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Deliverable 3.2

A generalized 3D depth model of the Entenschnabel region

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The 3D depth model of the Central Graben region, which has been built during July 2018 to March 2019, as part of WP3 of the 3DGEO-EU project, is a generalized model which will be used within the GARAH-project. The study area covers the Entenschnabel in the northwestern part of the German North Sea sector and the adjacent areas in Denmark and the Netherlands (see Figure 1). The model is based on 8 seismically interpreted horizons (see Table 1).

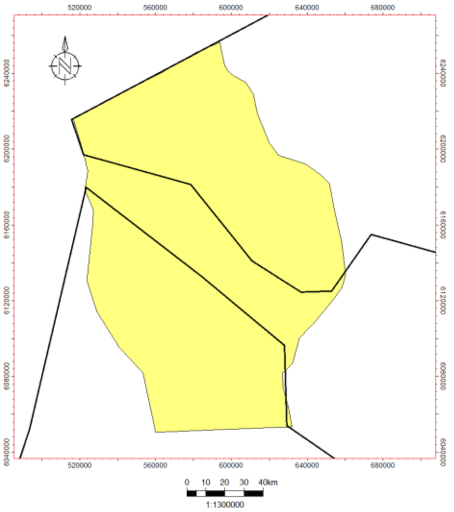


Figure 1 Study area of the Entenschnabel region covering parts of the Danish, German and the Dutch North Sea sectors

No	Horizon	Code	K-value
1	Near base Neogene	NU	0.118
2	Near base Paleogene	NL+NM	
3	Base Upper Cretaceous	CK	0.595
4	Near base Lower Cretaceous	KN	0.207
5	Near base Upper Jurassic	S	0.203
6	Near base Lower Jurassic	AT	0.448
7	Near base Triassic	TR	0.115
8	Base Zechstein	ZE	Not determined

Table 1 Seismically interpreted horizons, the lithostratigraphic unit code and the K-value which have been determined for the lithostratigraphic units.

The first step in the workflow to create a 3D depth model, consists in merging the time horizons of the 3 border areas provided by the contributing parties. The merged time horizons have been resampled at 250x250 m grid resolution and checked for crossing layers. The resulting geometrically coherently stacked 'Near base Neogene' to 'base Triassic' time horizons have been converted to depth using a V_0-K layer cake velocity model (see Appendix 1). In contrast to these horizons the Zechstein horizon has been depth converted by using interval velocities of the Zechstein unit.

After the conversion from time to depth for all horizons, the final generalized 3D depth model has been produced (see 3Dview of the model in Figure 2) with the following limitations:

- No final well correction to tie the depth converted horizons to the well depths has been performed.
- Furthermore, the model does not include multi-z, which implies that complex multi-z structures such as "mushroom" shape salt domes have been modified to a vertical shape.

The final thickness and depth maps are displayed in the figures below.

