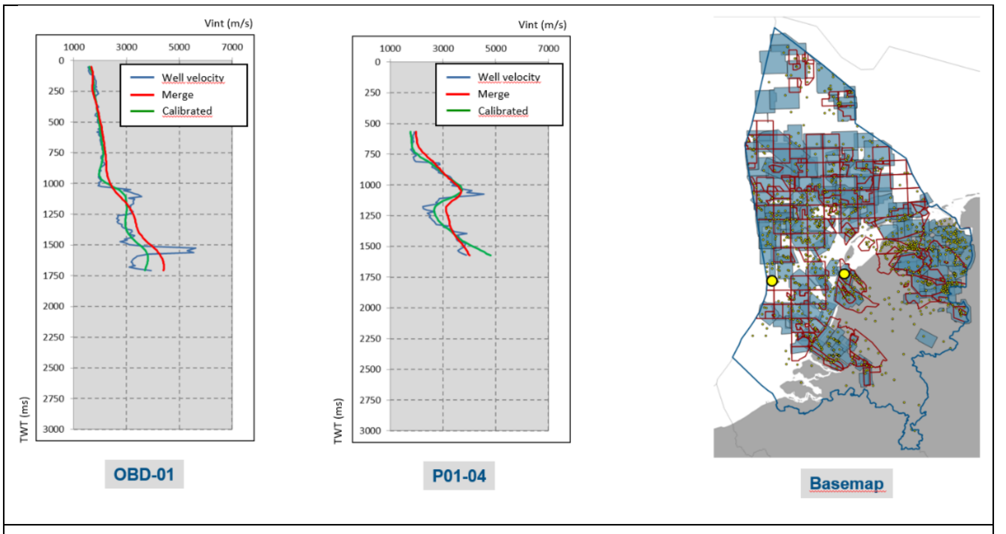

Figure 8: 3D calibration of seismic velocities

3.3.4 *STEP 4 – Layer cake model*

During the VELMOD-3.1 project the “layer cake” model parameters (such as the k-values) have been determined for the main Cenozoic and Mesozoic layers, except for the Jurassic layer (S+AT), whereof the parameters were determined during this VELMOD-4 project (Table 2 and Appendix A).

Layer	Strat	# Boreholes	k(s-1)
1	NU	660	0.436
2	NM+NL	757	0.235
3	CK	1160	0.889
4	KN	1225	0.536
5	S+AT	535	0.379
6	RN+RB	817	0.374

Table 2 Used model parameters (k-values) for 6 main Cenozoic and Mesozoic layers.

For the Zechstein layer (ZE) a provisional grid of interval velocities is built based on the travel times from seismic interpretation and a correlation between the Vint and ΔT-data in wells (Appendix A).

For each layer, Vint and V_0 observed on the wells (used in VELMOD-3.1) are kriged with the use of VELMOD-4a Vint as an external drift (Figure 9). The model is composed of a geological structure and of a nugget. The nugget is filtered out. Optimal geostatistical parameters are determined for each layer (Tables 3 and 4).

Results STEP 4:V0 and Vint maps for each layer (Appendix B and C).

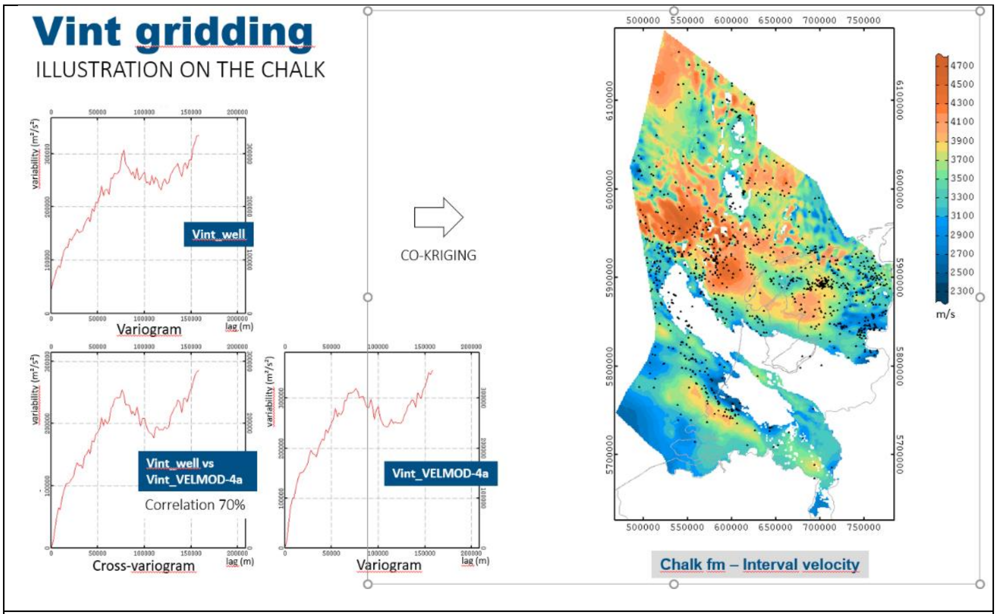

Figure 9: Vint gridding, illustration on the Chalk Group

Strat.layer	Geology	Artefact
NU	Exponential 120km (72%)	Nugget (28%)
NM+NL	Exponential 150km (67%)	Nugget (33%)
CK	Exponential 140km (82%)	Nugget (18%)
KN	Exponential 90km (83%)	Nugget (17%)
S+AT	Exponential 100km (81%)	Nugget (19%)
RN+RB	Exponential 150km (78%)	Nugget (22%)

Table 3 Variographic parameters for Vint in step 4 (ranges expressed in km).

Strat.layer	Geology	Artefact
NU	Exponential 50km (58%)	Nugget (42%)
NM+NL	Exponential 100km (44%)	Nugget (56%)
CK	Exponential 140km (63%)	Nugget (37%)
KN	Exponential 120km (46%)	Nugget (54%)
S+AT	Spherical 75km (68%)	Nugget (32%)
RN+RB	Spherical 100km (70%)	Nugget (30%)

Table 4 Variographic parameters for V0 in step 4 (ranges expressed in km).

3.3.5 *STEP 5 – Final residual calibration*

Finally, in order to get a model more in accordance with the well tops from the wells used in VELMOD-3.1, a residual calibration was carried out (Figure 10). Depths predicted with the previous model (STEP 4) were compared with the well tops. A variographic analysis of the mis-ties was performed (Tables 5 and 6). A long scale structure was observed for all the layers, thus authorizing a long-scale calibration. Short-scale structure was filtered out during that calibration step as it is related to local seismic processing issues or non-spatially correlated wells errors.

Results STEP 5: V0 and Vint maps for each layer (Appendix B and C) and depth maps for each layer (Appendix D), which have been produced by using the Vint maps.

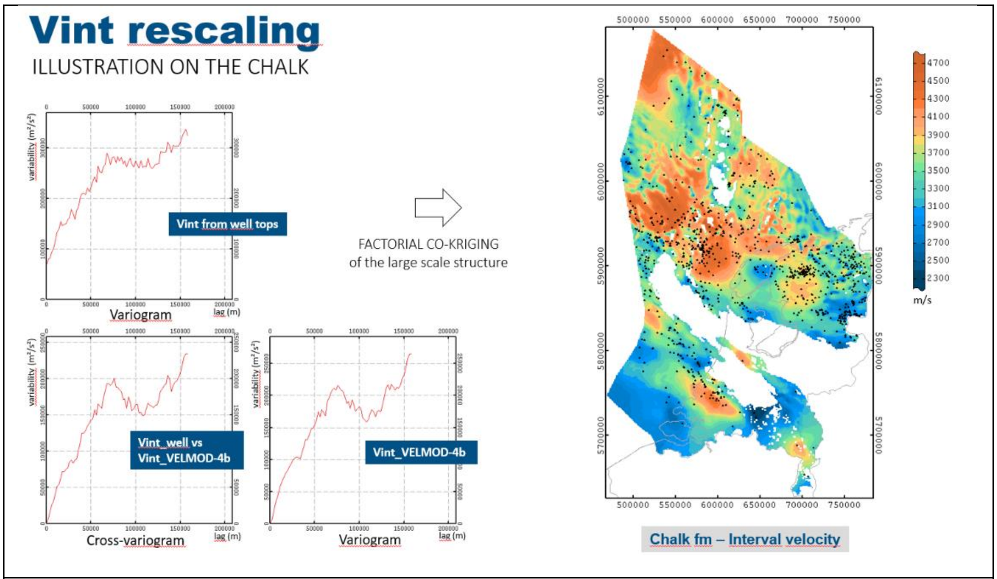

Figure 10: Vint rescaling, illustration on the Chalk Group

Strat.layer	Geology	Artefact
NU	Exponential 120km (71%)	Nugget (29%)
NM+NL	Exponential 150km (55%)	Nugget (45%)
CK	Spherical 80km (74%)	Nugget (26%)
KN	Exponential 70km (53%)	Nugget (47%)
S+AT	Exponential 120km (79%)	Nugget (21%)
RN+RB	Exponential 100km (65%)	Nugget (35%)

Table 5 Variographic parameters for Vint in step 5 (ranges expressed in km)

Strat.layer	Geology	Artefact
NU	Exponential 50km (68%)	Nugget (32%)
NM+NL	Exponential 150km (63%)	Nugget (37%)
CK	Spherical 150km (50%)	Nugget (50%)
KN	Exponential 20km (63%)	Nugget (37%)
S+AT	Exponential 100km (67%)	Nugget (33%)
RN+RB	Exponential 100km (72%)	Nugget (28%)

Table 6 Variographic parameters for V0 in step 5 (ranges expressed in km)

N.B. Tables 3-6: The variogram model is based on the interpretation of the experimental variogram. The variogram model that better fits the experimental variogram is not the same for each layer. The difference of structure ("geological content") between each layer could be responsible for the difference of the experimental variogram interpretation. Further for some cases strong nugget effects have been observed (up to 56%). In the case of nested structures (nugget + structure spatially correlated), both structures will be taken into account, so we can still speak of reliable correlations.

4 Results

Resulting regional Vint and V0 distribution grids for all 7 layers have been created for VELMOD-4b-s4 and -4b-s5; these maps have been compared with the corresponding maps for VELMOD-3.1 (see Appendix B, resp. Appendix C).

Depth maps for all layers have been computed for VELMOD-4b-s5 (Appendix D middle map) by using its VINT-maps. These depth maps could be compared with the depth maps created for VELMOD-3.1 (Appendix D left map). For each layer a depth-difference map has been prepared by subtracting $depth_{VELMOD\text{-}3.1}$ from $depth_{VELMOD\text{-}4b\text{-}s5}$ (Appendix D right map).

Appendix B	Vint maps (VELMOD-3.1, VELMOD-4b-s4 and VELMOD-4b-s5) of NU, NM+NL, CK, KN, S+AT, RN+RB and ZE. For VELMOD-3.1 no Vint map was produced for S+AT layer and for VELMOD-4b-s4 no Vint map was produced for ZE layer.
Appendix C	V0 maps (VELMOD-3.1, VELMOD-4b-s4 and VELMOD-4b-s5) of NU, NM+NL, CK, KN, S+AT and RN+RB. For VELMOD-3.1 no V0 map was produced for S+AT layer.
Appendix D	Depth maps (VELMOD-3.1 and VELMOD-4b-s5) and the depth difference map (VELMOD-4b-s5 minus VELMOD-3.1) of NU, NM+NL, CK, KN, S+AT, RN+RB and ZE.

5 Evaluation

For the evaluation of the models a so-called ‘blind’ well dataset has been used. This blind well dataset has been compiled of all existing wells with the following criteria:

- Wells that are used in the construction of the DGM-deep V3 (offshore) and -V4 (onshore) models and are located in the on- and offshore of the Netherlands (see https://www.nlog.nl/en/geological-maps).
- Wells that are NOT used in the construction of the VELMOD-3.1 and the VELMOD-4 models
- Wells that are NOT in the Schoonebeek area
- Layer specific criteria
    - Wells that are within the extent of a specific layer
    - Wells that fully penetrate a specific layer
    - Wells that do NOT have a thickness difference >250m in comparison with the model

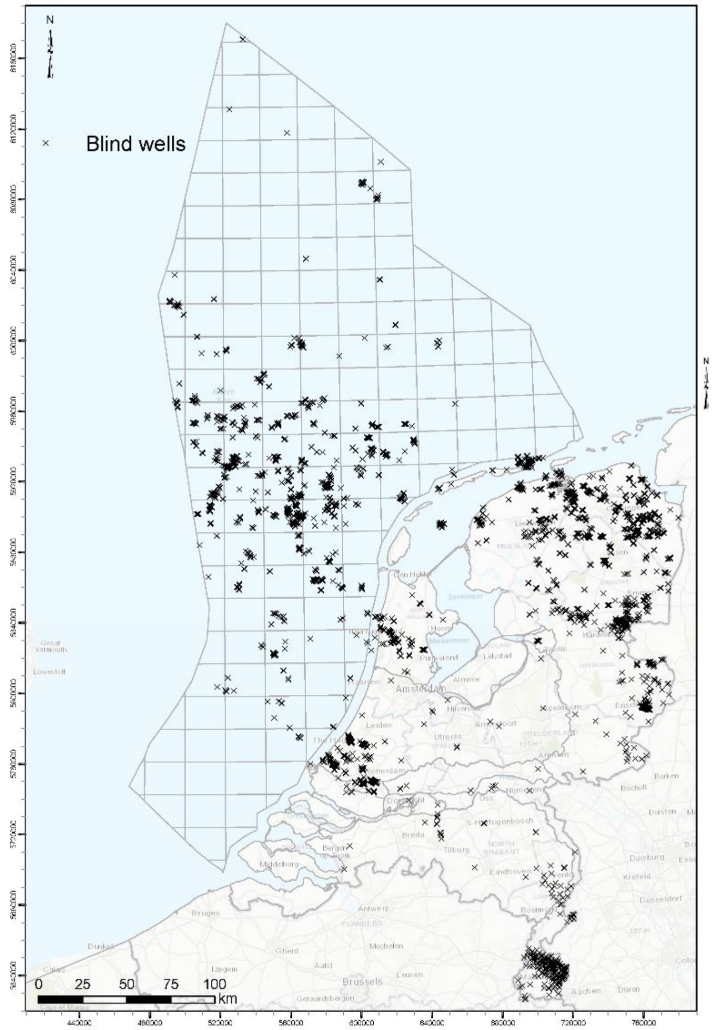

Figure 11: Dataset of blind wells

A comparison of the residual thickness errors for both VELMOD-3.1 and VELMOD-4b-s5 has been performed with a dataset of 2333 ‘blind’ wells (Figure 11). In the dataset of blind wells has, understandably, omitted a dense cluster of wells for the Schoonebeek area. Also it was tested to leave out another dense cluster of wells: the South Limburg coal wells. Mainly these wells are not containing Mesozoic layers, but also for the Cenozoic layers the blind well test results didn’t change.

The corresponding graphs with depth and thickness differences between the VELMOD-3.1 and VELMOD-4b-s5 models have been displayed in Appendix E.

The standard deviations of the depth error are retrieved from these graphs (Table 7). From this table we could conclude that the thickness prediction is better for all layers in the VELMOD-4b-s5 model in comparison with VELMOD-3.1 model. Especially for the NM+NL, CK and ZE layers it is significant better (>20%).

Strat. layer	**VELMOD-3.1**	**VELMOD-4b-s5**	**Prediction improvement**	
NU	27	25	+7%	marginal better
NM+NL	36	25	+30%	Significant better
CK	42	31	+26%	Significant better
KN	32	27	+16%	better
S+AT	28	23	+18%	better
RN+RB	38	36	+5%	marginal better
ZE	140	100	+40%	Significant better

Table 7: Standard deviation of the depth error (m)

It could be concluded that the results after time-depth conversion by using the VELMOD-4b-s5 is much better than VELMOD-3.1 (and VELMOD-4b-s4). During step 4, the model is calibrated to the well tops data (regional calibration). After step 4, there are still remaining mis-ties at well tops. Those remaining mis-ties are corrected during step 5 (low frequency correction).

6 Deliverables

1. Input seismic velocities > raw seismic velocity data file (standardized ASCII format) for each seismic velocity data set (2D and 3D).

2. Geostatistical QC report (pdf) for each seismic velocity data set (2D and 3D).

3. Regional velocity model VELMOD-4a:
   a) merge velocity cube (1000m x 1000m x 40mstwt) – VAVG, VINST
   b) calibrated velocity cube (1000m x 1000m x 40mstwt) – VAVG, VINST
   c) depth uncertainty cube (1000m x 1000m x 40mstwt)

4. Regional velocity model VELMOD-4b:
   STEP 4:
   a) VINT grids (1km x 1km) for each geological layer (NU, NM+NL, CK, KN, S+AT, RN+RB and ZE) : see the maps in Appendix B.
   b) V0 grids (1km x 1km) for each geological layer (NU, NM+NL, CK, KN, S+AT, RN+RB) : see the maps in Appendix C.
   STEP 5:
   a) VINT grids (1km x 1km) for each geological layer (NU, NM+NL, CK, KN, S+AT, RN+RB and ZE) : see the maps in Appendix B.
   b) V0 grids (1km x 1km) for each geological layer (NU, NM+NL, CK, KN, S+AT, RN+RB) : see the maps in Appendix C.
   c) Depth converted surfaces (250m x 250m) for the base of each geological layer (NU, NM+NL, CK, KN, S+AT, RN+RB and ZE) : see the maps in Appendix D.

5. Final report 'VELMOD-4': description of data, models and parameters used for building the regional velocity models VELMOD-4a and -4b covering the onshore and the offshore of the Netherlands. This report includes the following 5 appendices:.

A Determination model-parameters
B Vint maps (VELMOD-3.1, VELMOD-4b-s4 and VELMOD-4b-s5)
C V0 maps (VELMOD-3.1, VELMOD-4b-s4 and VELMOD-4b-s5)
D Depth maps (VELMOD-3.1 and VELMOD-4b-s5) and depth difference maps
E Comparison between VELMOD-3.1 and VELMOD-4b-s5 models

7 Discussion and recommendations

7.1 Reliability

Within VELMOD-4 seismic velocities are integrated and a residual calibration is performed to get results more consistent with the well tops spatial distribution. The prediction capacity of the model is reinforced for all the layers.

7.2 More seismic velocity data

From the seismic coverage map (Figure 1) it could be concluded that there are still several ‘white’ areas without seismic velocity data. For a next update of VELMOD it will be good to cover also these areas. The availability of more advanced velocity information, like velocities coming from tomography in pre-stack imaging workflows, could improve the current model.

7.3 Spatial velocity distributions

Limited effort has been given to the modelling of the spatial velocity distributions. For all layers one single k was derived for the complete regional dataset of the layer, except for the Zechstein Group. In several distributions of the Vint (for example for the Chalk Group Appendix A-Figure 4) a bimodal distribution of Vint could be clearly seen and this questions the validity of the use of one single k.

7.4 Geological aspects

The primary goal of VELMOD-4 was the construction of a regional velocity model for the use of time-depth conversion of regional seismic interpreted horizons. However, the V_0-distributions for a number of layers can be interpreted in geological terms of for example: overpressured pore fluids, burial anomalies or variations in lithology/reservoir properties. The spatial interpolation of the velocity data can be improved by incorporating regional knowledge on overpressured areas and areas subject to phases with major uplift.

8 References

Van Adrichem Boogaert, H.A. & Kouwe, W.F.P., 1993-1997 (eds). Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA, Mededelingen Rijks Geologische Dienst, nr. 50.
Van Dalfsen, W., van Gessel, S.F. & Doornenbal, J.C., 2007. VELMOD 2 Joint Industry Project. TNO report 2007-U-R1272C.
VELMOD3.1, 2017. Final report: https://www.nlog.nl/VELMOD-31

9 Signature

Name of the principal
Nederlandse Aardolie Maatschappij

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Signature:

ValidSigned by Hans Doornenba
on 2022-01-21 14:26:51

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on 2022-01-20 14:58:33

Drs. D. Maljers
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A Determination model-parameters

Appendix A: Determination model-parameters

For the creation of the VELMOD-3.1 a set of 1642 wells has been used. For almost every well multiple sources of velocity data were available. For each interval in a borehole the most optimal velocity source was used depending on coverage of the interval depth range and the quality of the velocity data. For this reason for one borehole multiple velocity sources could be used to compile the velocity curve for the whole depth range of the borehole.

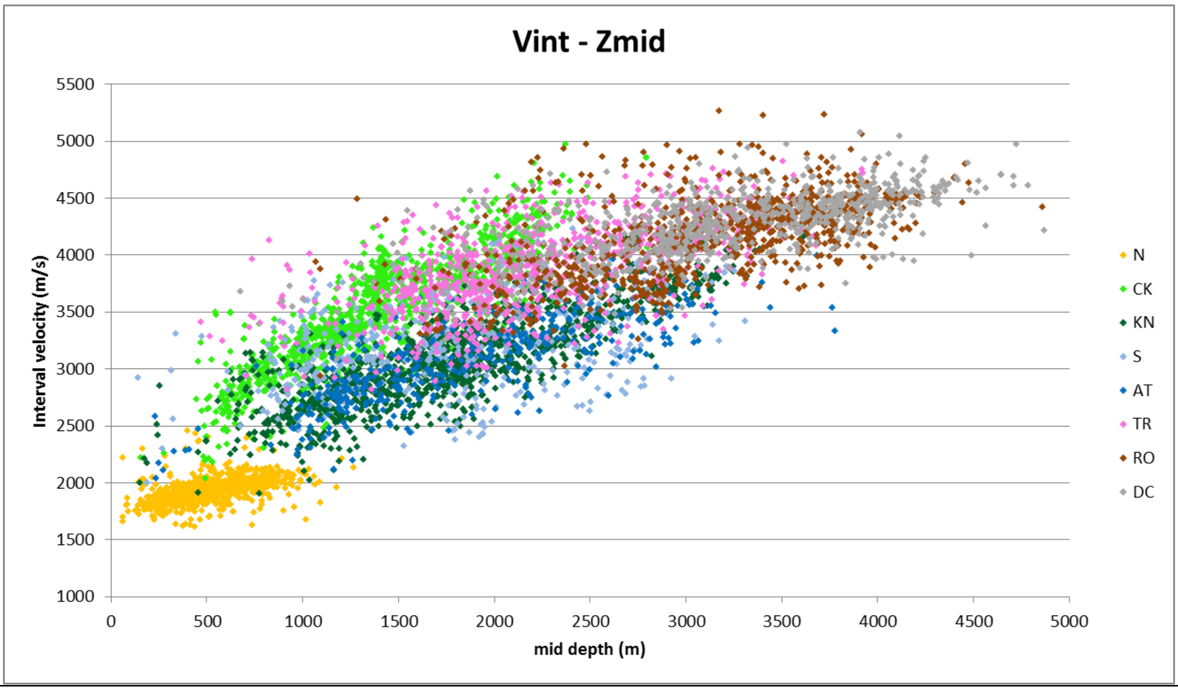


Figure 1 Interval velocity V_{int} vs mid depth Z_{mid} for each main lithostratigraphic group

The V_0 and k model parameters were determined according to the V_{int} - Z_{mid} method applied per statigraphic layer. This method approximates the regional velocity-depth gradient, as well as a regional normalized velocity. In figure 1 all interval velocity values (V_{int}) for all lithostratigraphic groups except Zechstein Group have been plotted against the mid depth (Z_{mid}). From this figure could be clearly concluded that there is a general increase of velocity with depth but also that the values per interval could be grouped or characterised by a certain dip (k value) and a certain V0 value: see for example the clear differences in the North Sea Supergroup values (yellow), Chalk Group (light green), Rijnland Group (dark green) and most of the other groups.