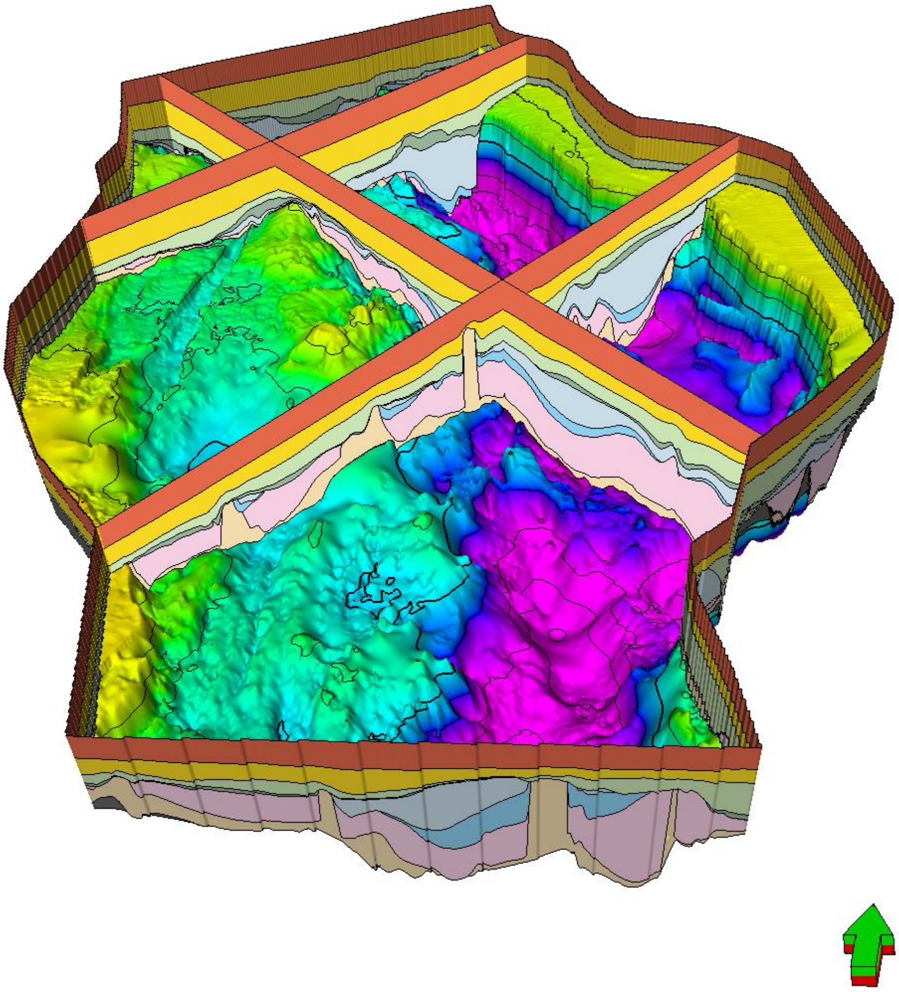
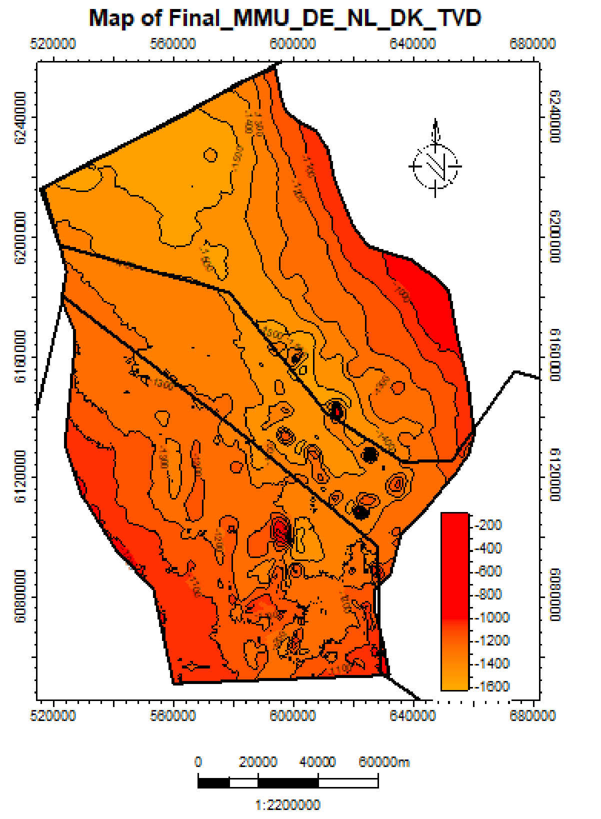
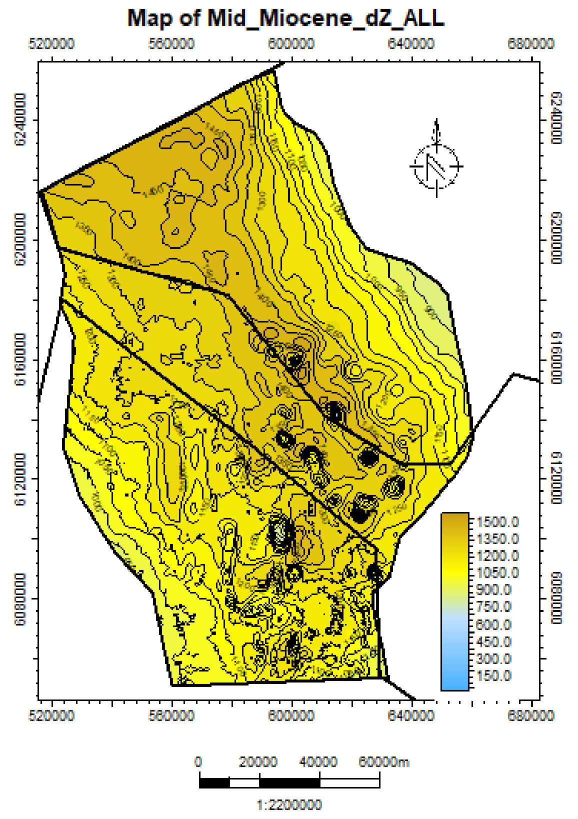