Velocity curves which cover less than 25% of the drilled stratigraphic interval were discarded from the regression analysis. Also velocity curves with an interval velocity lower than 1600 m/s and higher than 6500 m/s were discarded from analysis. If the remaining dataset contained multiple velocity curves for a single well, the velocity curve with the smallest deviation with respect to the global V_{int} - Z_{mid} regression line was marked as the preferred velocity curve. After manual QC the “preferred” label was in some occasions changed to a different velocity curve. The global regression line is based on a linear least-square regression of V_{int} on Z_{mid}.

Table 1 and Figures 2 to 7 show the results of the V_0 and k parameterization.

Layer	Strat	# Boreholes	# velocity curves	k(s-1)	V0(m/s)	R^2
1	NU	660	1506	0.436	1761	0.32
2	NM+NL	757	1763	0.235	1779	0.32
3	CK	1160	2556	0.889	2257	0.74
4	KN	1225	2710	0.536	2133	0.69
5	S+AT	535	1314	0.379	2441	0.35
6	RN+RB	817	1792	0.374	3046	0.38

Table 1 V_{int} - Z_{mid} regression data for the main layers of VELMOD-4, except ZE.

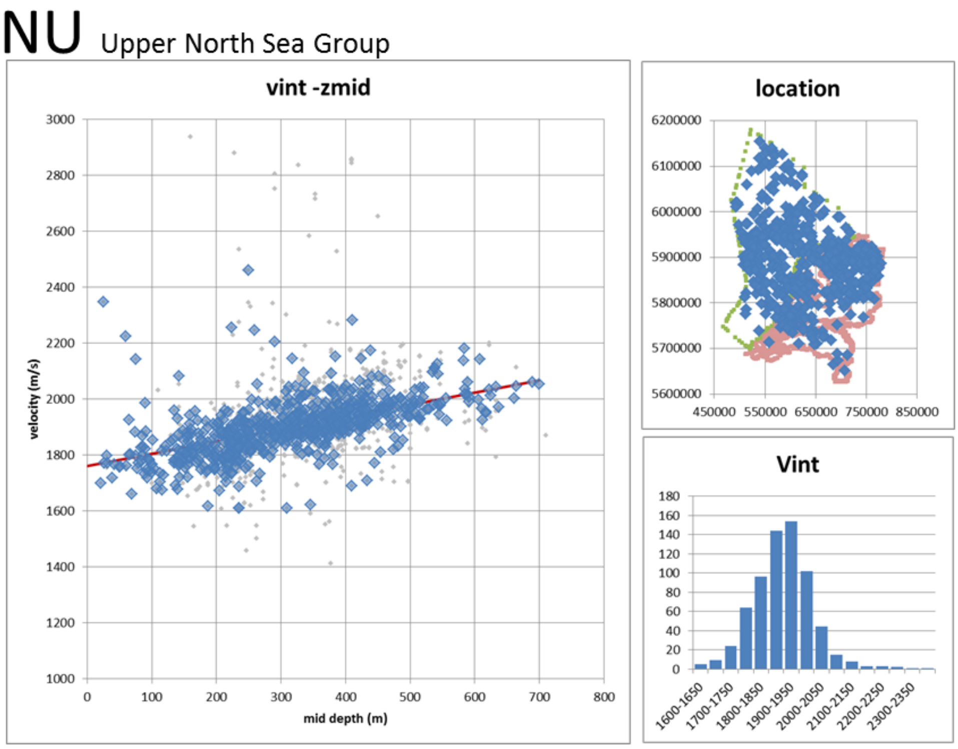


Figure 2 Interval velocity vs mid-depth (left; grey points are discarded from regression analysis), distribution (lower right) and location (upper right) of interval velocities of the Upper North Sea Group

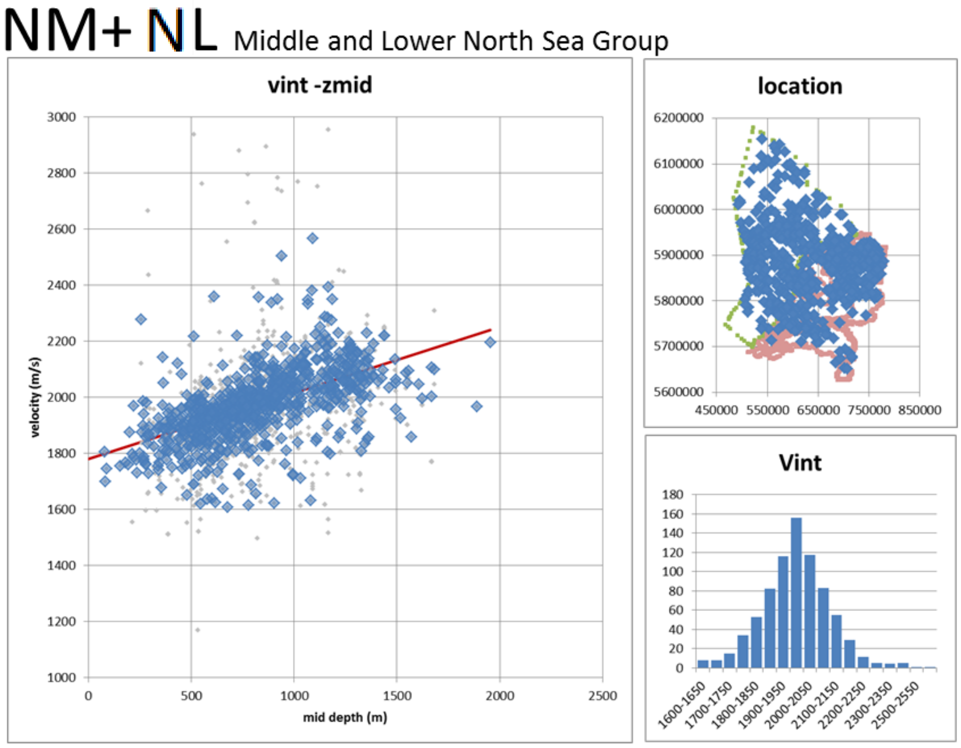


Figure 3 *Interval velocity vs mid-depth (left; grey points are discarded from regression analysis), distribution (lower right) and location (upper right) of interval velocities of the Middle and Lower North Sea groups*

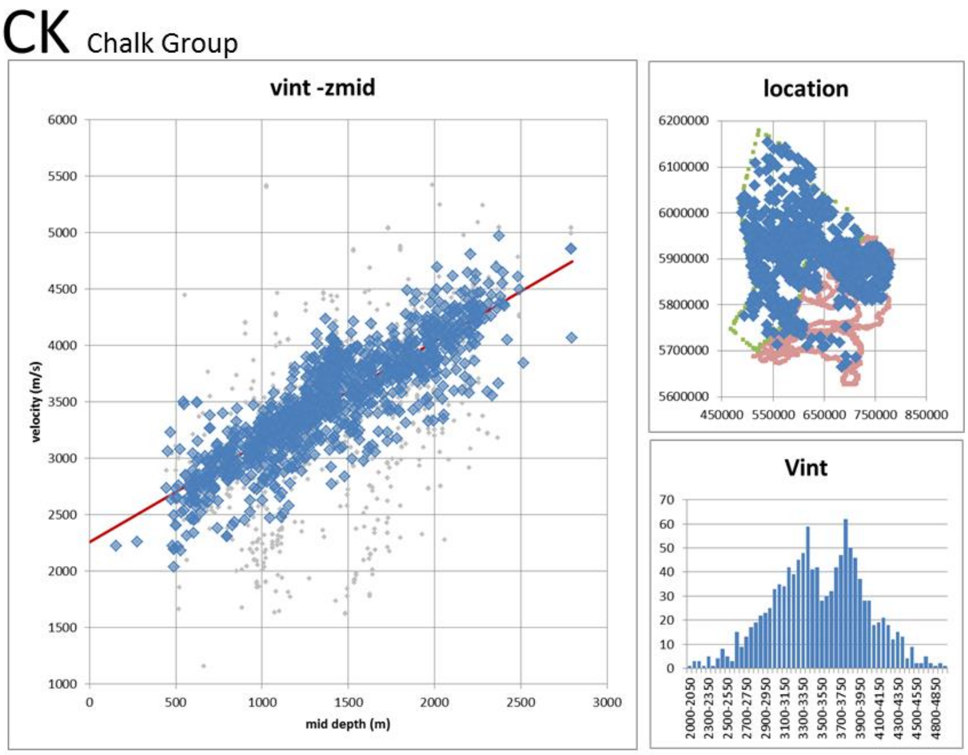


Figure 4 *Interval velocity vs mid-depth (left; grey points are discarded from regression analysis), distribution (lower right) and location (upper right) of interval velocities of the Chalk Group*

KN Rijnland Group

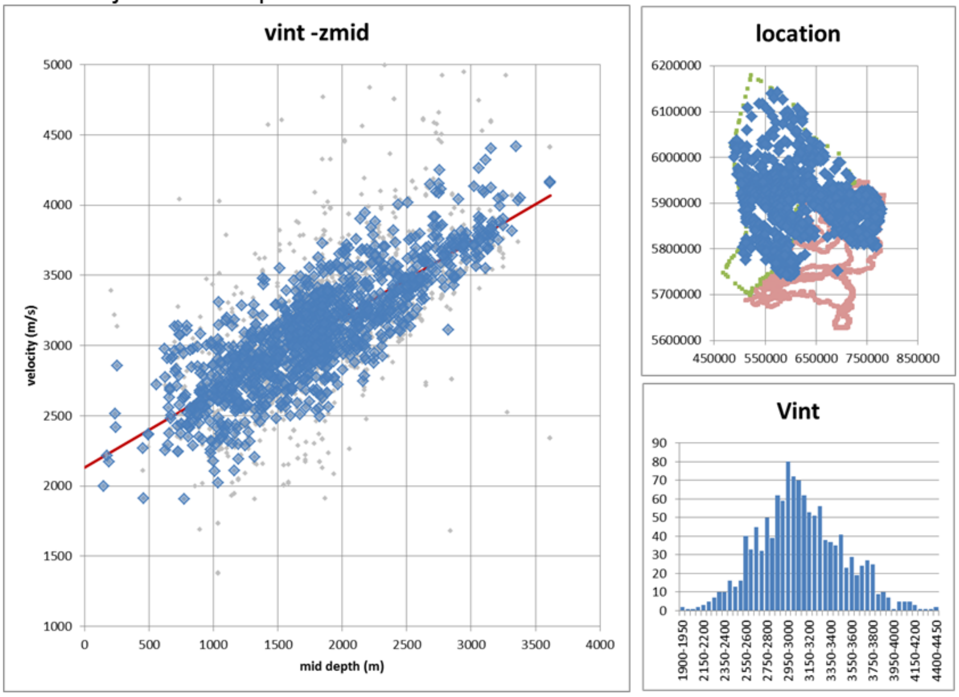


Figure 5 *Interval velocity vs mid-depth (left; grey points are discarded from regression analysis), distribution (lower right) and location (upper right) of interval velocities of the Rijnland Group*

S+AT Upper Jurassic groups + Altena Group

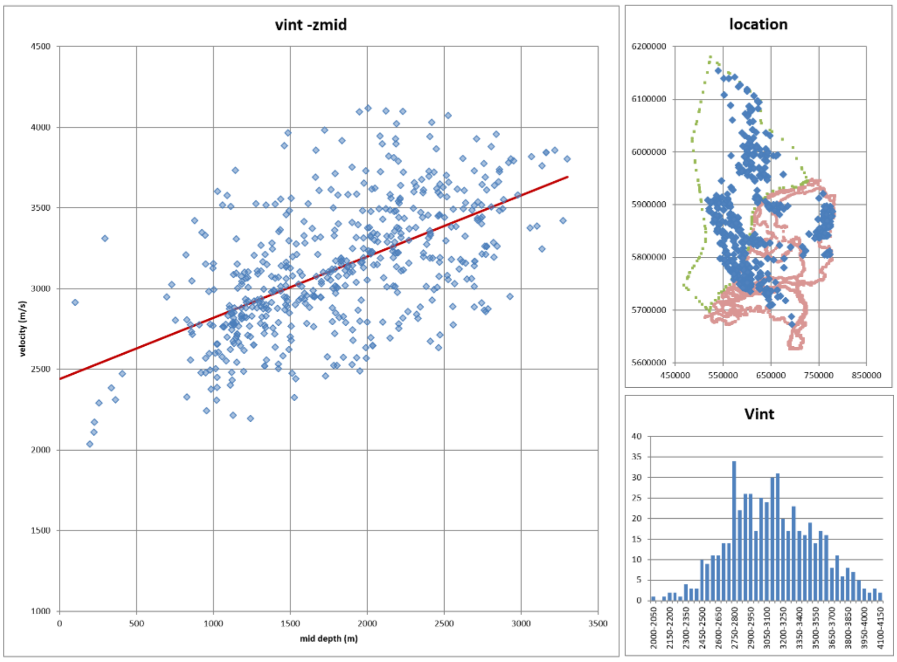


Figure 6 *Interval velocity vs mid-depth (left; grey points are discarded from regression analysis), distribution (lower right) and location (upper right) of interval velocities of the Jurassic (Upper Jurassic groups + Altena Group).*

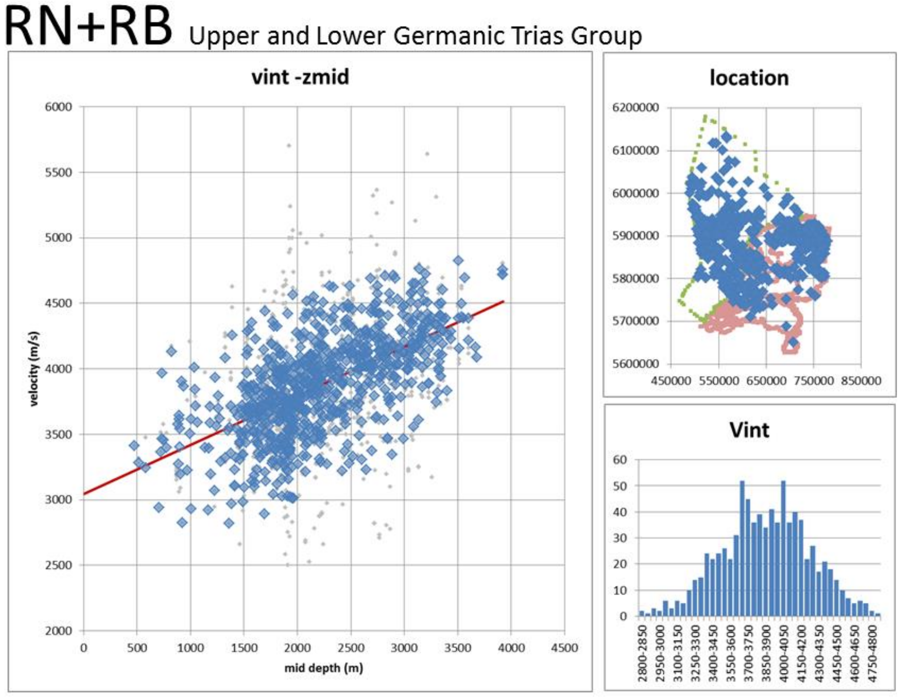


Figure 7 Interval velocity vs mid-depth (left; grey points are discarded from regression analysis), distribution (lower right) and location (upper right) of interval velocities of the Upper and Lower Germanic Trias groups.

Zechstein Group

The lithology of the Zechstein Group in general consist of anhydrite, halite, and/or carbonate. The lithological composition of this layer is the most dominant factor for the interval velocity. The influence of compaction on the interval velocity is considered very minor.

The Zechstein interval velocity is modelled based on velocity - thickness (or ΔT) relation from wells (Figure 8). In general, the Zechstein layer with limited thickness show the relative high abundance of high velocity carbonate layers (Kombrink et al, 2012). For the Zechstein layer a provisional grid of interval velocities is built based on the travel times from seismic interpretation and a correlation between the Vint and ΔT-data in wells:

Vintprov = 4500 m/s if $\Delta TZE \geq 170$ ms

Vintprov = 4950 – 450 · cos(ΔTZE + 10) if $\Delta TZE < 170$ ms

The final Vint-grid was obtained by kriging the difference (Vintprov – Vintborehole) at borehole locations, and by subtracting the kriged differences from the Vintprov-values. In this step the minimum Vint-value in the final velocity grid was constrained to 4400 m/s.

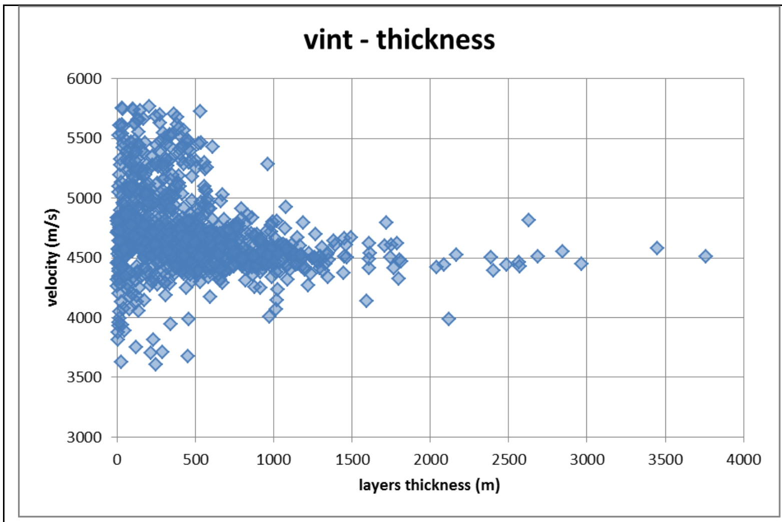


Figure 8

Thickness versus interval velocity of the Zechstein layer.

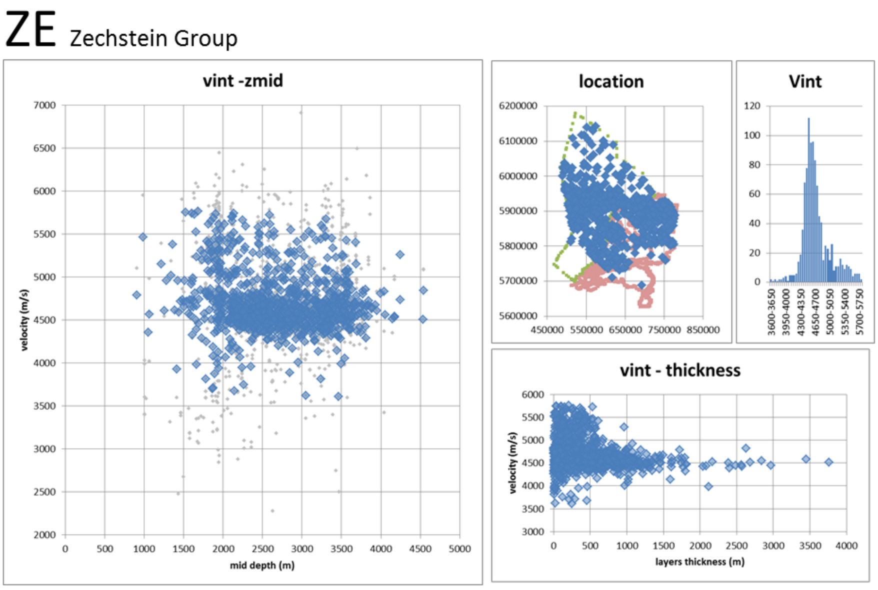


Figure 9

Interval velocity vs mid-depth (left; grey points are duplicates), distribution & location (upper right) of interval velocities and interval velocity vs thickness (lower right) of the Zechstein Group.

On the basis of the global parameterization of k, the local V_0 at the well-location is estimated by 2 different methods:

1) "*Local V0_basefit*" calibration based on the total vertical travel time ΔT of the sonic data (Japsen, 1993) using the following calibration formula:

$$V_0 = \frac{k\,(Z_b - Z_t\, e^{k\Delta T})}{e^{k\Delta T} - 1}$$

2) "*Local V0_rms*" calibration based on the least square error of all velocity data points per well with regard to the velocities derived from the V0-k model.

An example of the difference between the two methods is visualized in Figure 10. Although the *Local V0_basefit* calibration results in a zero depth error at the base of the stratigraphic interval, the *Local V0_rms* calibration gives the smallest average depth error over the complete stratigraphic interval.

VELMOD-3 is a large scale regional velocity model and will primary be used for seismic time-depth conversion of main layers, therefore V_0 results based on the *Local V0_basefit* calibration were used for the construction of regional V_0 distribution maps. Results of both methods are reported (see Appendix B of VELMOD3.1, 2017).

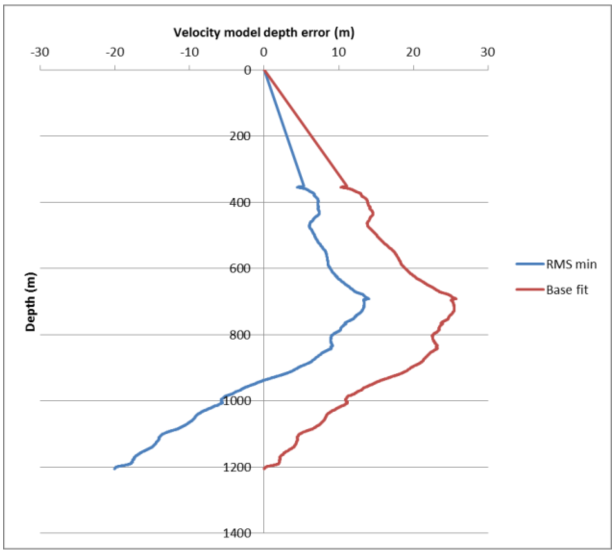


Figure 10 Depth error of Local V0 model (basefit and rms) estimates at well KDK-01. Shown depth error is the difference between modelled velocity and instantaneous velocity from sonic log.

References:

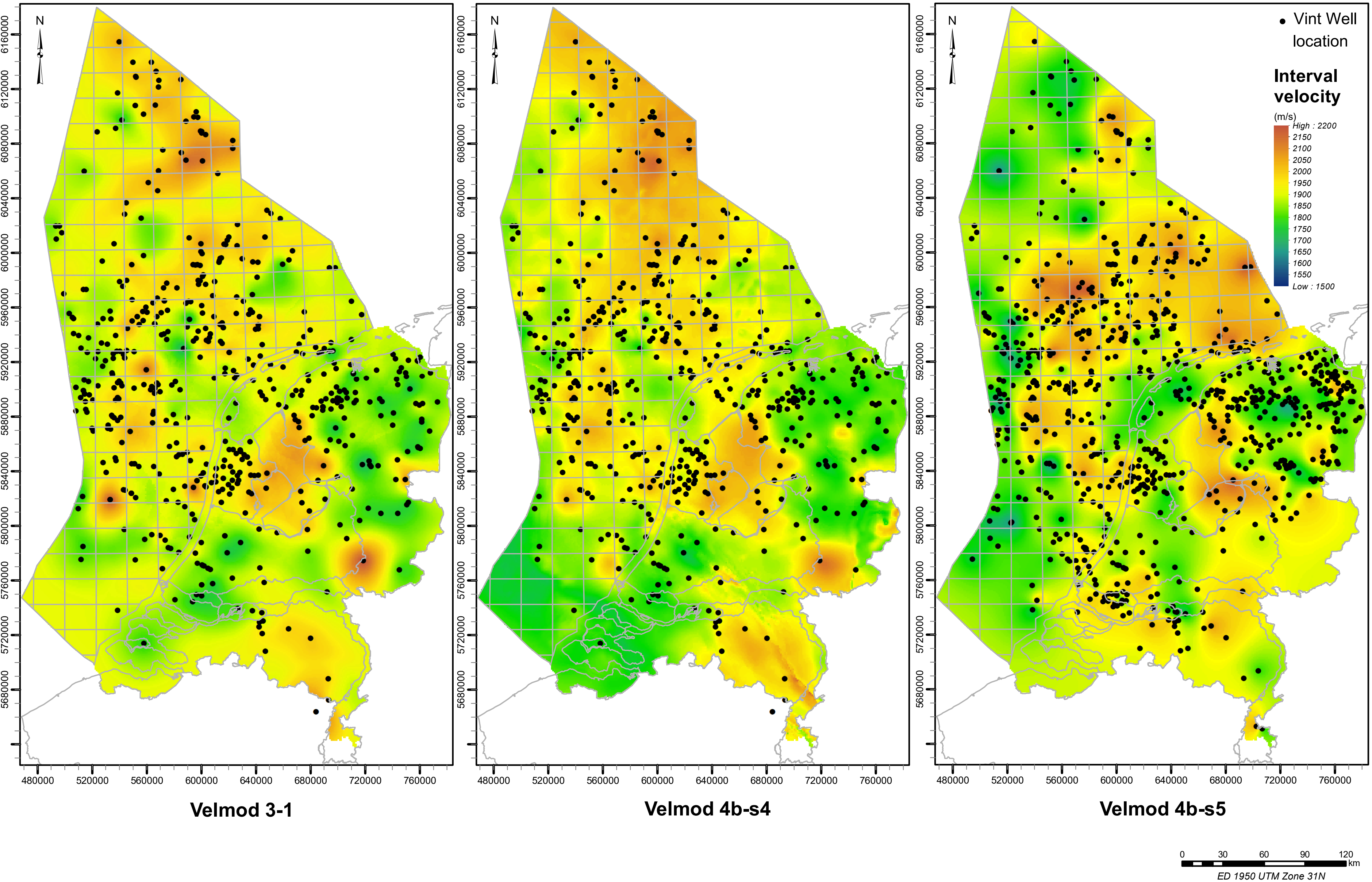
Japsen, P., 1993. Influence of lithology and Neogene uplift on seismic velocities in Denmark: implications for depth conversion of maps. American Association of Petroleum Geologists Bulletin 77, No.2: 194-211.

Kombrink, H., Doornenbal, J.C., Duin, E.J.T., den Dulk, M., van Gessel, S.F., ten Veen, J.H. & Witmans, N., 2012. New insights into the geological structure of the Netherlands; results of a detailed mapping project. Netherlands Journal of Geosciences 91-4, 419 - 446.

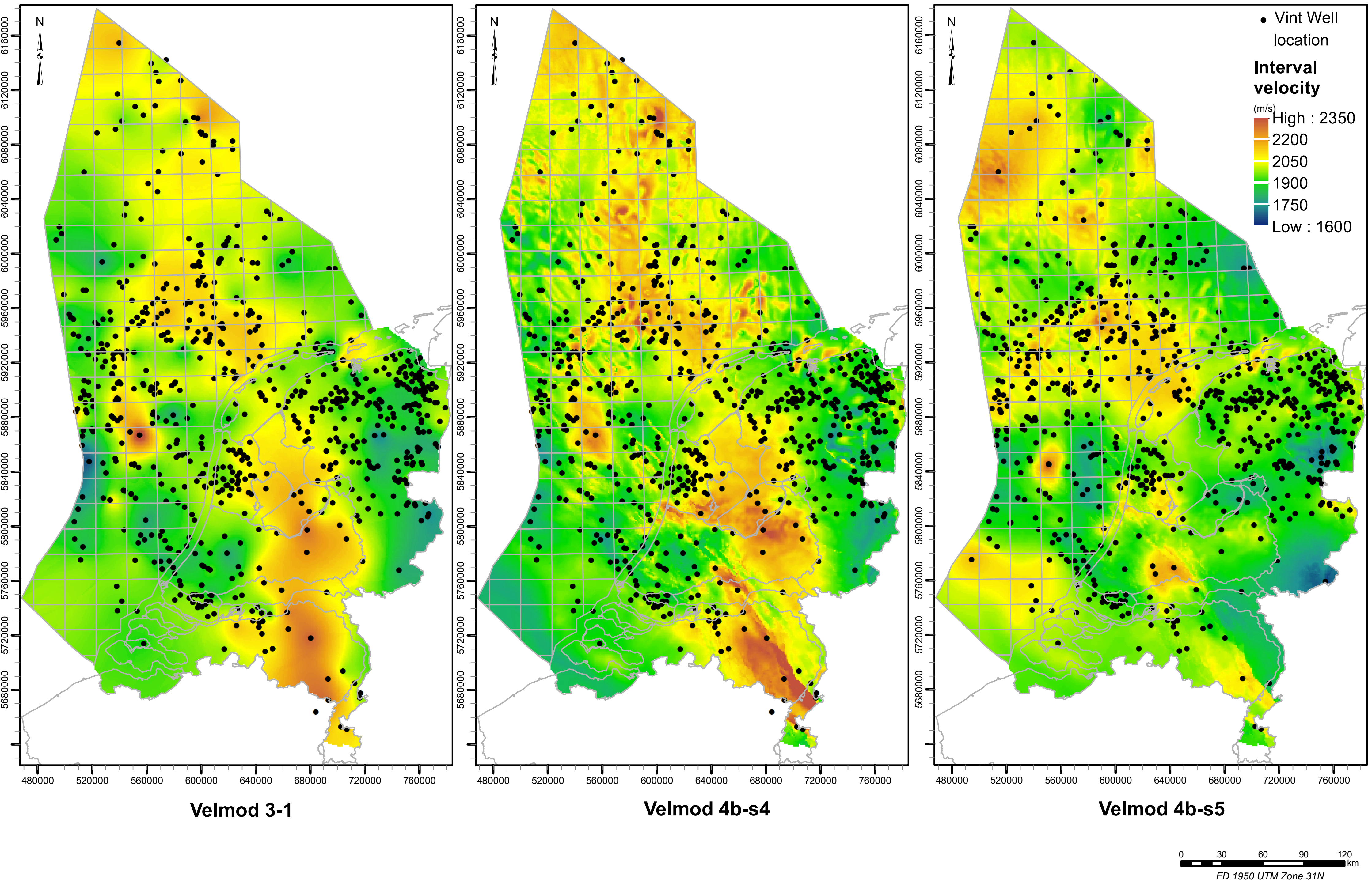
VELMOD3.1, 2017. Final report: https://www.nlog.nl/VELMOD-31

B Vint maps (VELMOD-3.1, VELMOD-4b-s4 and VELMOD-4b-s5)

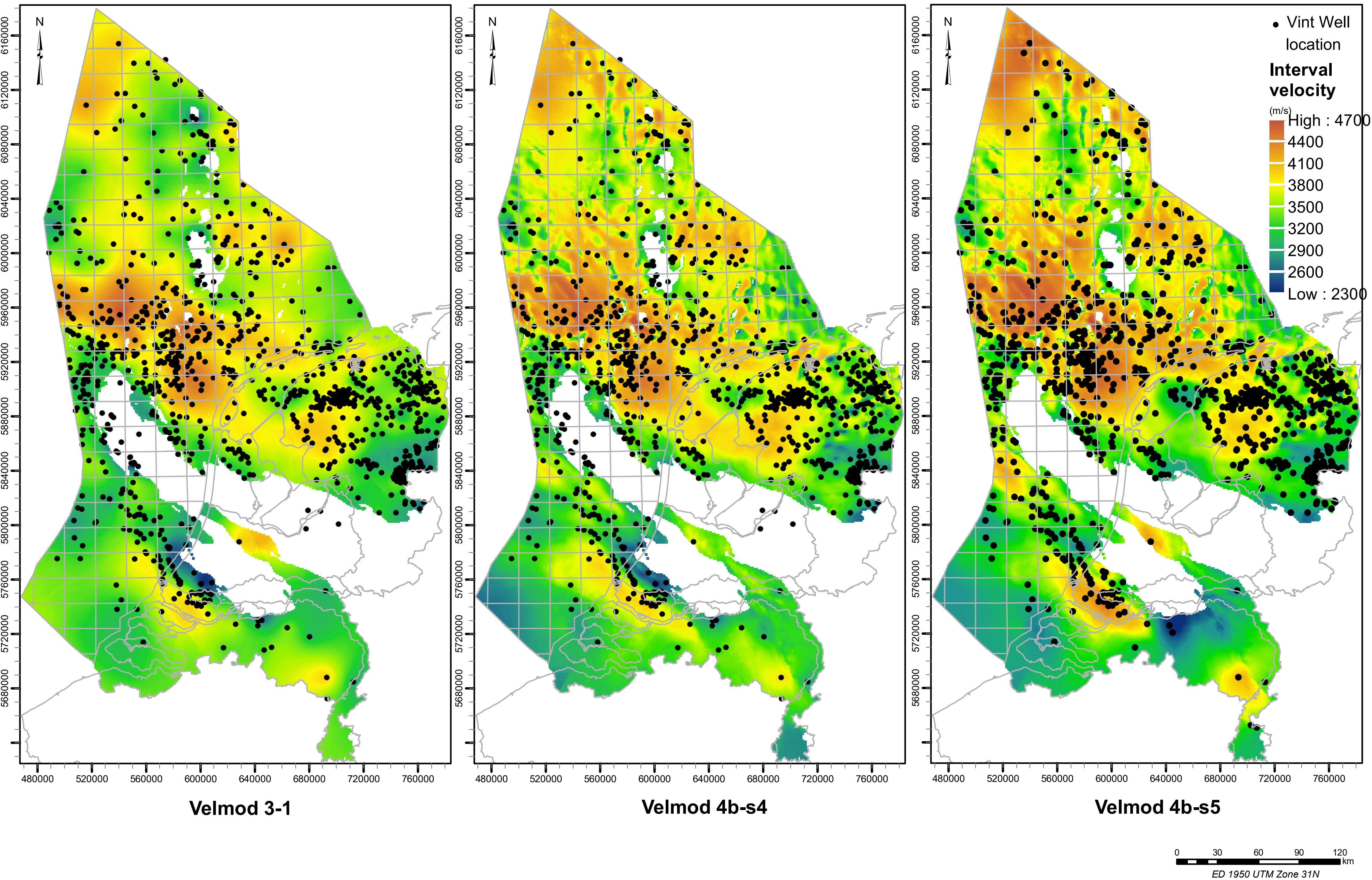
Vint-distribution of the Upper North Sea Group (NU)



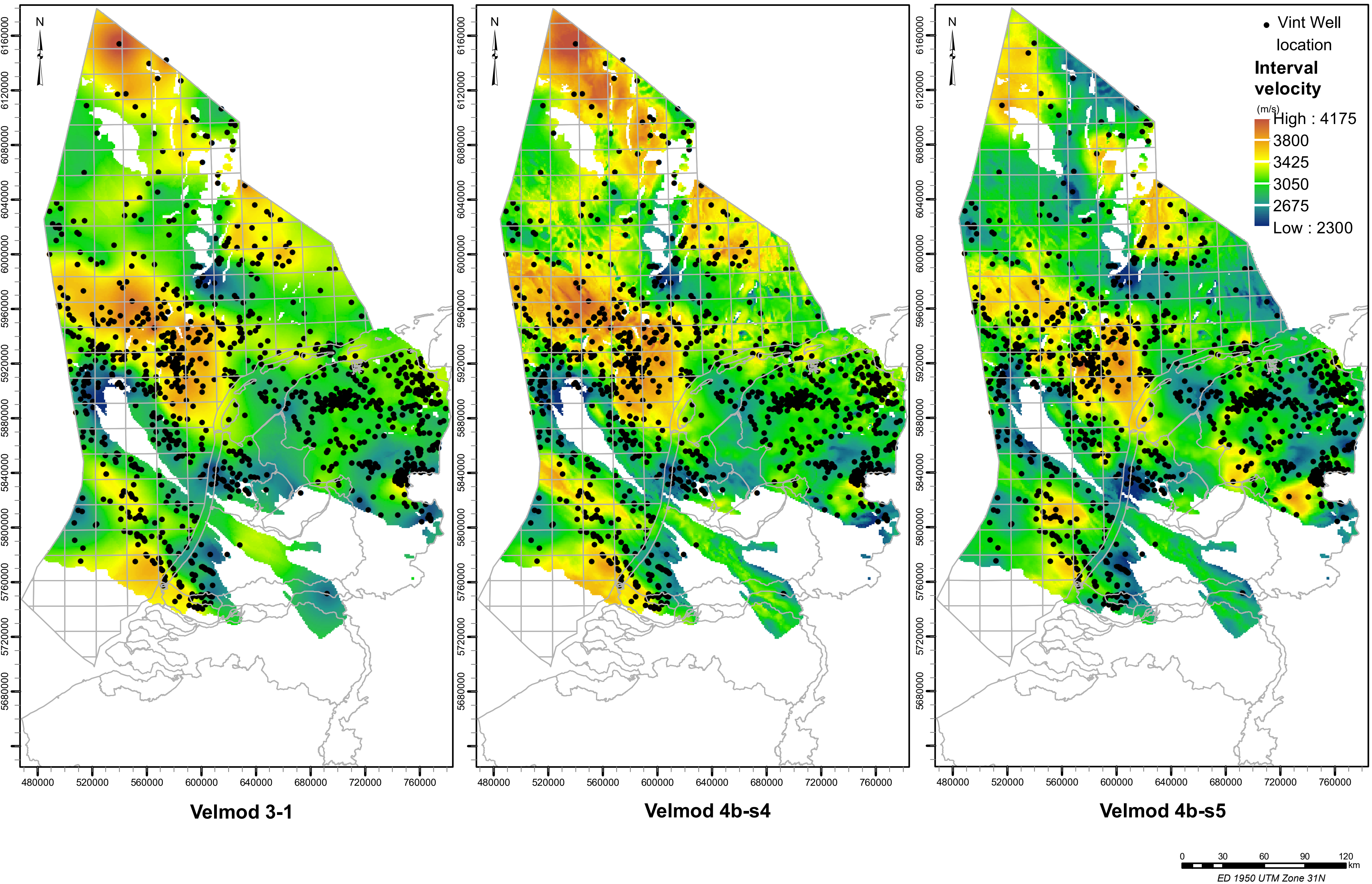
Vint-distribution of the Middle and Lower North Sea groups (NM+NL)



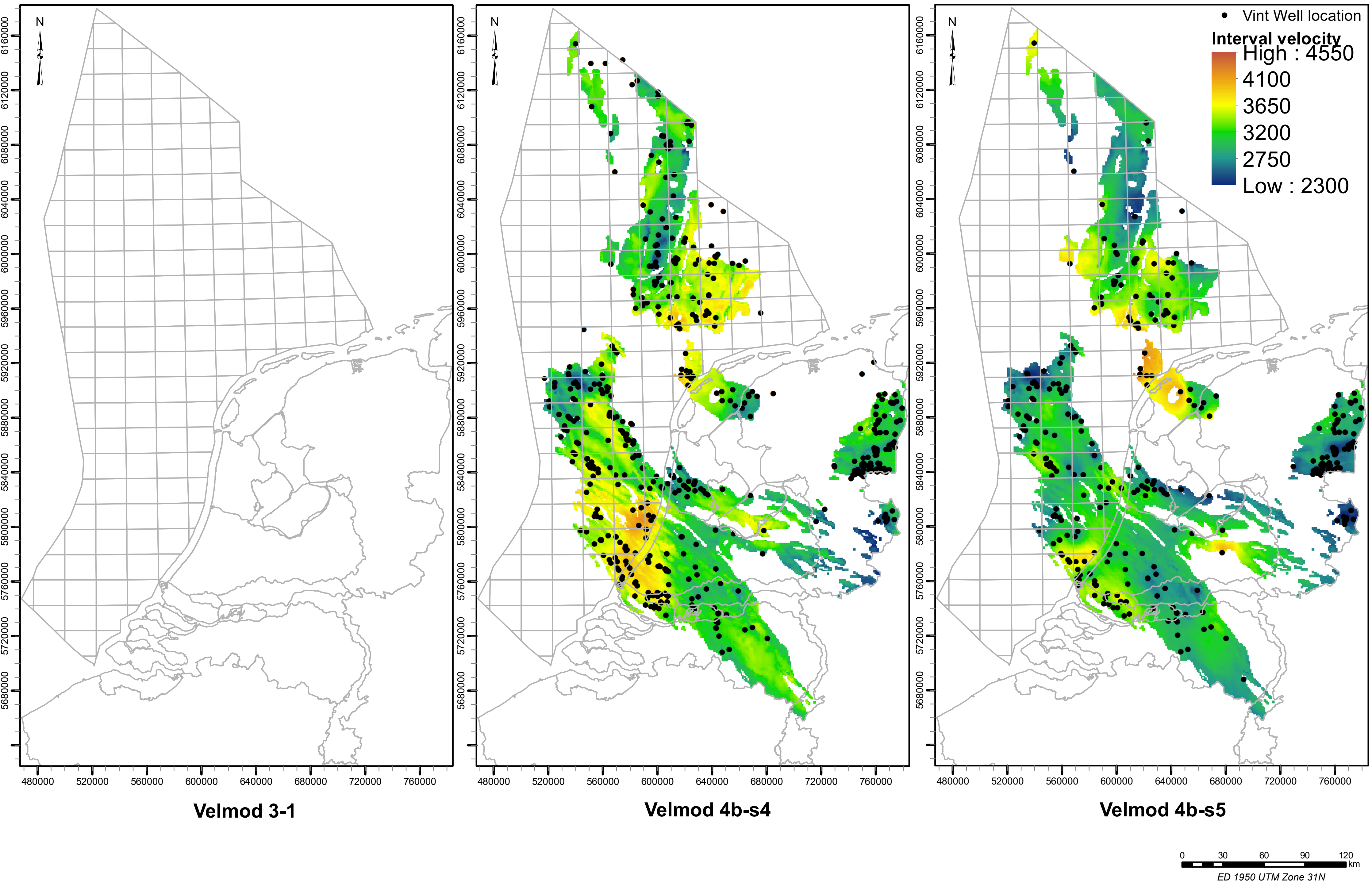
Vint-distribution of the Chalk Group (CK)