Figure 2 3D-view of the depth of the base Zechstein, which is part of the 3D depth model of the Entenschnabel region. Also several x-sections through the model are shown.

Depth maps:


Map of Final_MMU_DE_NL_DK_TVD
-200
-400
-600
-800
-1000
-1200
-1400
-1600
0 20000 40000 60000m
1:2200000


Map of Mid_Miocene_dZ_ALL
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1350.0
1200.0
1050.0
900.0
750.0
600.0
450.0
300.0
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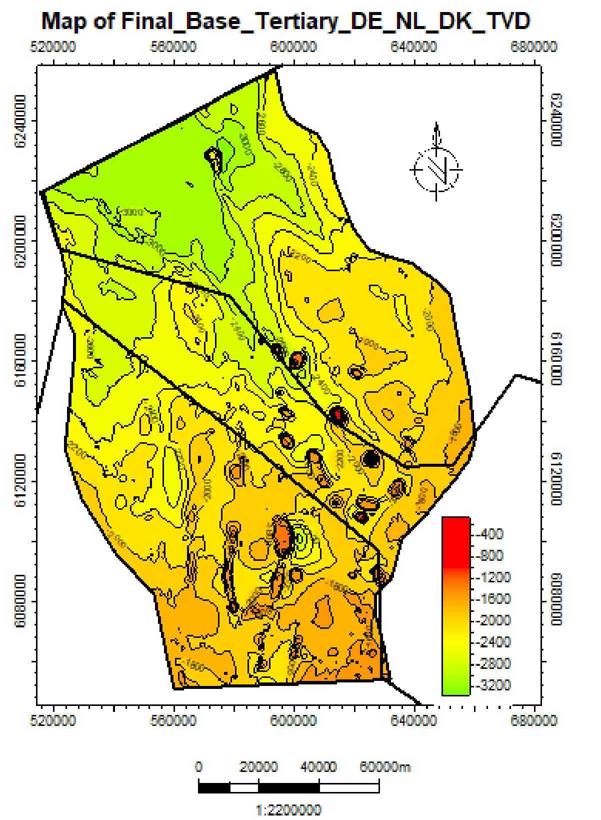
1:2200000