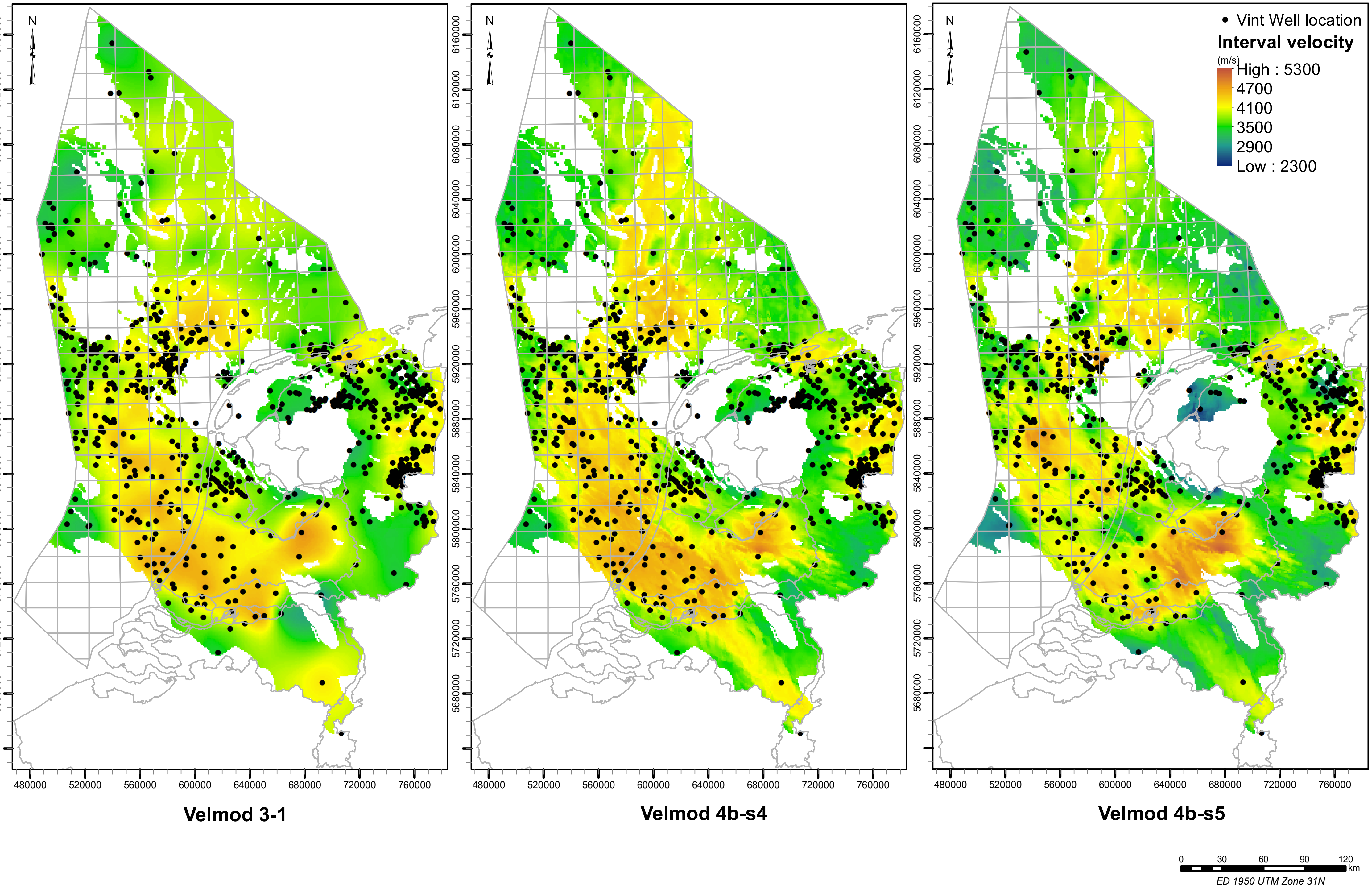
Vint-distribution of the Rijnland Group (KN)



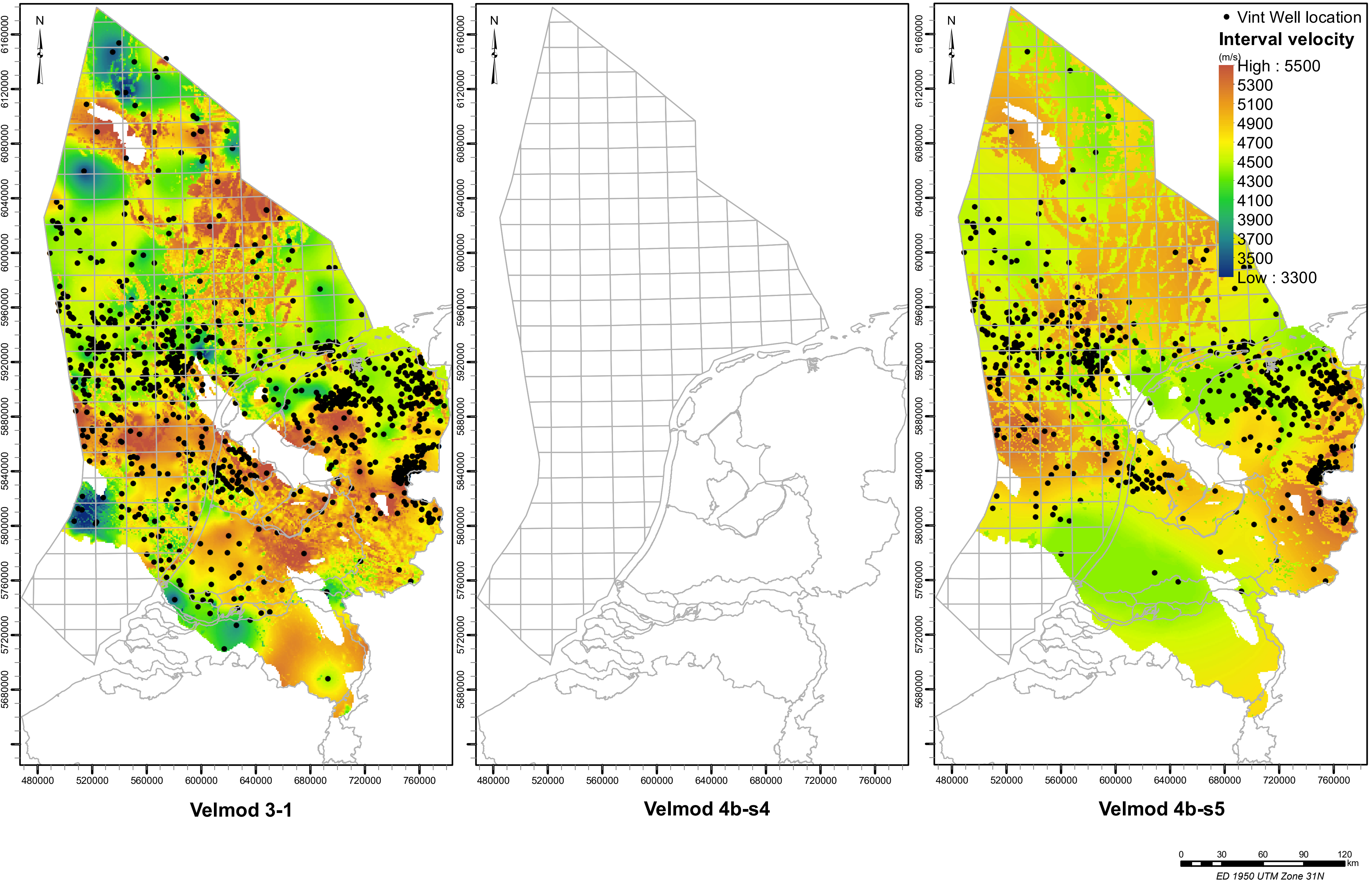
Vint-distribution of the Upper Jurassic and Altena groups (S+AT)



Vint-distribution of the Upper and Lower Germanic Trias groups (RN+RB)

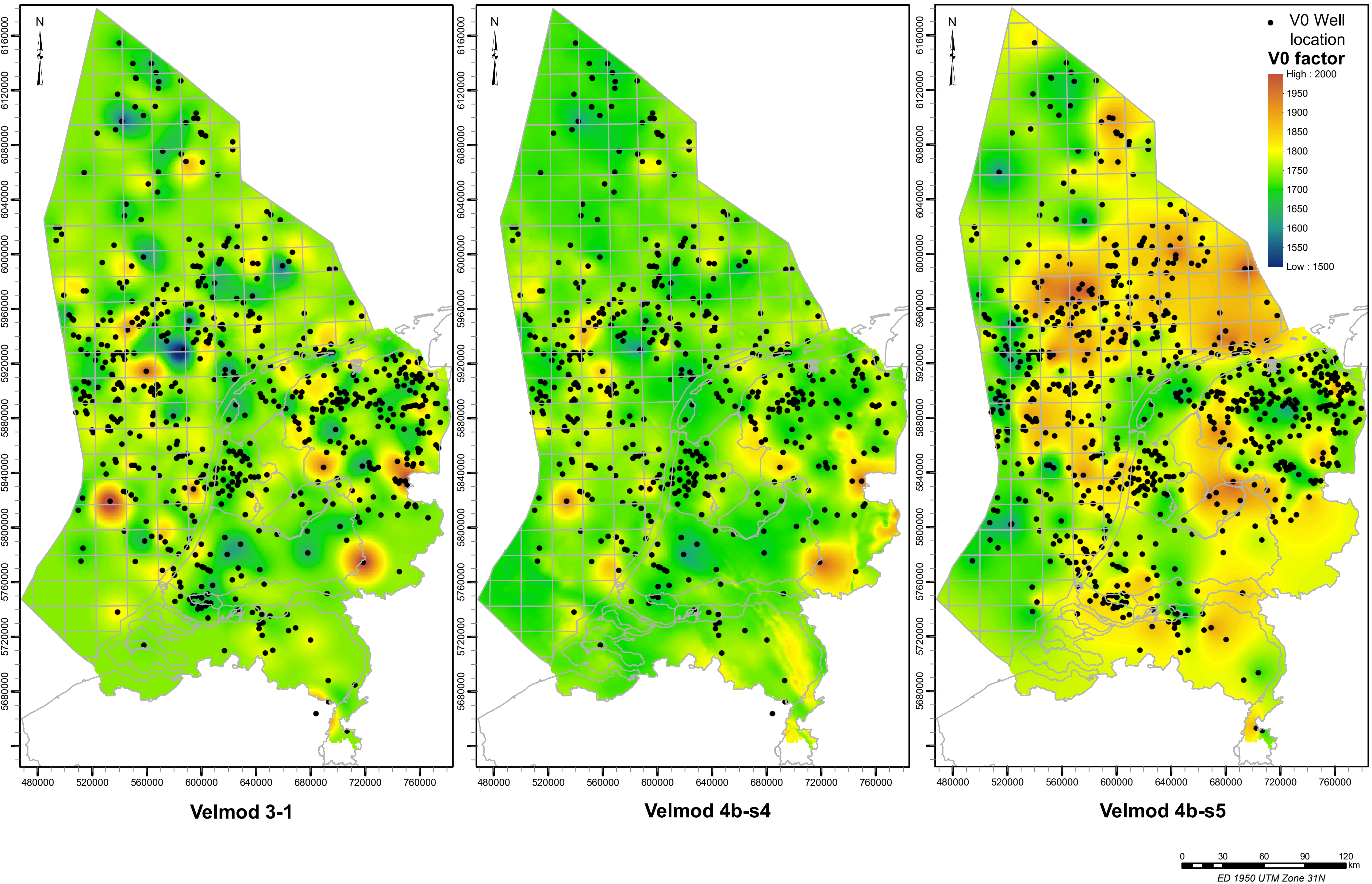


Vint-distribution of the Zechstein Group (ZE)



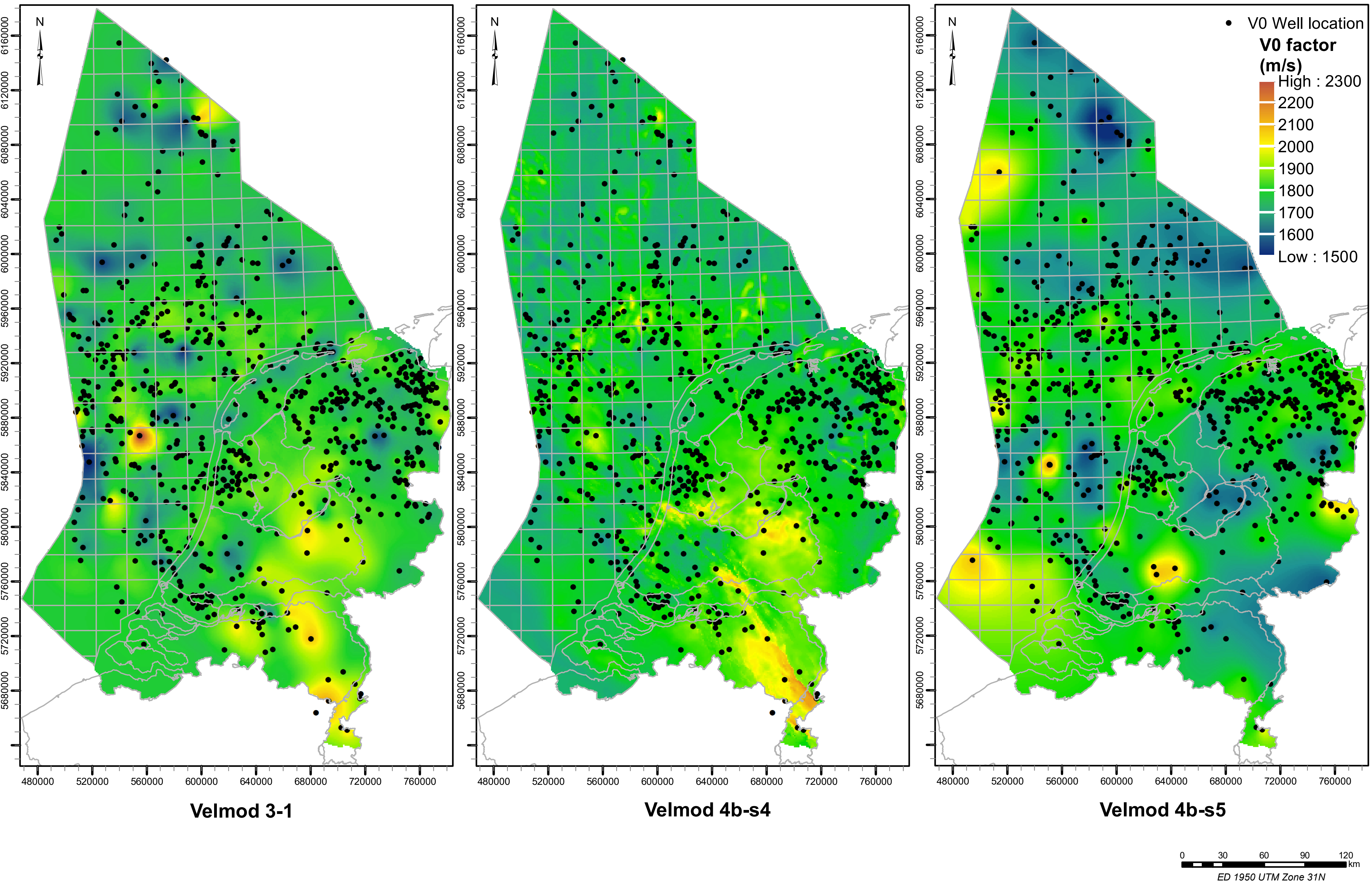
C V0 maps (VELMOD-3.1, VELMOD-4b-s4 and VELMOD-4b-s5)

V0-distribution of the Upper North Sea Group (NU)

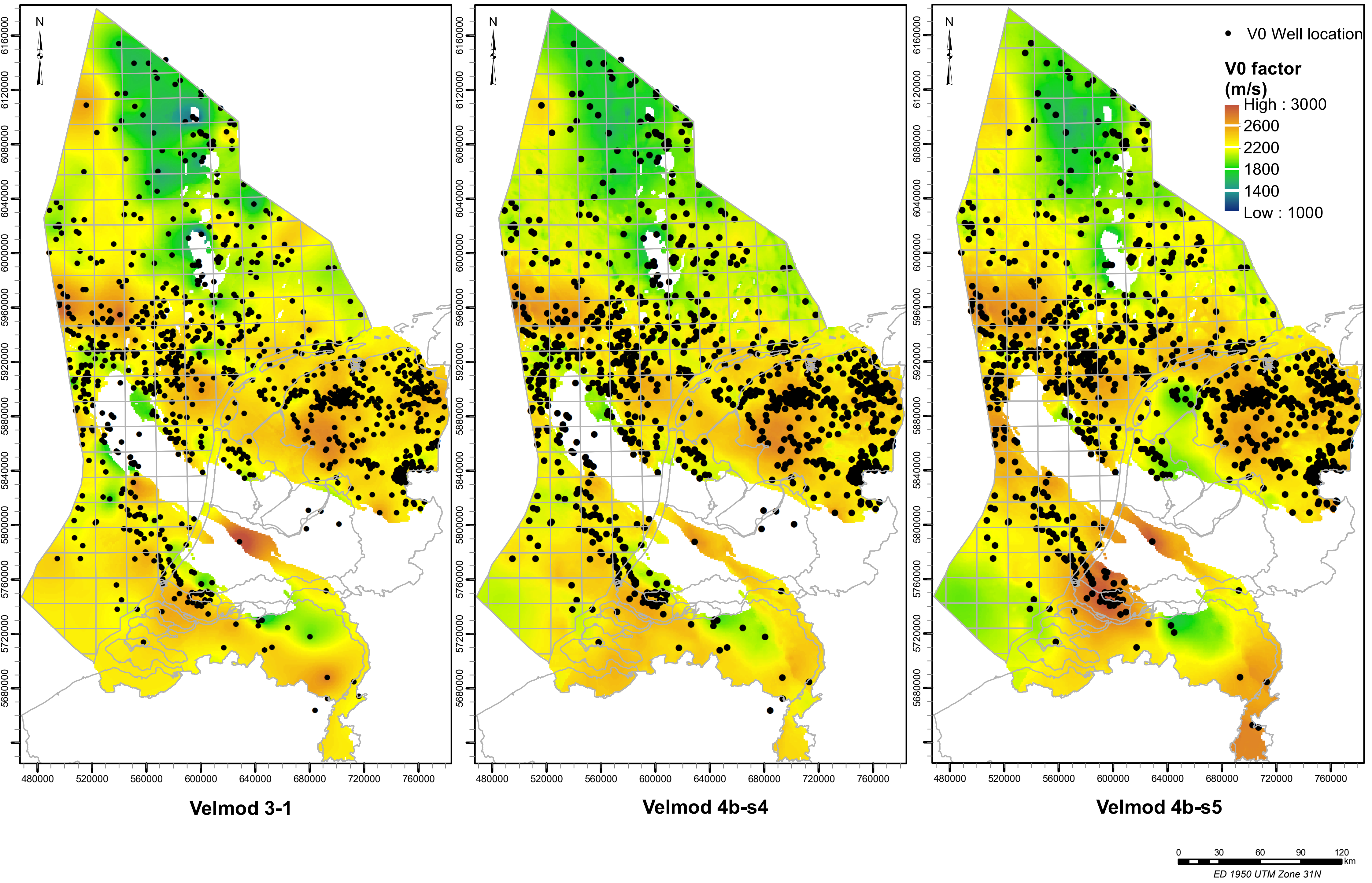


Velmod 3-1 **Velmod 4b-s4** **Velmod 4b-s5**

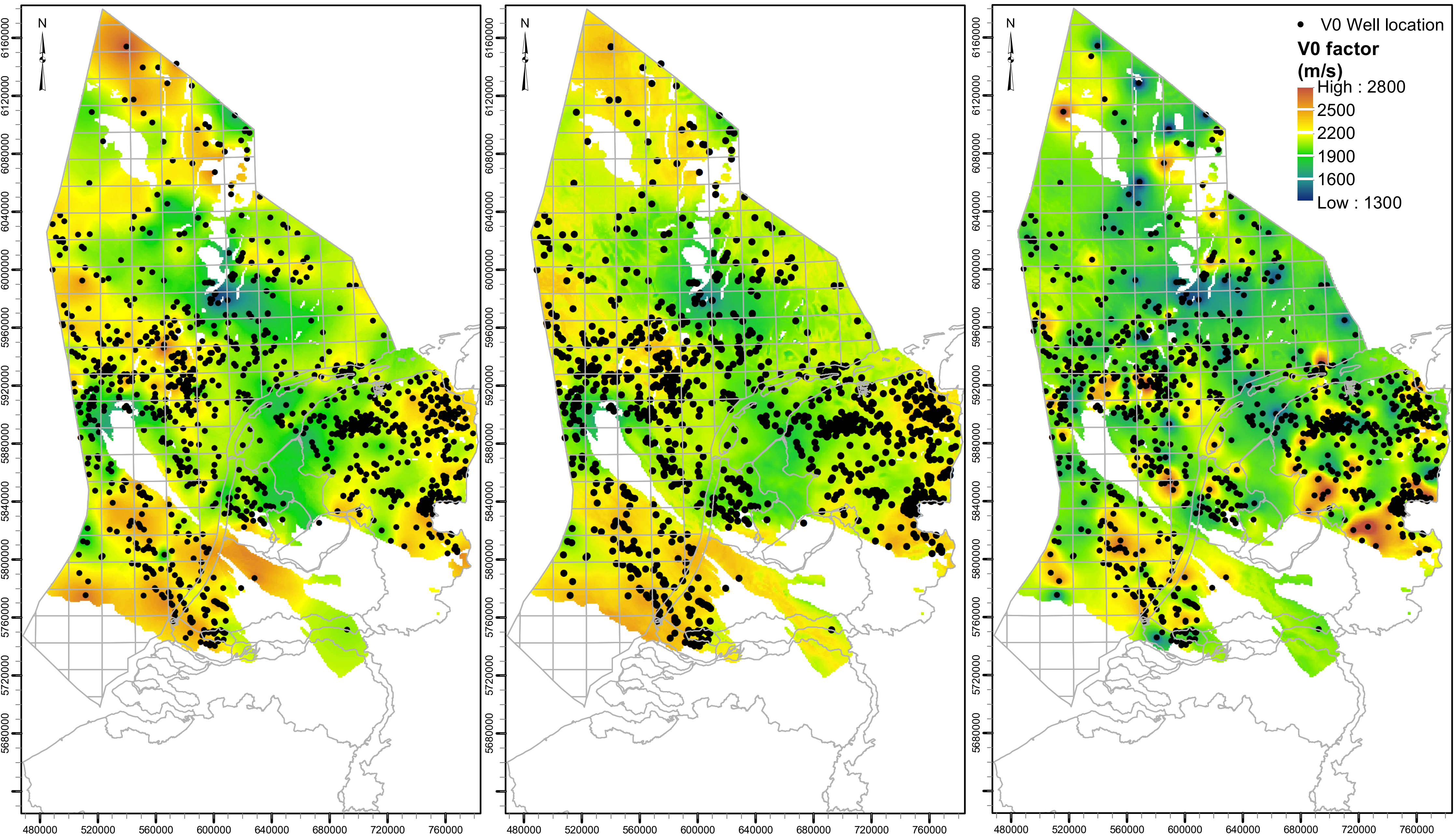
V0-distribution of the Middle and Lower North Sea groups (NM+NL)



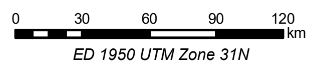
V0-distribution of the Chalk Group (CK)