Map of Final_Base_Tertiary_DE_NL_DK_TVD
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-2400
-2800
-3200
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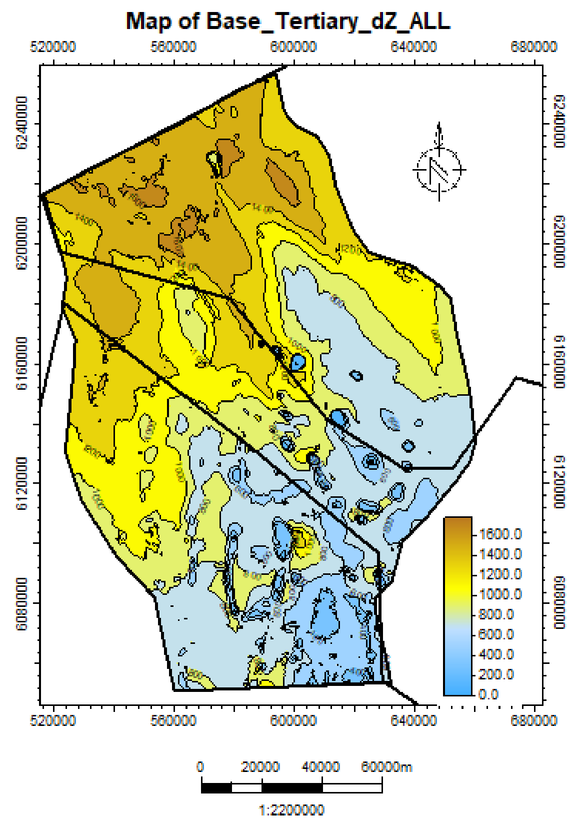
Map of Base_Tertiary_dZ_ALL
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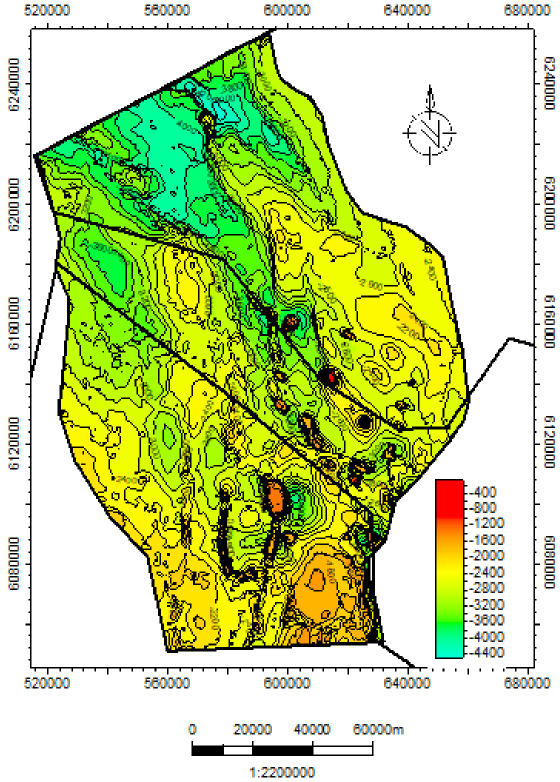
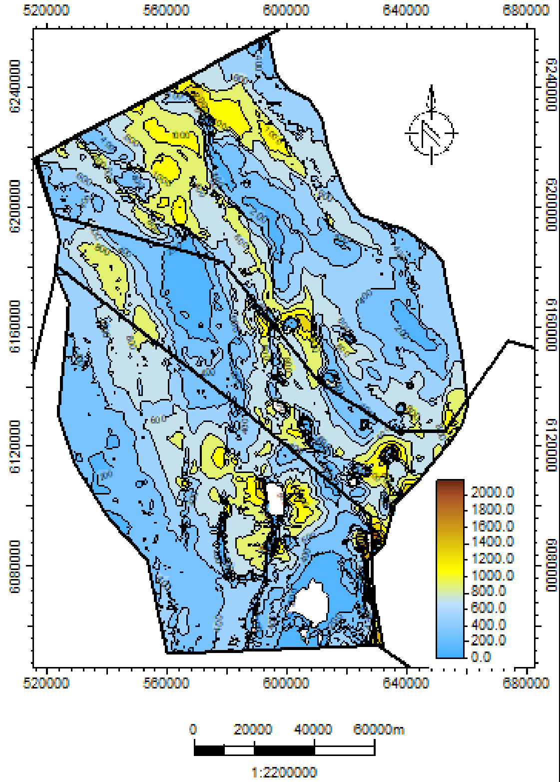
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0 20000 40000 60000m
1:2200000

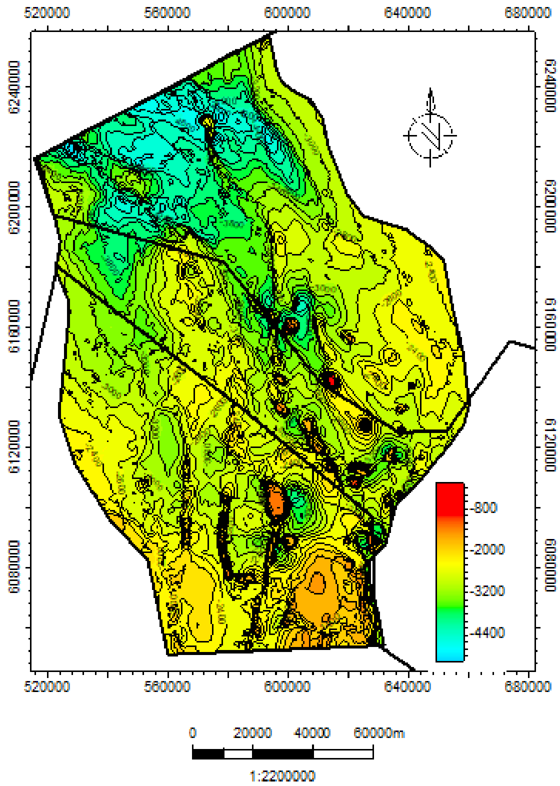
Map of Final_Upper_Cretaceous_DE_NL_DK_TVD



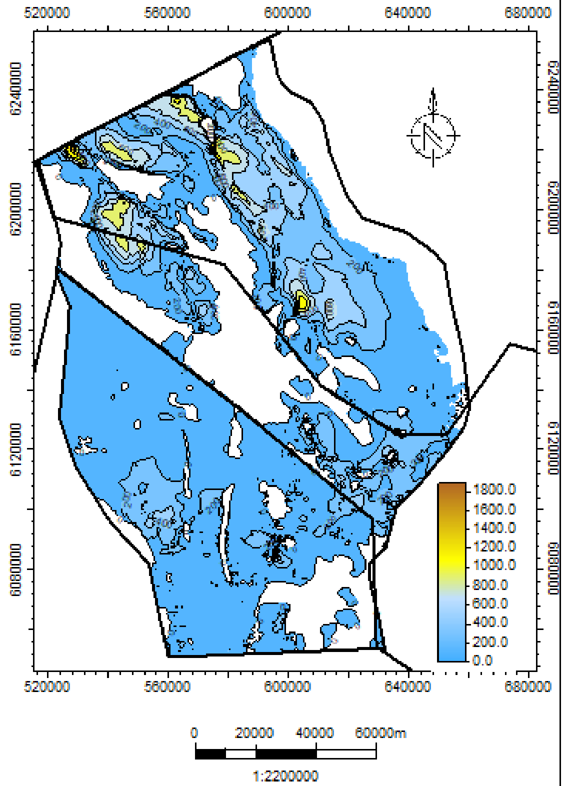
Map of Base_Upper_Cretaceous_dZ_ALL

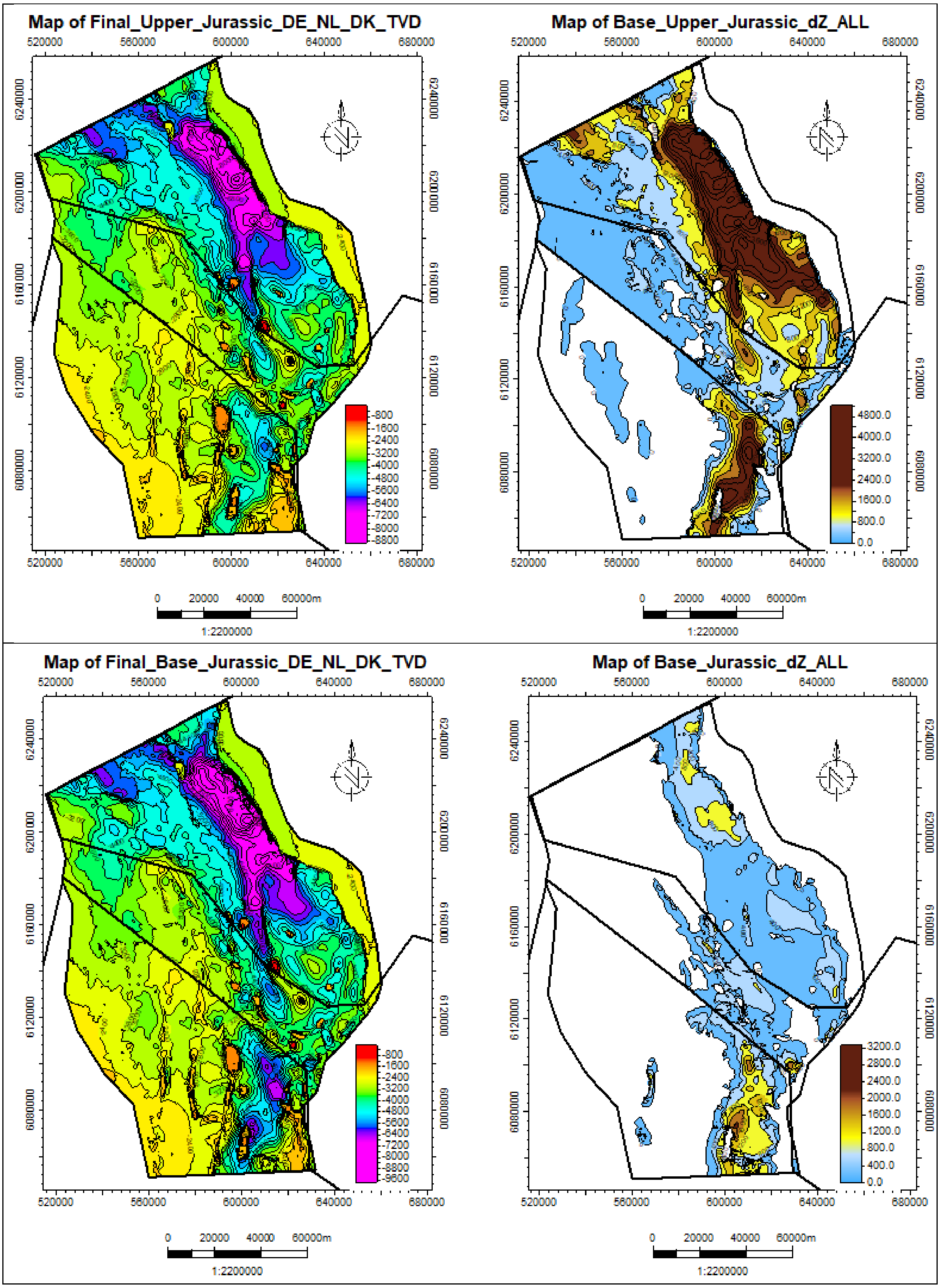


Map of Final_ Base_Cretaceous_DE_NL_DK_TVD



Map of Base_Cretaceous_dZ_ALL




Map of Final_Upper_Jurassic_DE_NL_DK_TVD
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6240000 6200000 6160000 6120000 6080000
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0 20000 40000 60000m
1:2200000
Map of Base_Upper_Jurassic_dZ_ALL
520000 560000 600000 640000 680000
6240000 6200000 6160000 6120000 6080000
4800.0 4000.0 3200.0 2400.0 1600.0 800.0 0.0