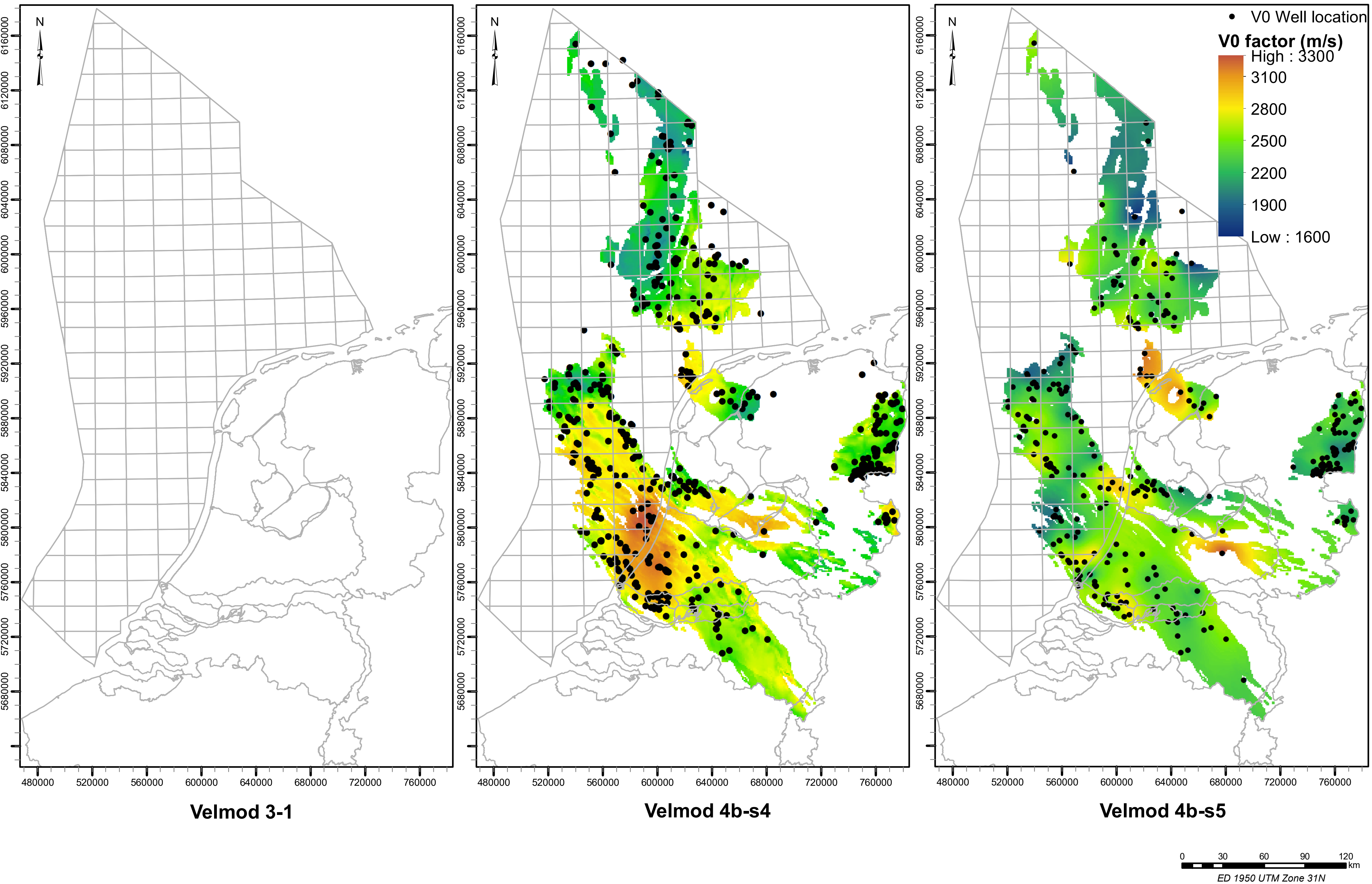
V0-distribution of the Rijnland Group (KN)



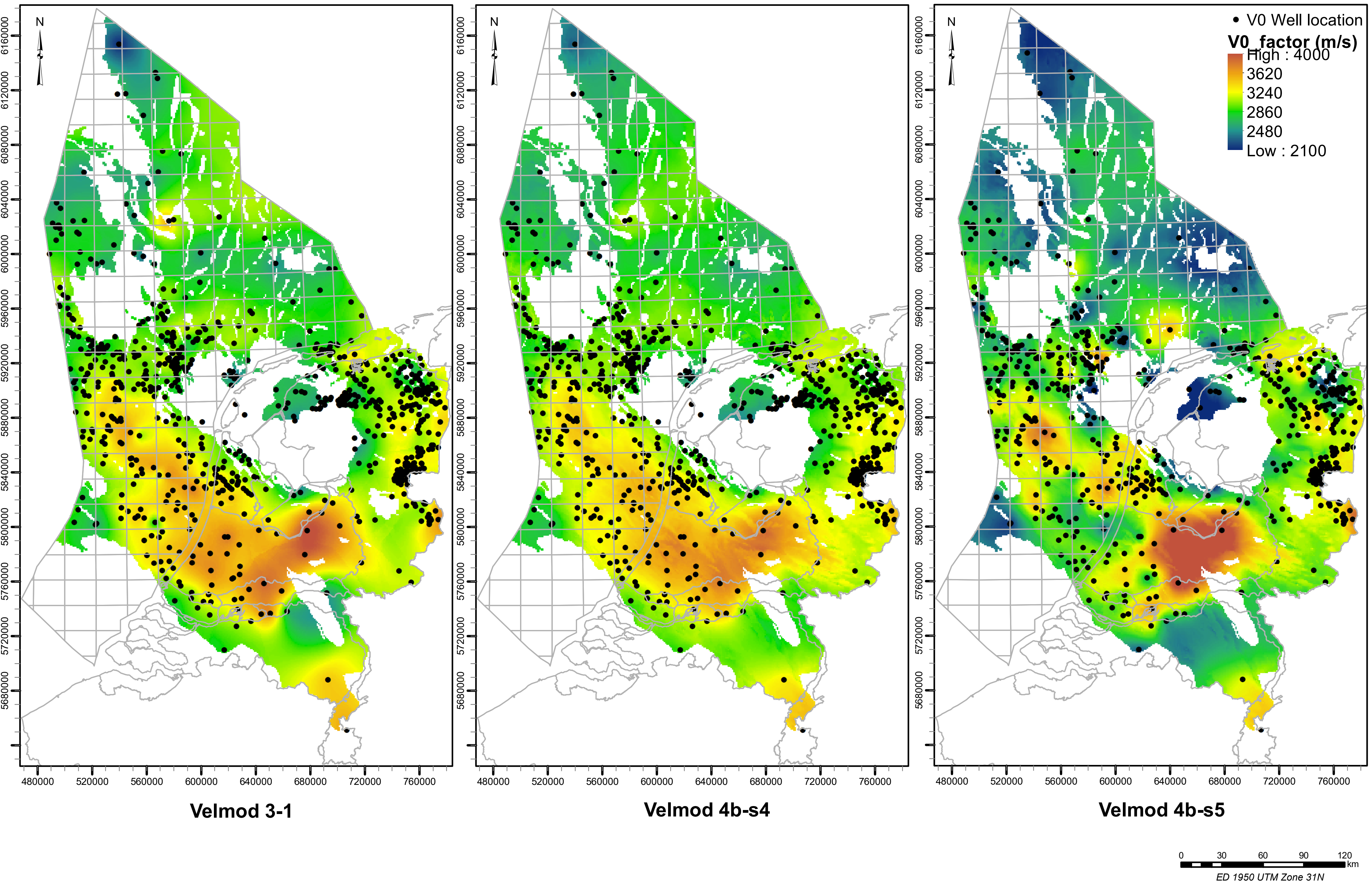
Velmod 3-1 **Velmod 4b-s4** **Velmod 4b-s5**



V0-distribution of the Upper Jurassic and Altena groups (S+AT)

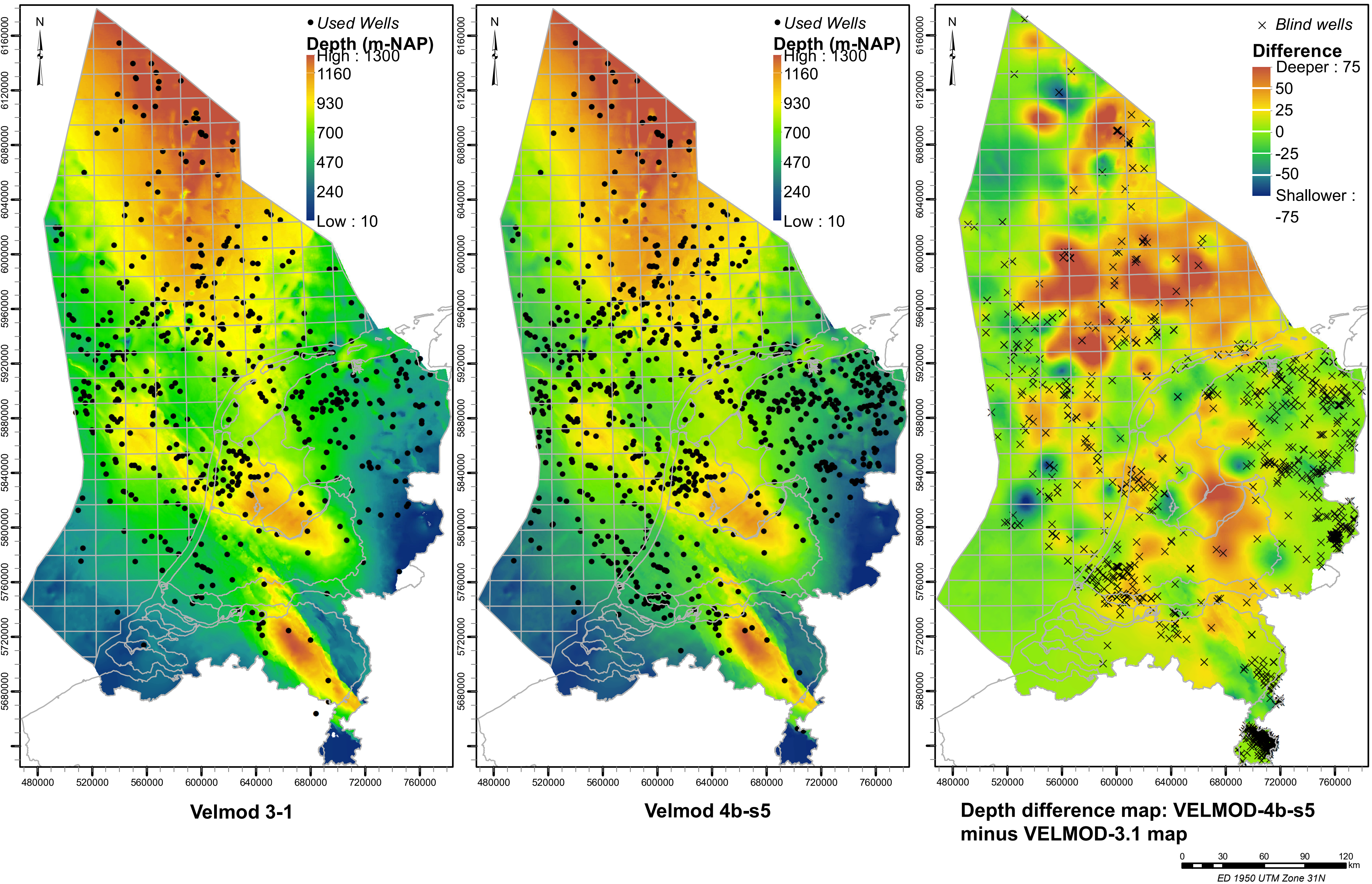


V0-distribution of the Upper and Lower Germanic Trias groups (RN+RB)



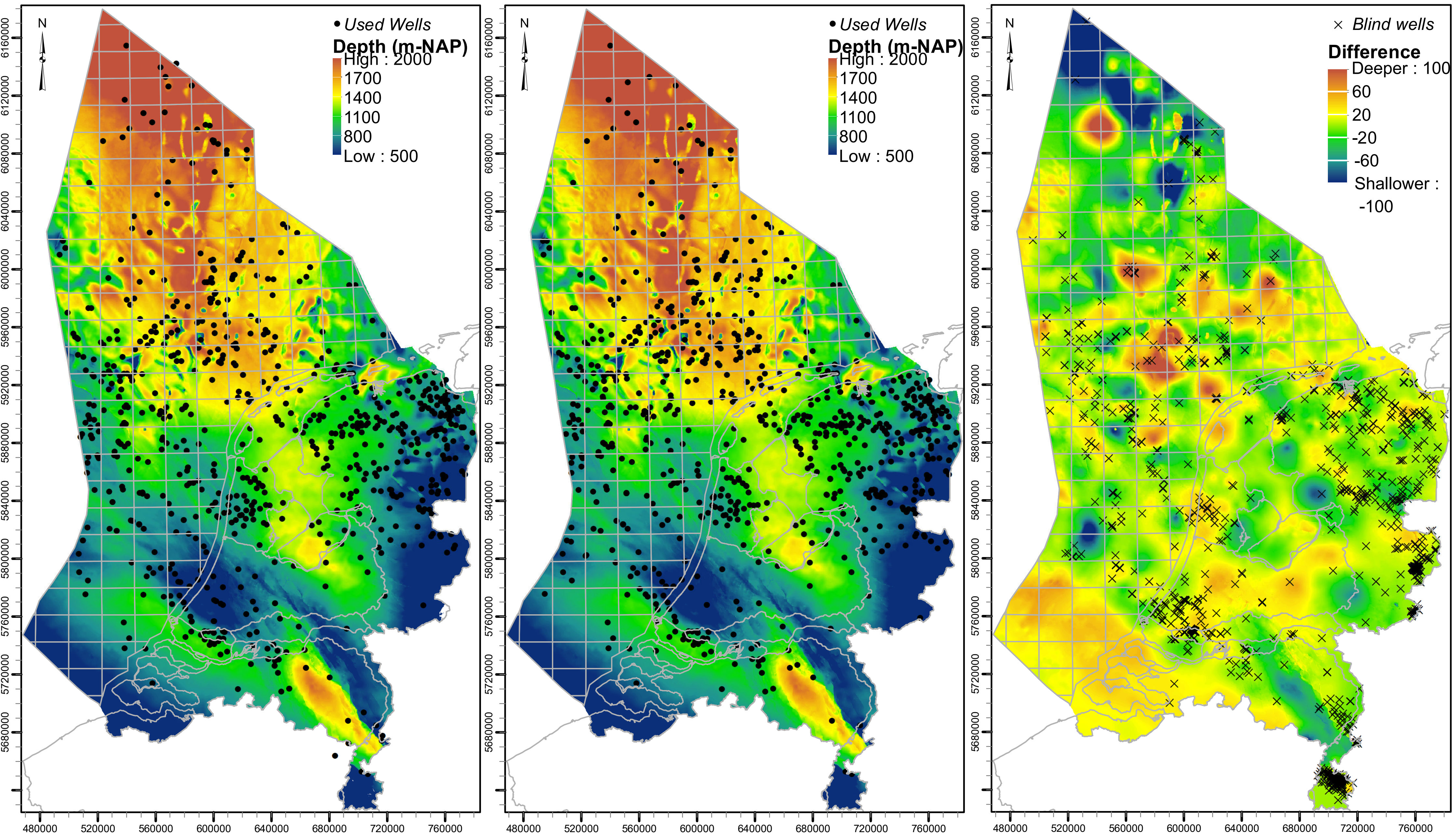
D Depth maps (VELMOD-3.1 and VELMOD-4b-s5) and depth difference maps

Depth maps and depth difference map of the Upper North Sea Group (NU)



Depth difference map: VELMOD-4b-s5 minus VELMOD-3.1 map

Depth maps and depth difference map of the Middle and Lower North Sea groups (NM+NL)



Velmod 3-1

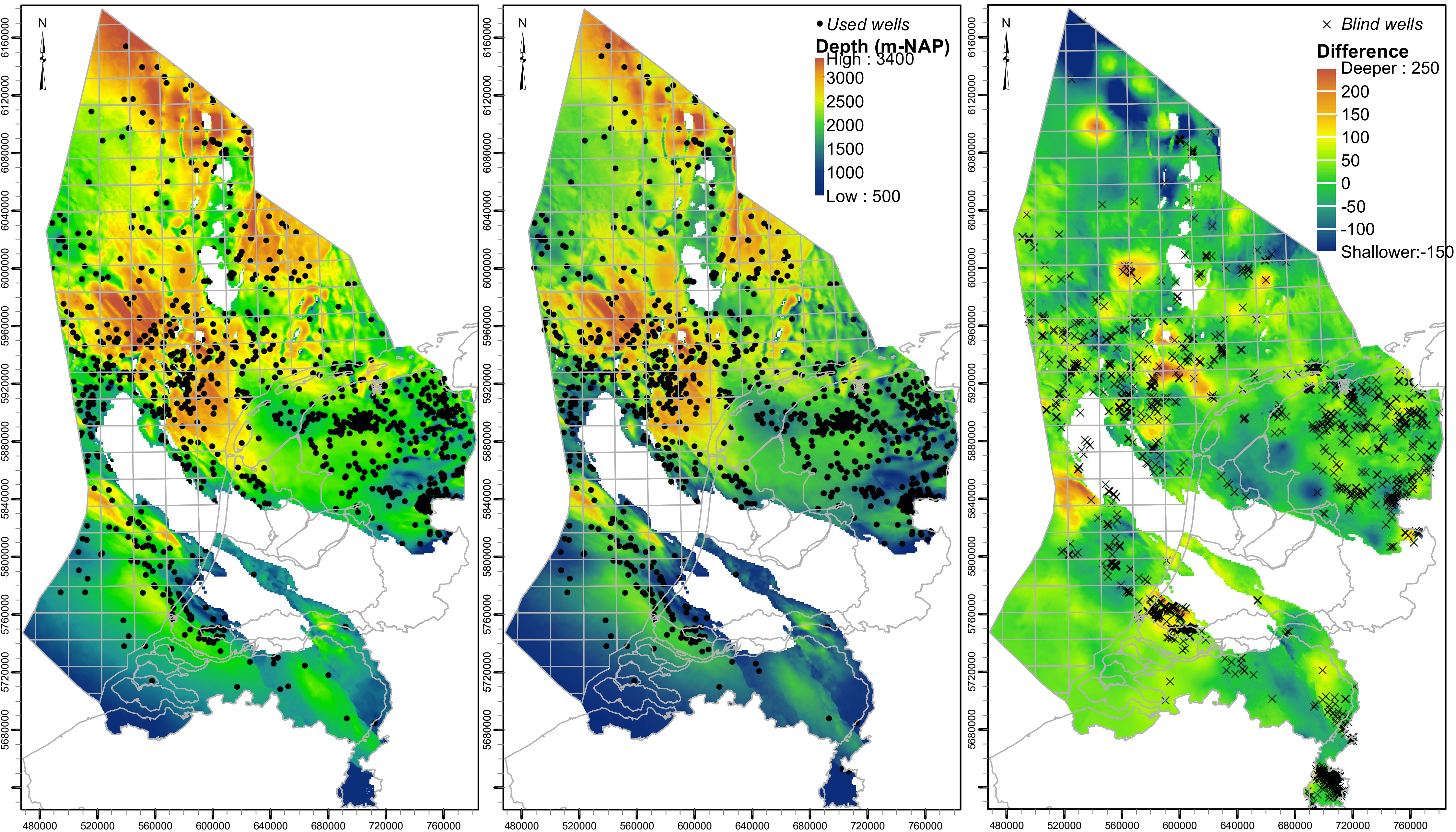
Velmod 4b-s5

Depth difference map: VELMOD-4b-s5 minus VELMOD-3.1 map

0 30 60 90 120 km

ED 1950 UTM Zone 31N

Depth maps and depth difference map of the Chalk Group (CK)