0 20000 40000 60000m
1:2200000
Map of Final_Base_Jurassic_DE_NL_DK_TVD
520000 560000 600000 640000 680000
6240000 6200000 6160000 6120000 6080000
-800 -1600 -2400 -3200 -4000 -4800 -5600 -6400 -7200 -8000 -8800 -9600
0 20000 40000 60000m
1:2200000
Map of Base_Jurassic_dZ_ALL
520000 560000 600000 640000 680000
6240000 6200000 6160000 6120000 6080000
3200.0 2800.0 2400.0 2000.0 1600.0 1200.0 800.0 400.0 0.0
0 20000 40000 60000m
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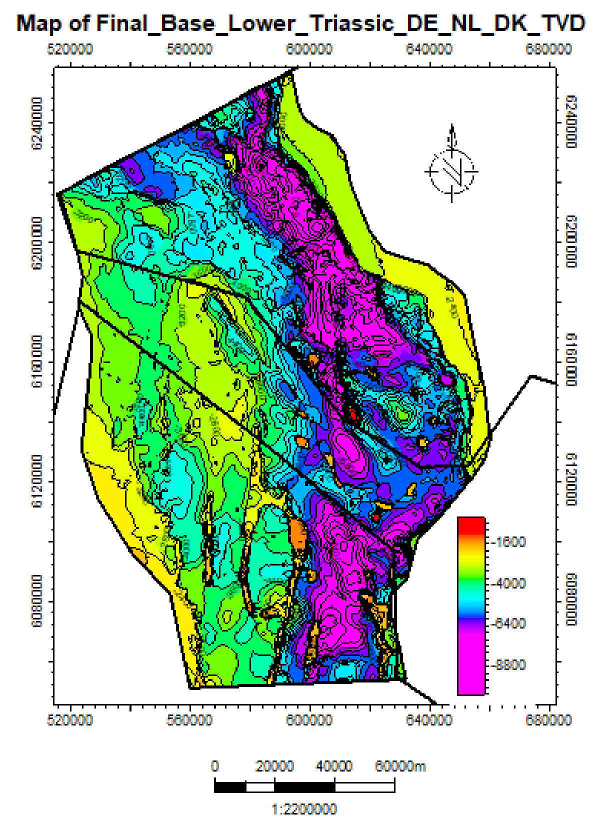
Map of Final_Base_Lower_Triassic_DE_NL_DK_TVD
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560000
600000
640000
680000
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6080000
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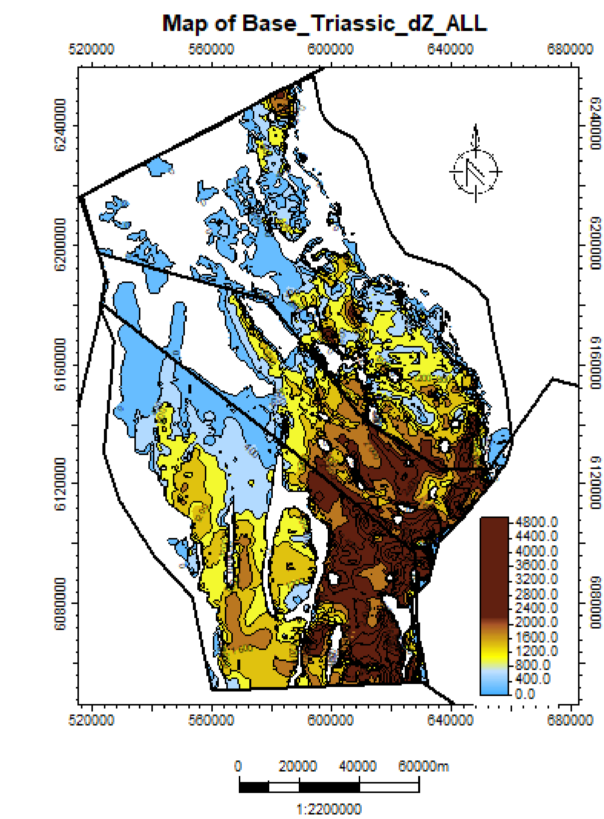
-4000
-6400
-8800
0
20000
40000
60000m
1:2200000


Map of Base_Triassic_dZ_ALL
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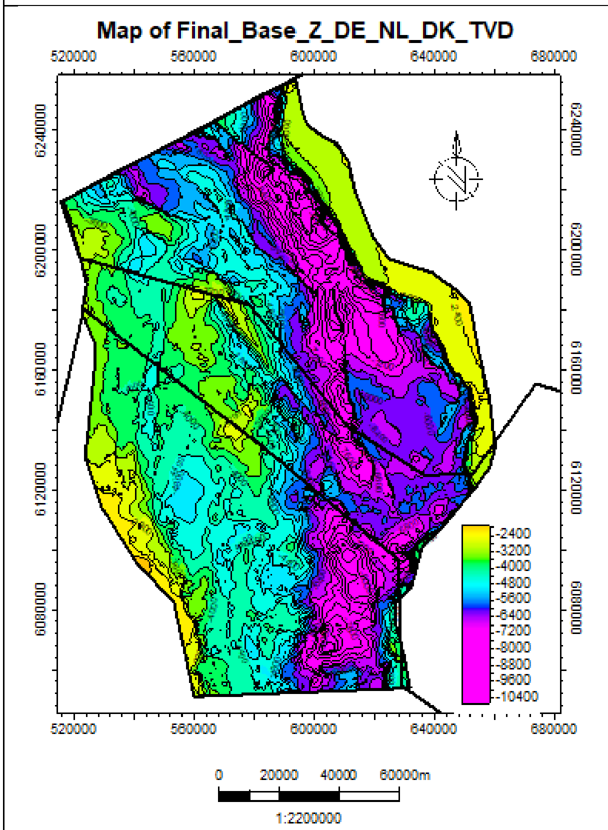
560000
600000
640000
680000
6240000
6200000
6160000
6120000
6080000
4800.0
4400.0
4000.0
3600.0
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0
20000
40000
60000m
1:2200000