Velmod 3-1

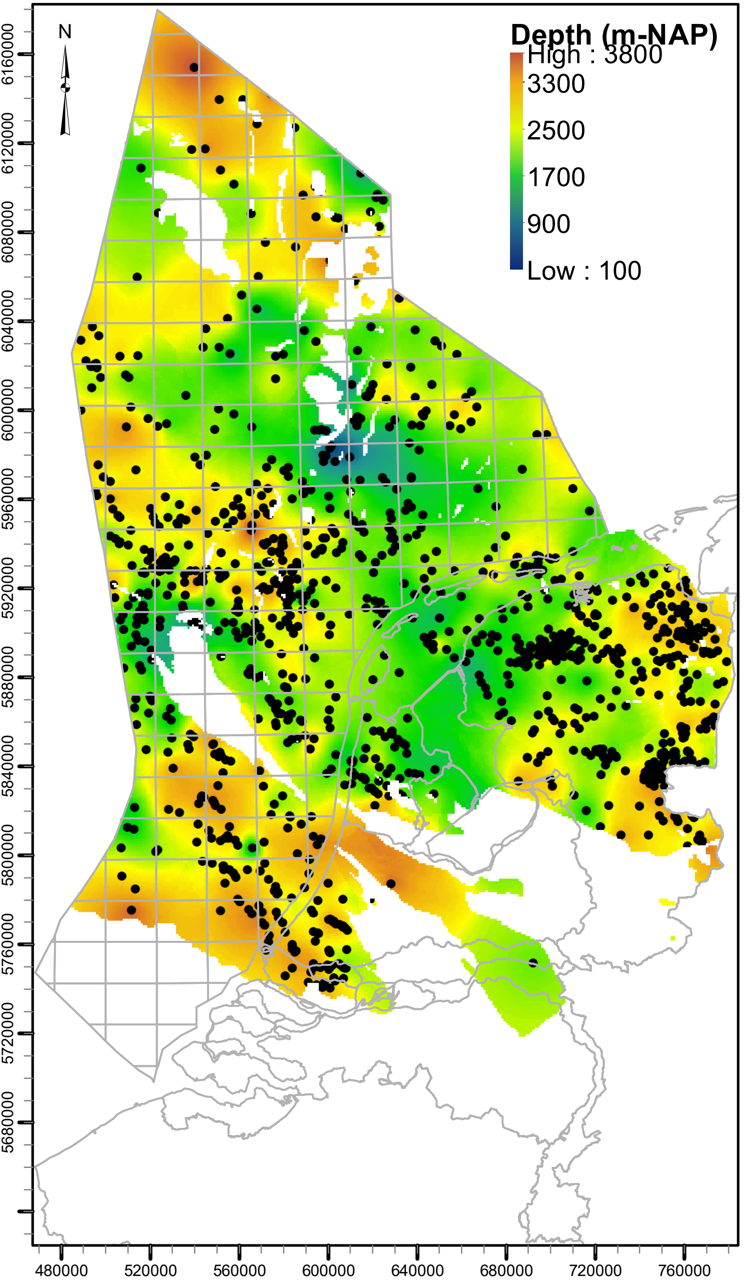
Velmod 4b-s5

Depth difference map: VELMOD-4b-s5 minus VELMOD-3.1 map

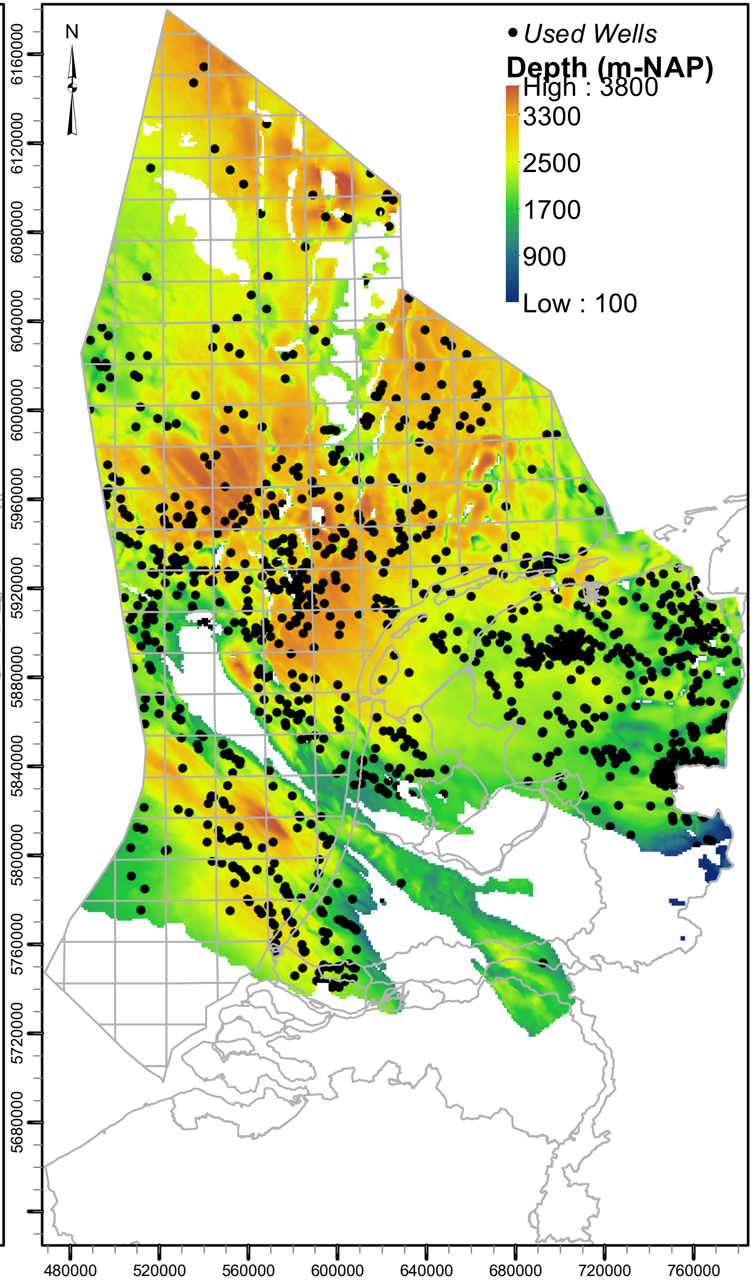
0 30 60 90 120 km

ED 1950 UTM Zone 31N

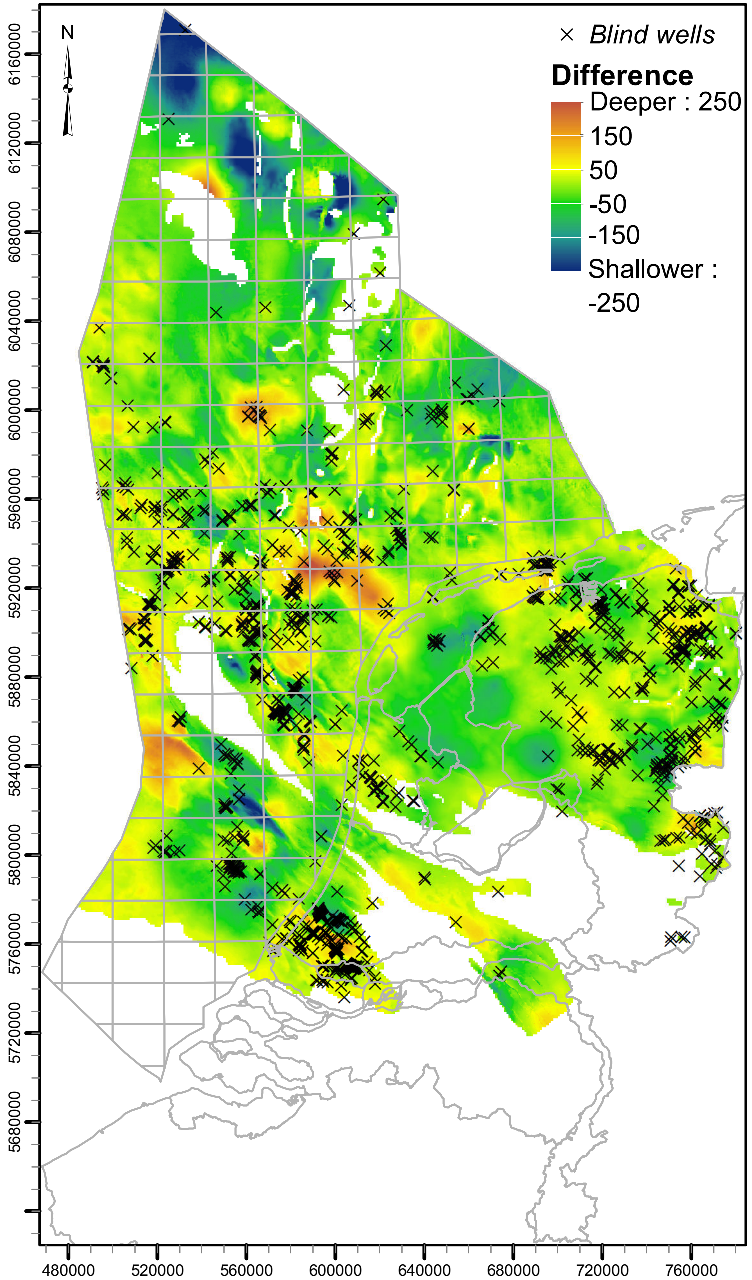
Depth maps and depth difference map of the Rijnland Group (KN)



Velmod 3-1

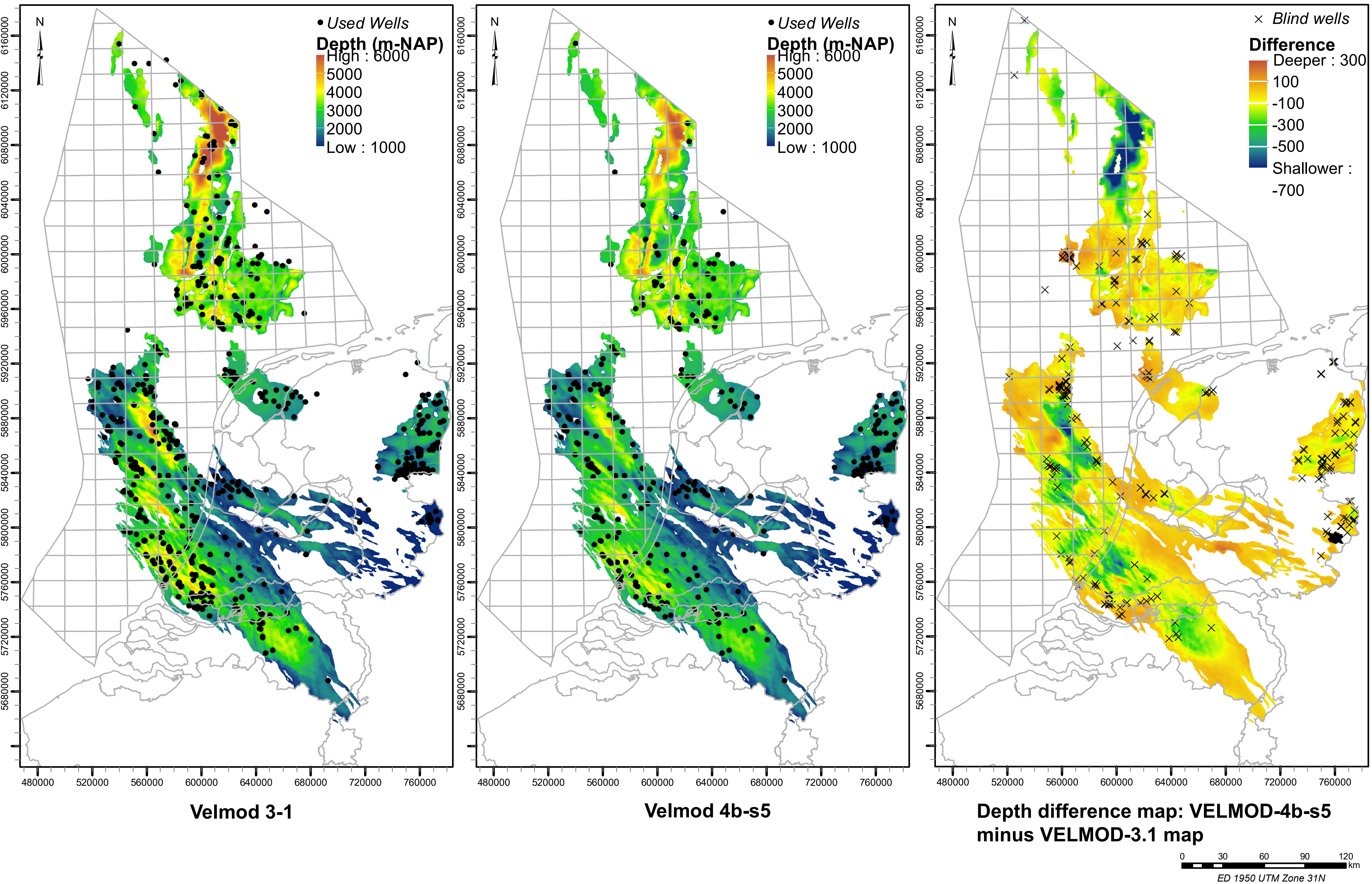


Velmod 4b-s5



Depth difference map: VELMOD-4b-s5 minus VELMOD-3.1 map

Depth maps and depth difference map of the Upper Jurassic and Altena groups (S+AT)

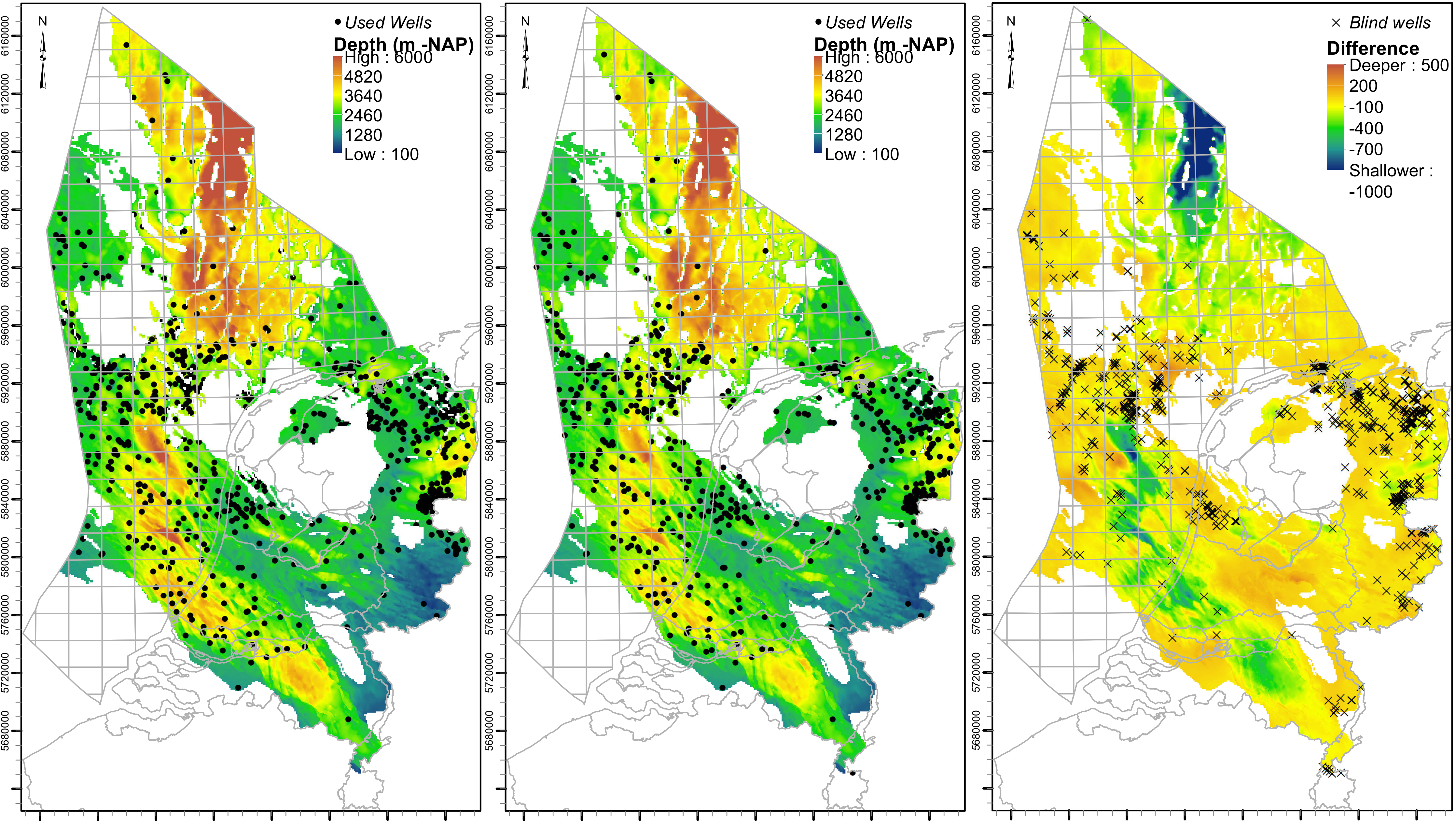


Velmod 3-1

Velmod 4b-s5

Depth difference map: VELMOD-4b-s5 minus VELMOD-3.1 map

Depth maps and depth difference map of the Upper and Lower Germanic Trias groups (RN+RB)



Velmod 3-1

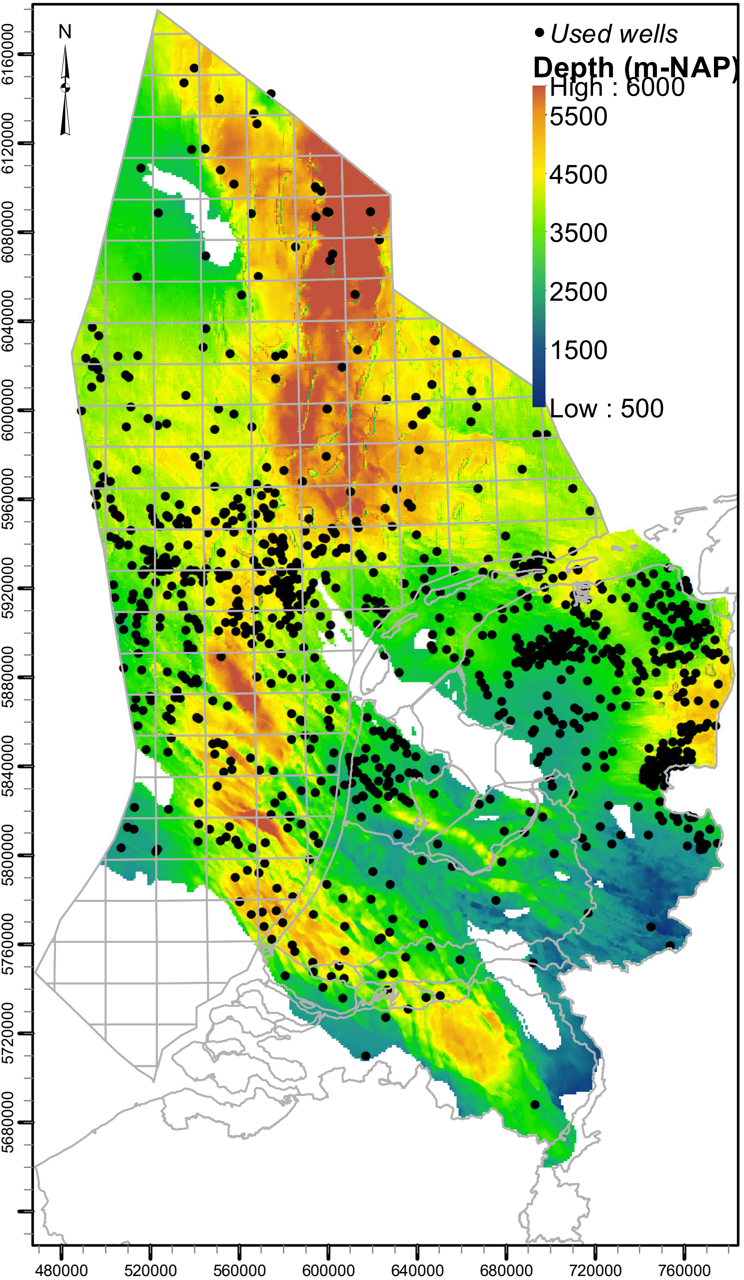
Velmod 4b-s5

Depth difference map: VELMOD-4b-s5 minus VELMOD-3.1 map

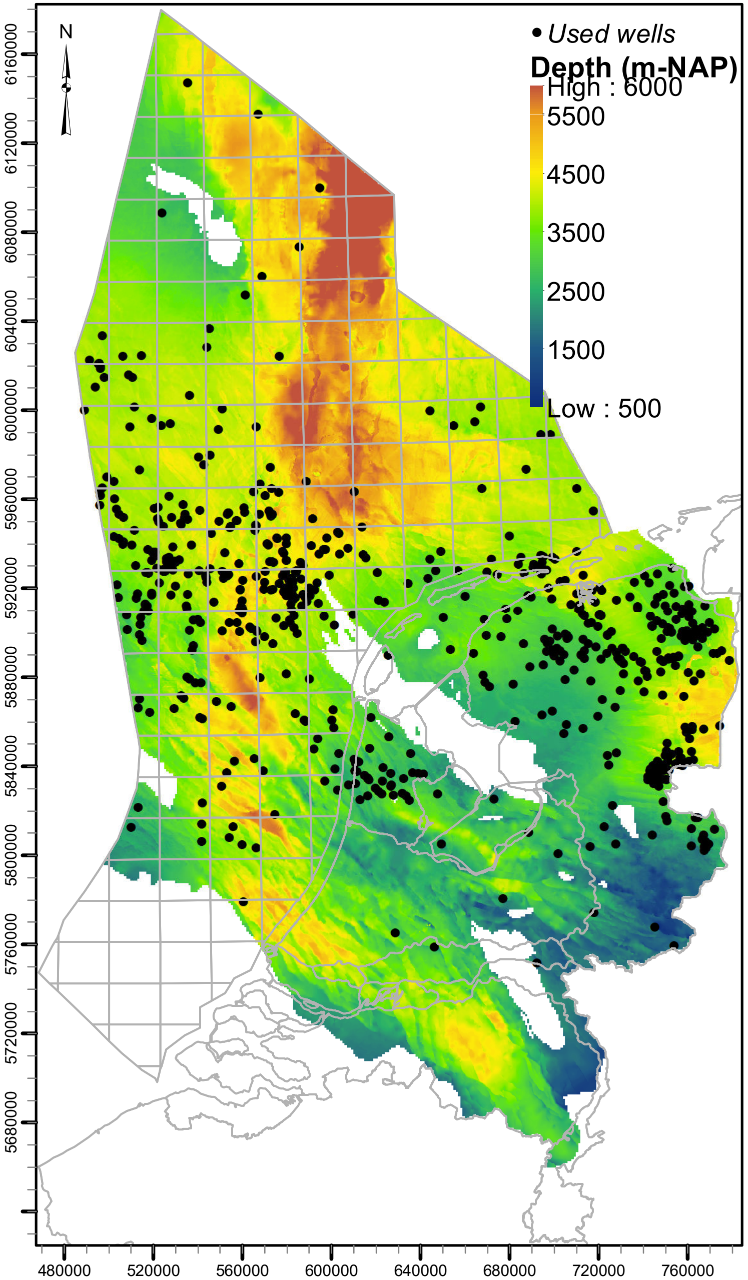
0 30 60 90 120 km

ED 1950 UTM Zone 31N

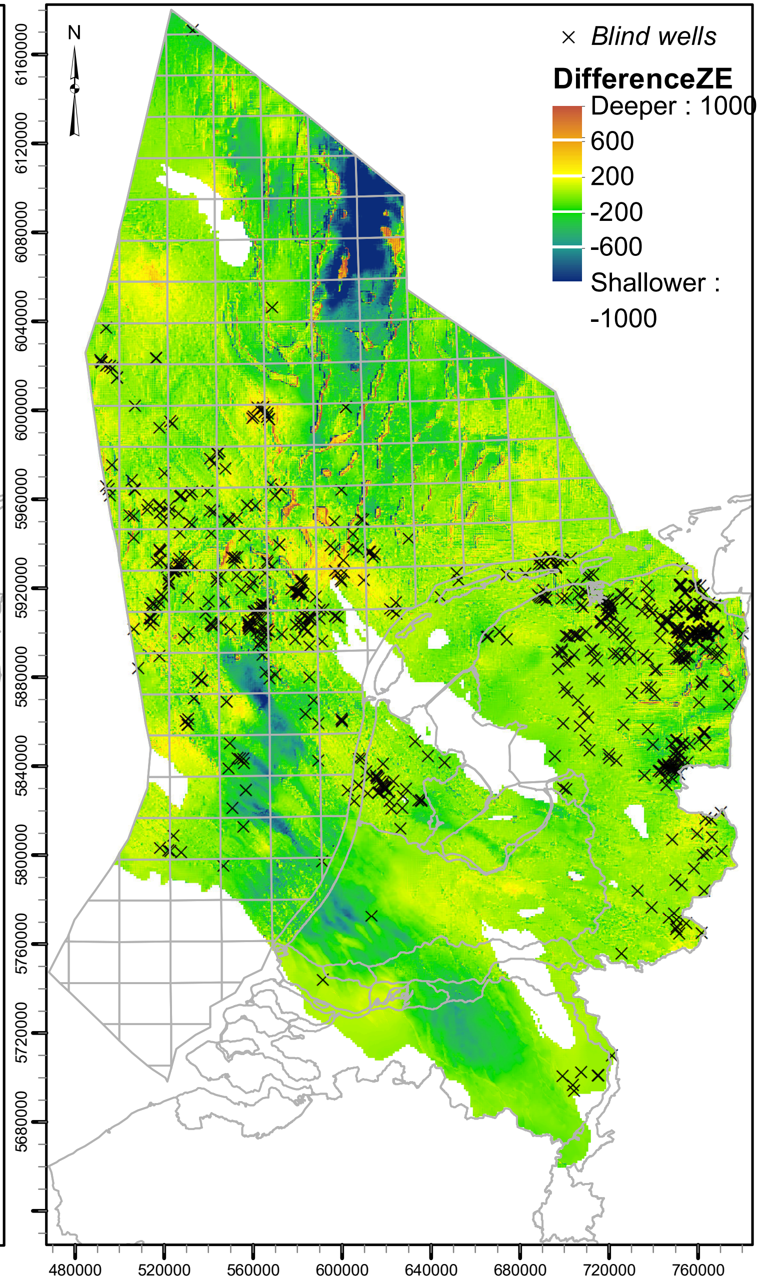
Depth maps and depth difference map of the Zechstein Group (ZE)



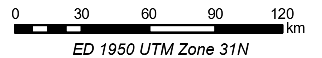
Velmod 3-1



Velmod 4b-s5



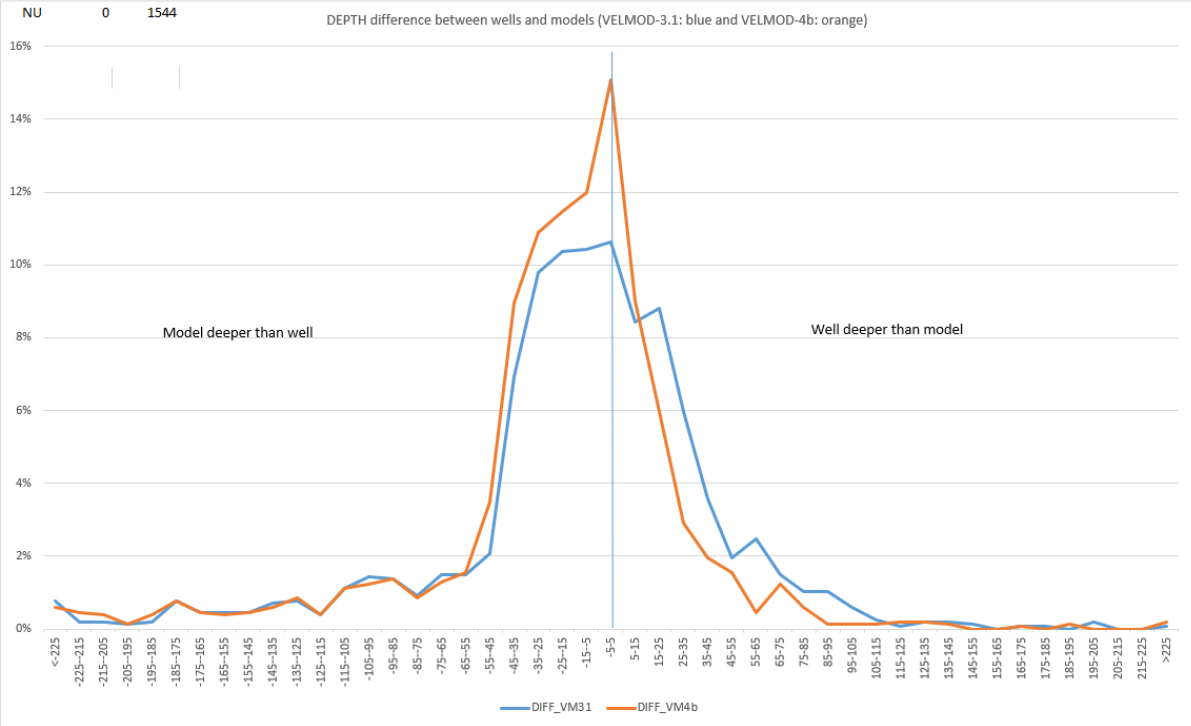
Depth difference map: VELMOD-4b-s5 minus VELMOD-3.1 map

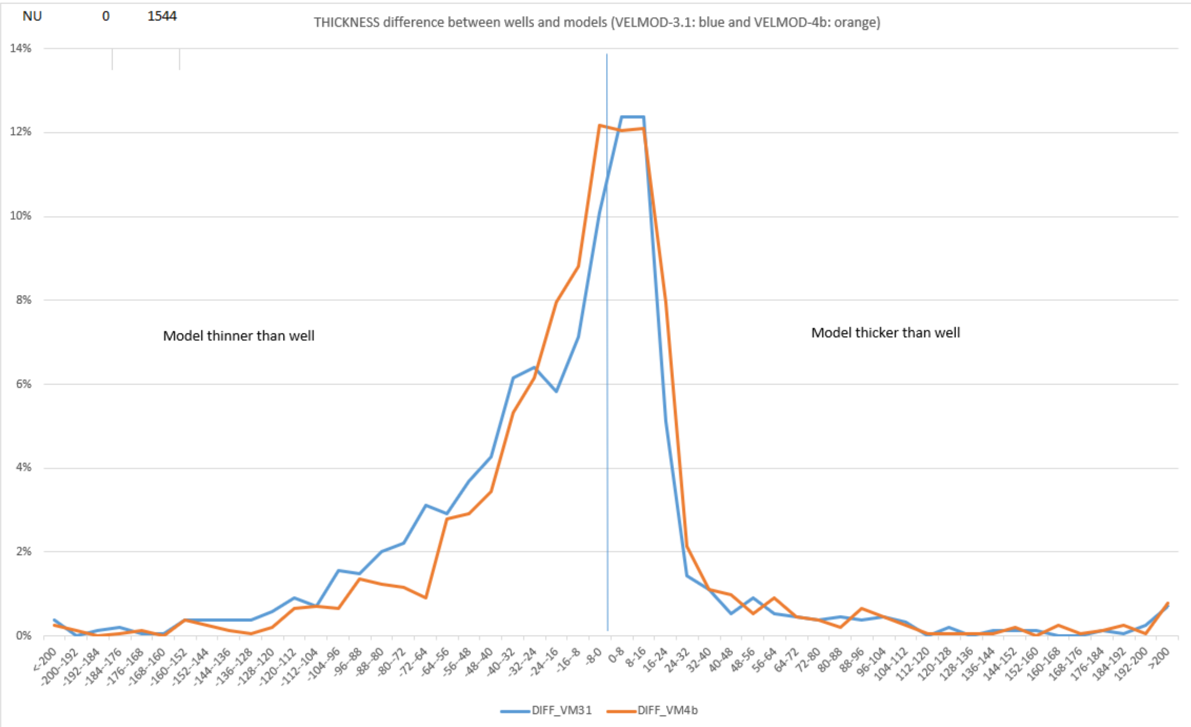


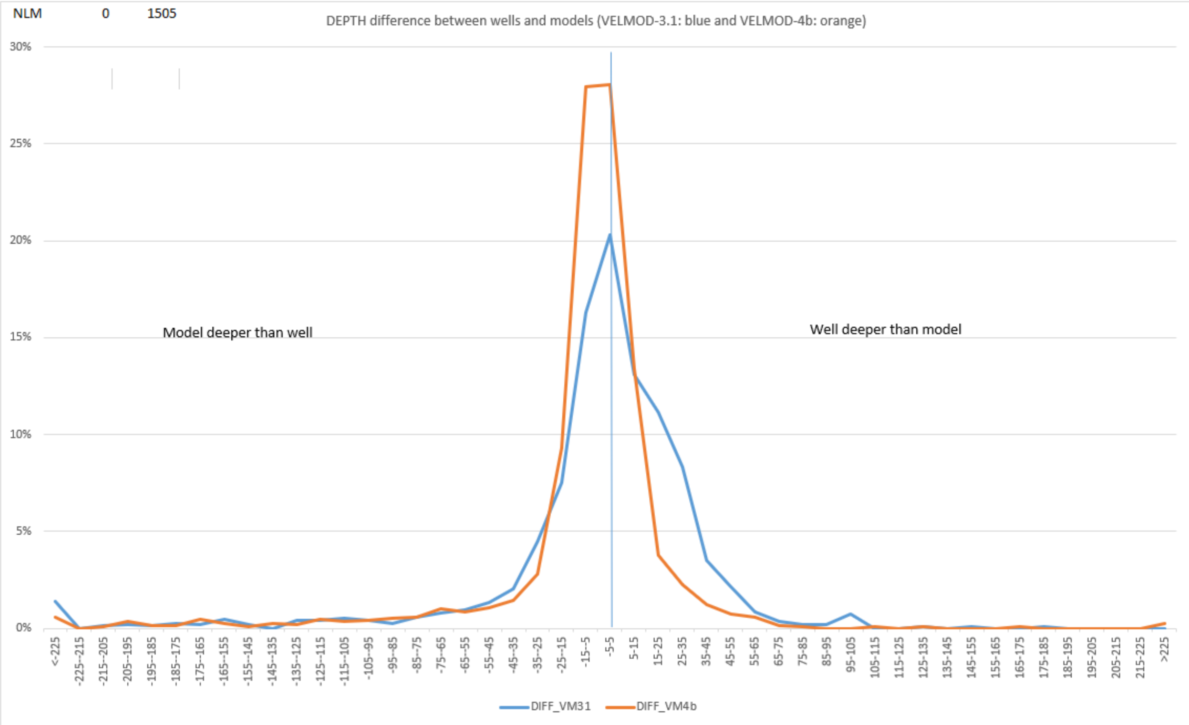
E Comparison between VELMOD-3.1 and VELMOD-4b-s5 models

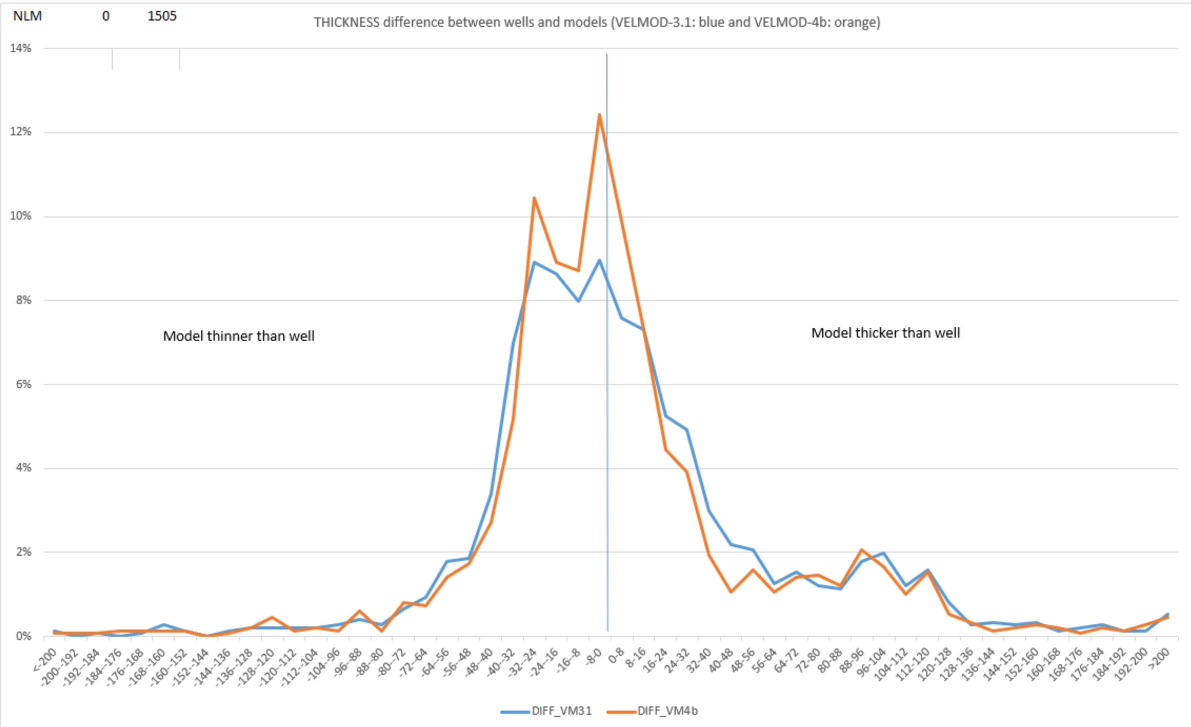
Appendix E Comparison VELMOD-3.1 and VELMOD-4b-s5 by using 'blind set' of wells

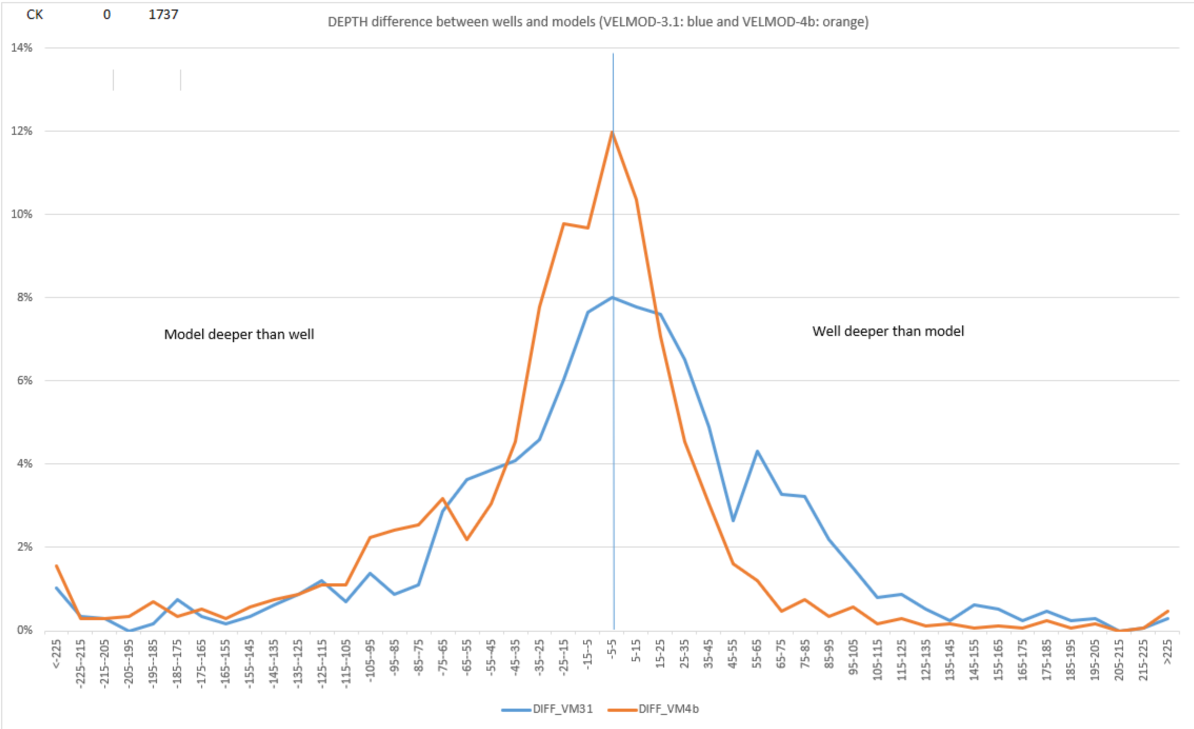
Number wells used for	NU	NM+NL	CK	KN	S+AT	RN+RB	ZE	Total
Velmod-3.1	660	757	1160	1225	631	1024	1063	1642
Velmod-4a	375	376	471	478	207	310	244	577
Velmod-4b	902	925	1321	1343	560	869	698	1623
Velmod-4b-s4	535	748	1148	1207	516	802	-	1493
Velmod-4b-s5	863	823	1172	1239	350	694	698	1550
blindset Velmod-4b	1544	1505	1737	1693	503	921	907	2980

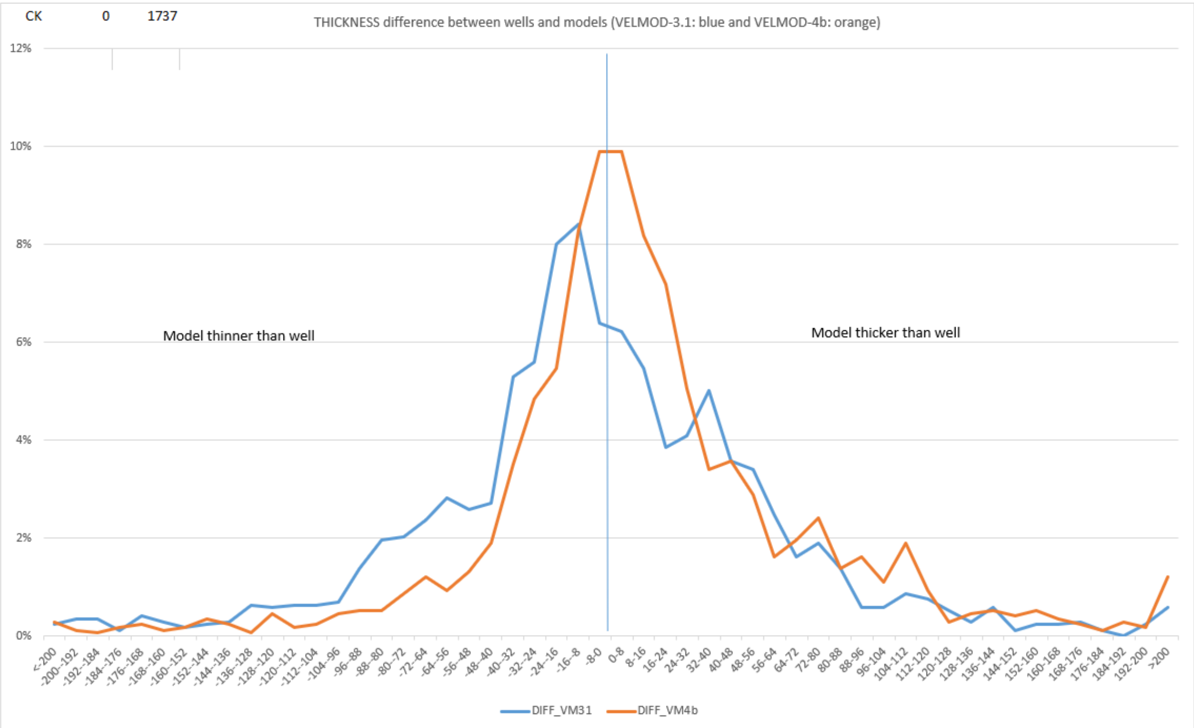

NU 0 1544
DEPTH difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model deeper than well
Well deeper than model
DIFF_VM31
DIFF_VM4b

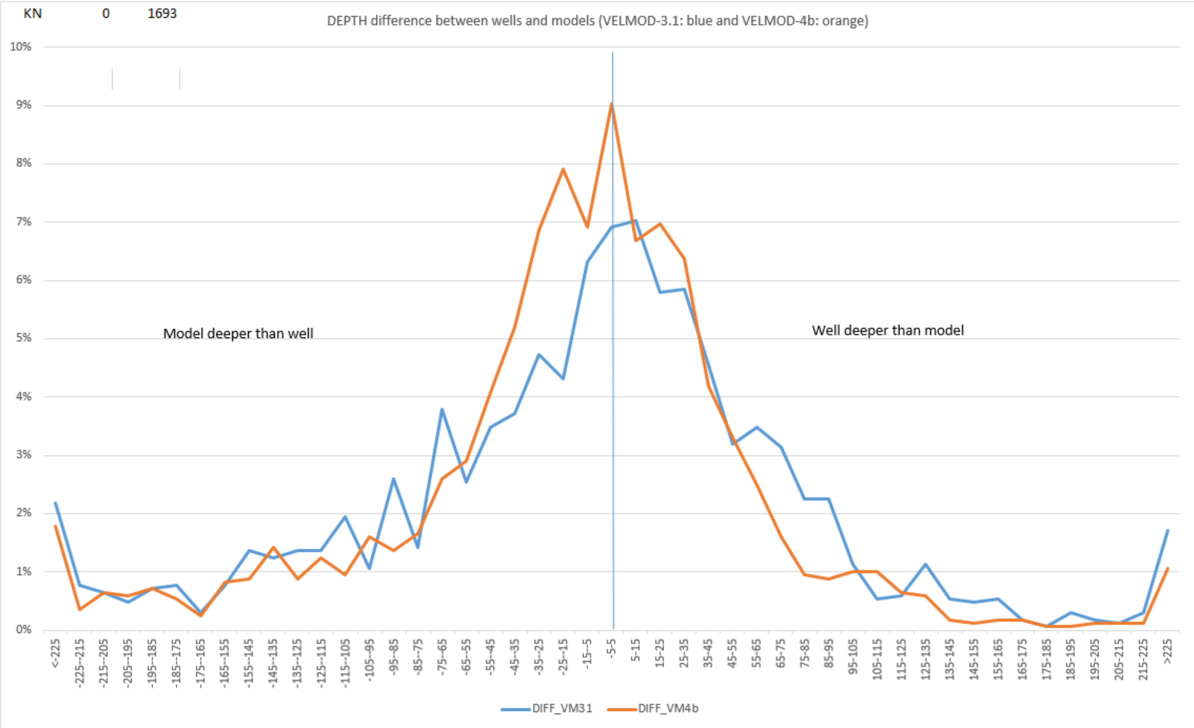

NU 0 1544
THICKNESS difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model thinner than well
Model thicker than well
DIFF_VM31
DIFF_VM4b

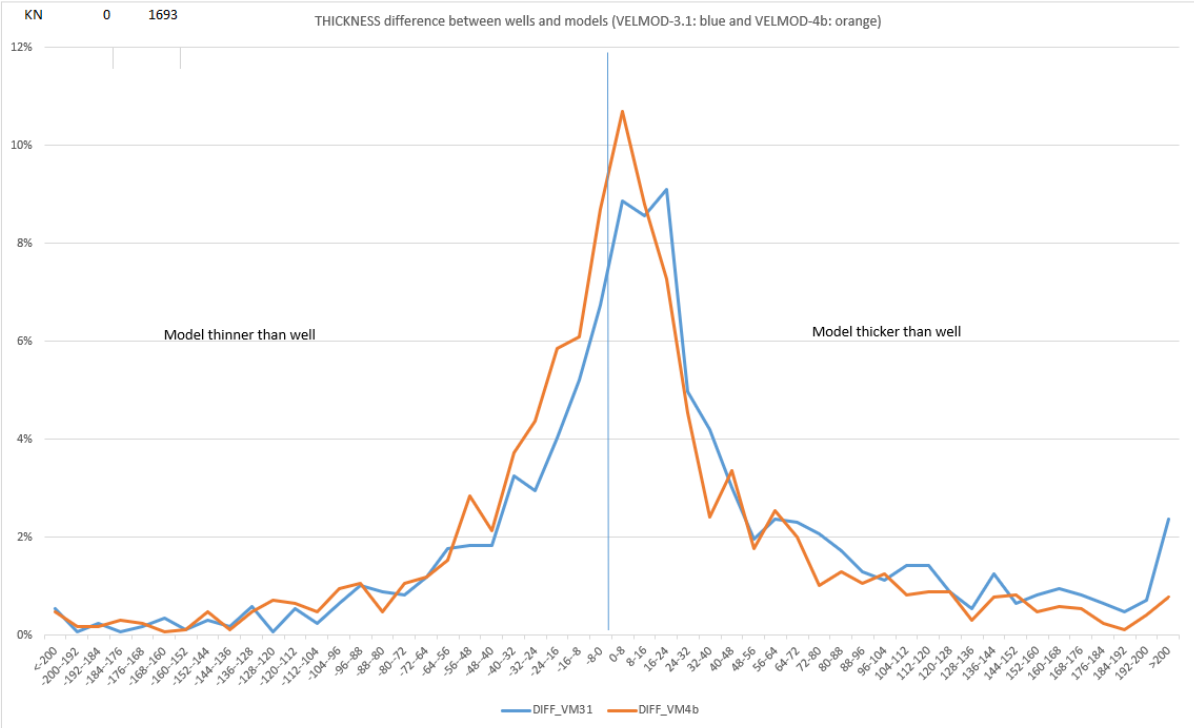

NLM 0 1505
DEPTH difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model deeper than well
Well deeper than model
DIFF_VM31
DIFF_VM4b

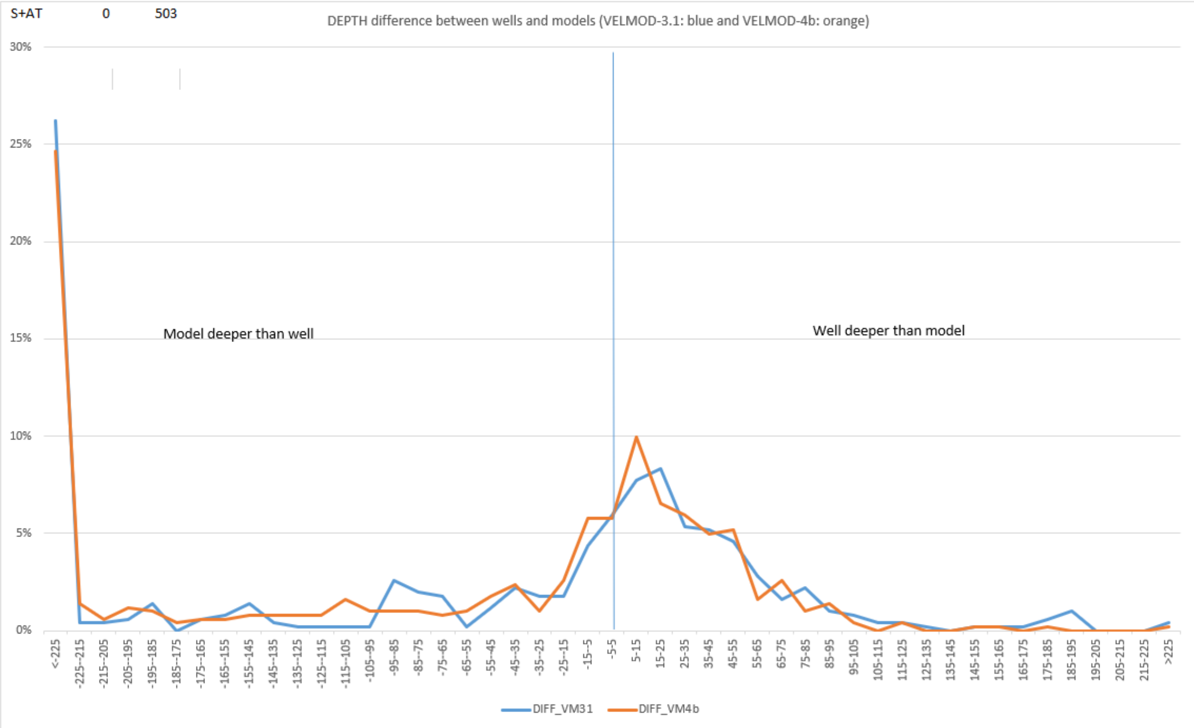

NLM 0 1505
THICKNESS difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model thinner than well
Model thicker than well
DIFF_VM31
DIFF_VM4b

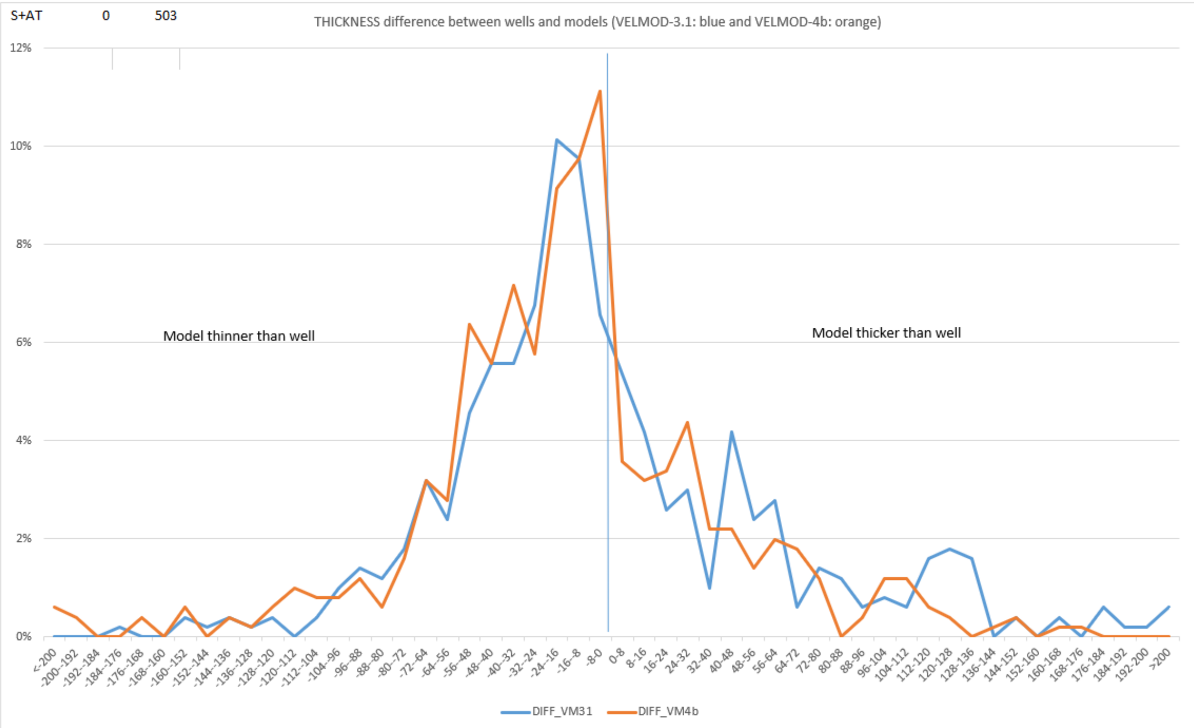

CK 0 1737
DEPTH difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model deeper than well
Well deeper than model
DIFF_VM31
DIFF_VM4b

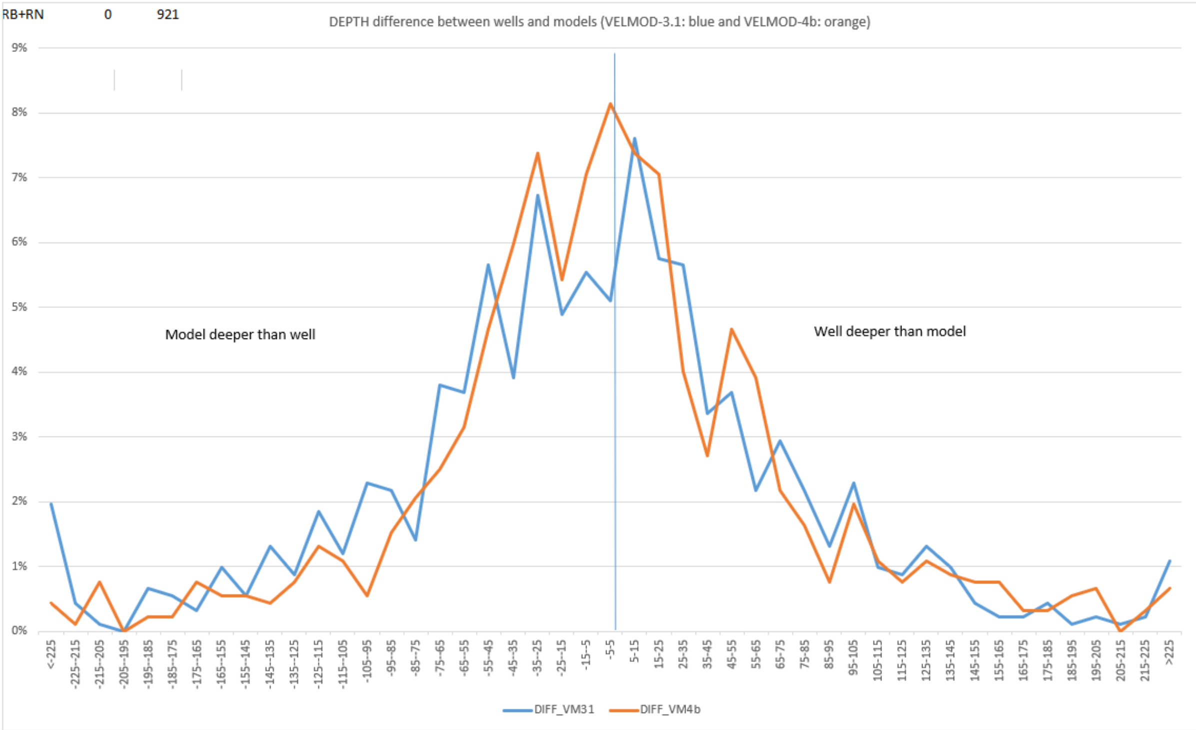

CK 0 1737
THICKNESS difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model thinner than well
Model thicker than well
DIFF_VM31
DIFF_VM4b


KN 0 1693
DEPTH difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model deeper than well
Well deeper than model
DIFF_VM31
DIFF_VM4b

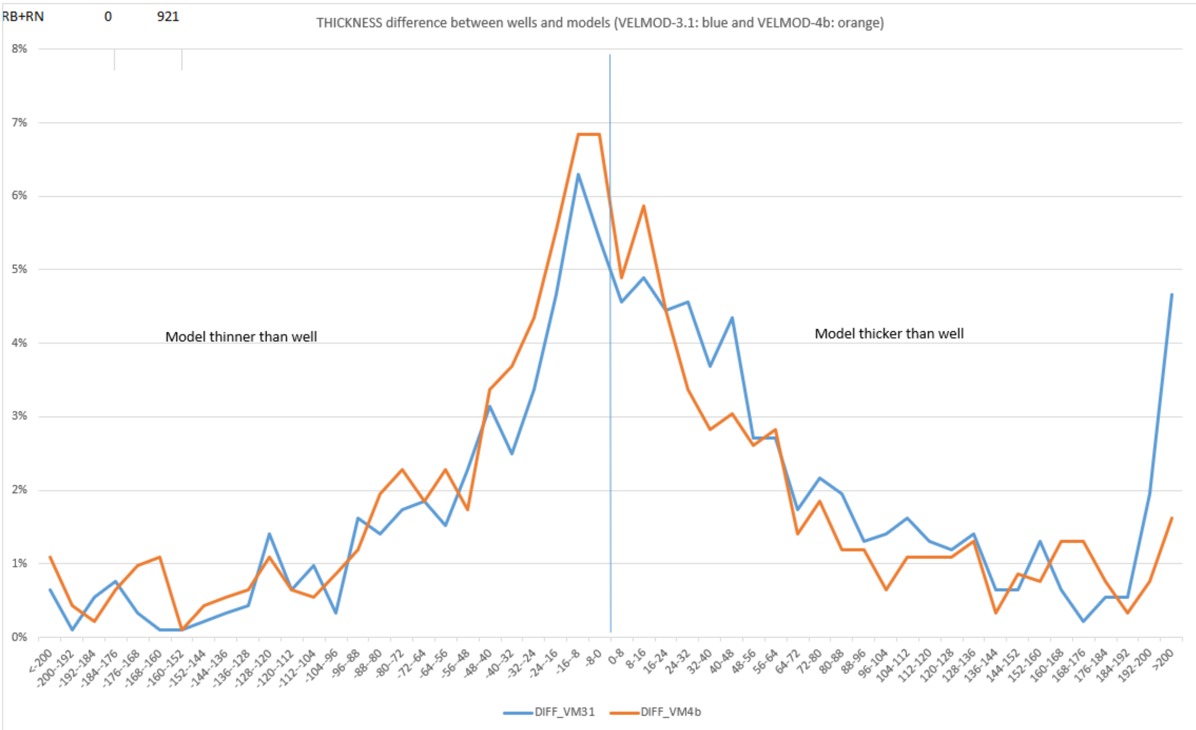

KN 0 1693
THICKNESS difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model thinner than well
Model thicker than well
DIFF_VM31
DIFF_VM4b


S+AT
0
503
DEPTH difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model deeper than well
Well deeper than model
DIFF_VM31
DIFF_VM4b

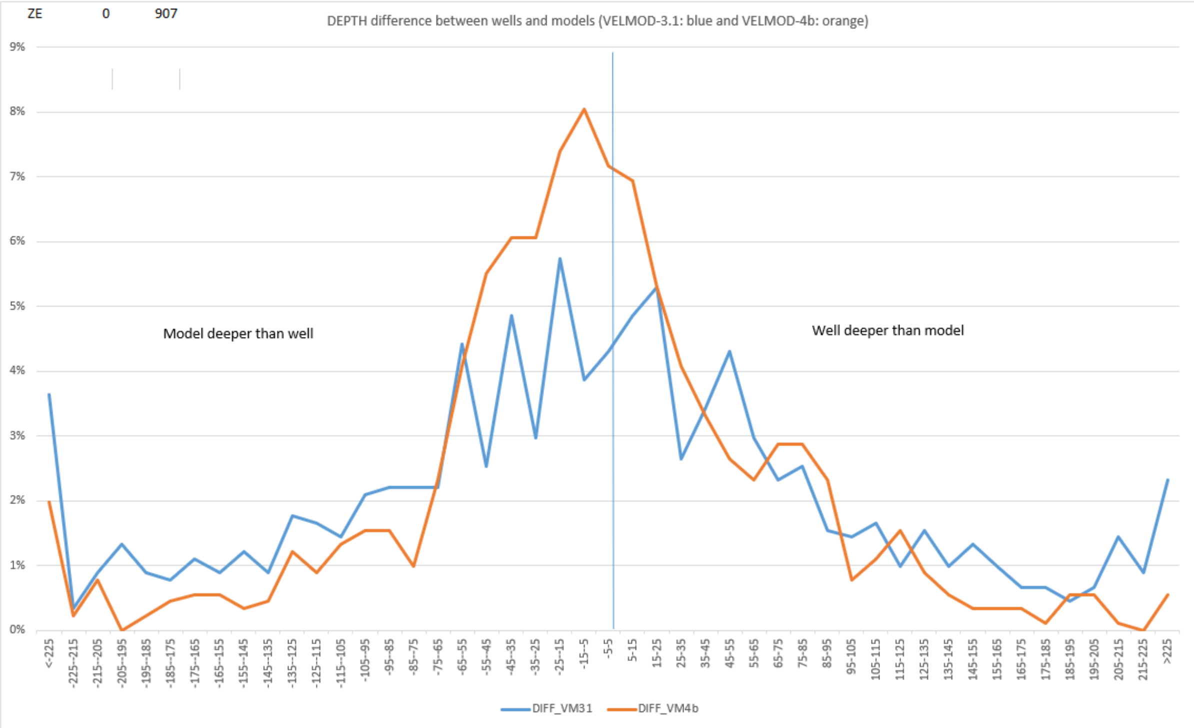

S+AT
0
503
THICKNESS difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model thinner than well
Model thicker than well
DIFF_VM31
DIFF_VM4b



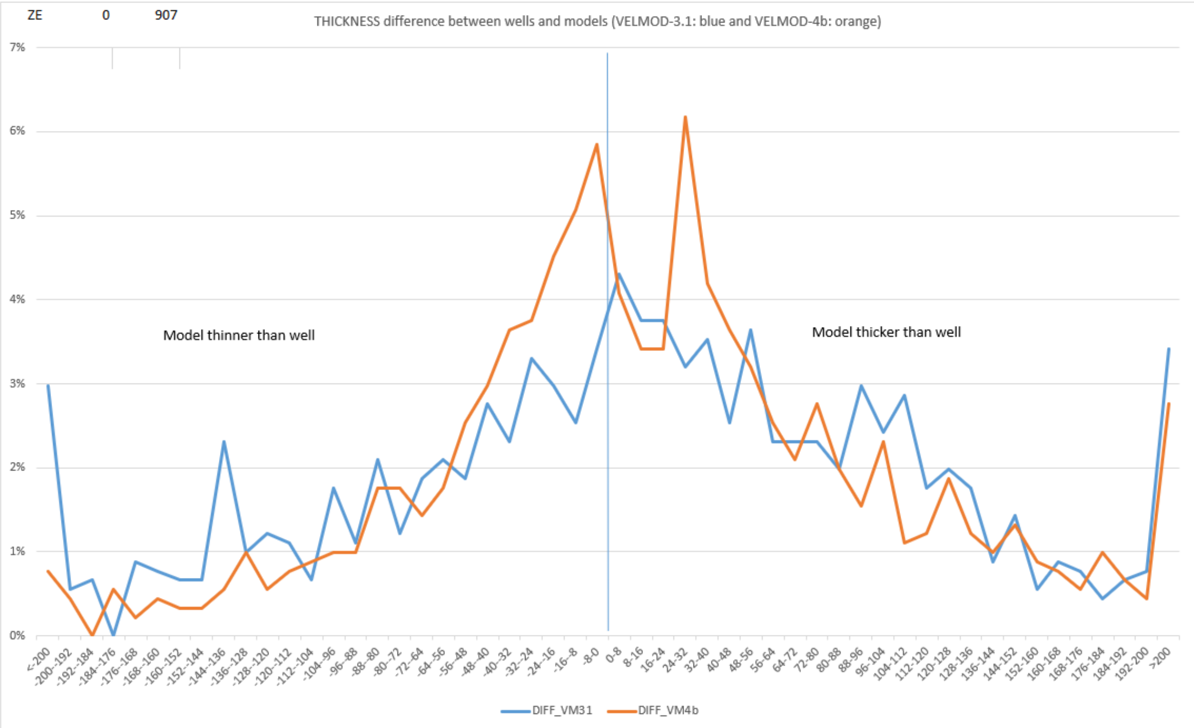
RB+RN
0
921
DEPTH difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
Model deeper than well
Well deeper than model
<-225
-225--215
-215--205
-205--195
-195--185
-185--175
-175--165
-165--155
-155--145
-145--135
-135--125
-125--115
-115--105
-105--95
-95--85
-85--75
-75--65
-65--55
-55--45
-45--35
-35--25
-25--15
-15--5
-5-5
5-15
15-25
25-35
35-45
45-55
55-65
65-75
75-85
85-95
95-105
105-115
115-125
125-135
135-145
145-155
155-165
165-175
175-185
185-195
195-205
205-215
215-225
>225
DIFF_VM31
DIFF_VM4b



RB+RN
0
921
THICKNESS difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
8%
7%
6%
5%
4%
3%
2%
1%
0%
Model thinner than well
Model thicker than well
<-200
-200-192
-192-184
-184-176
-176-168
-168-160
-160-152
-152-144
-144-136
-136-128
-128-120
-120-112
-112-104
-104-96
-96-88
-88-80
-80-72
-72-64
-64-56
-56-48
-48-40
-40-32
-32-24
-24-16
-16-8
-8-0
0-8
8-16
16-24
24-32
32-40
40-48
48-56
56-64
64-72
72-80
80-88
88-96
96-104
104-112
112-120
120-128
128-136
136-144
144-152
152-160
160-168
168-176
176-184
184-192
192-200
>200
DIFF_VM31
DIFF_VM4b



ZE 0 907
DEPTH difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model deeper than well
Well deeper than model
DIFF_VM31
DIFF_VM4b



ZE 0 907
THICKNESS difference between wells and models (VELMOD-3.1: blue and VELMOD-4b: orange)
Model thinner than well
Model thicker than well
DIFF_VM31
DIFF_VM4b