Map of Final_Base_Z_DE_NL_DK_TVD
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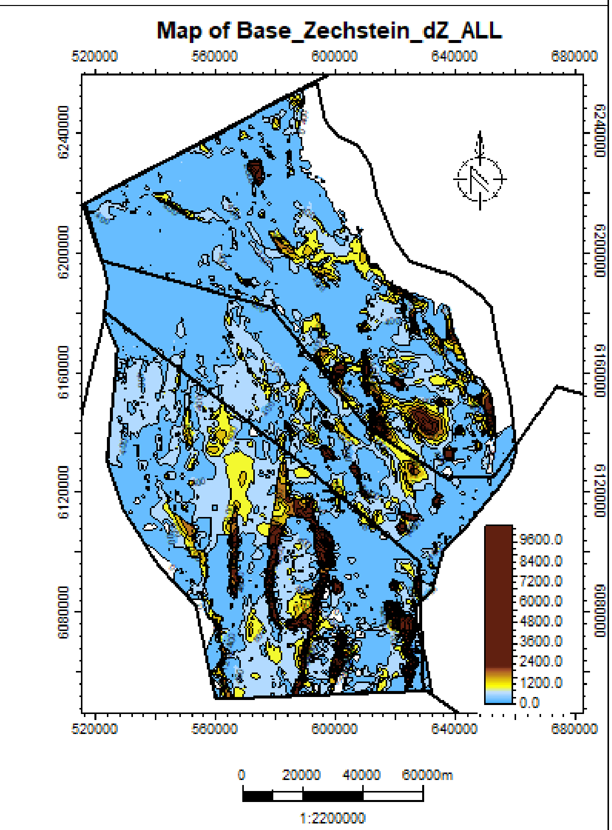
560000
600000
640000
680000
6240000
6200000
6160000
6120000
6080000
-2400
-3200
-4000
-4800
-5600
-6400
-7200
-8000
-8800
-9600
-10400
0
20000
40000
60000m
1:2200000


Map of Base_Zechstein_dZ_ALL
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640000
680000
6240000
6200000
6160000
6120000
6080000
9600.0
8400.0
7200.0
6000.0
4800.0
3600.0
2400.0
1200.0
0.0
0
20000
40000
60000m
1:2200000

Appendix 1: Velocity model of the Entenschnabel region

Purpose of this velocity model is the time depth conversion of the seismic interpreted time-grids to depth. For the Cenozoic to Triassic units a V_0-K layer cake velocity model has been used, which assumes that the acoustic velocity of a unit increases linearly with depth under the influence of burial and compaction.

$$V(x,y,z) = V_0(x,y) + K \cdot z$$

$V(x,y,z)$	= velocity of the unit at depth z
$V_0(x,y)$	= velocity at ordnance level
K	= factor determining the linear increase of velocity with depth

For the conversion of the base Zechstein time horizon to depth, the interval velocities of the Zechstein layer have been used.
In the following at first the determination of the K-factor is described, then the production of the $V_0(x,y)$-grids per lithostratigraphic unit and finally the velocity model used for the Zechstein.

(i) Determination of K-factor

K-factor is determined per lithostratigraphic unit with time-depth pairs for all wells available in the area by plotting V_{int} - Z_{mid} pairs in a scatterplot using the linear least square relation between V_{int} and Z_{mid}: $V_{int}(z_{mid}) = V_0 + K \cdot z_{mid}$
Subdivision of the dataset in the three structural elements, i.e. Mid North Sea High (mnsh), Step Graben (sg) and Central Graben (cg), is examined but did not show clear difference in characteristics. The velocity model is created for a minimal lithostratigraphic unit configuration as the dataset appeared to be too limited for a detailed unit configuration. The following sub-units are merged:

- NU and NL+NM are merged to N (Cenozoic)
- AT1 and AT2 are merged to AT
- RN (RN1 and RN2) and RB are merged to TR

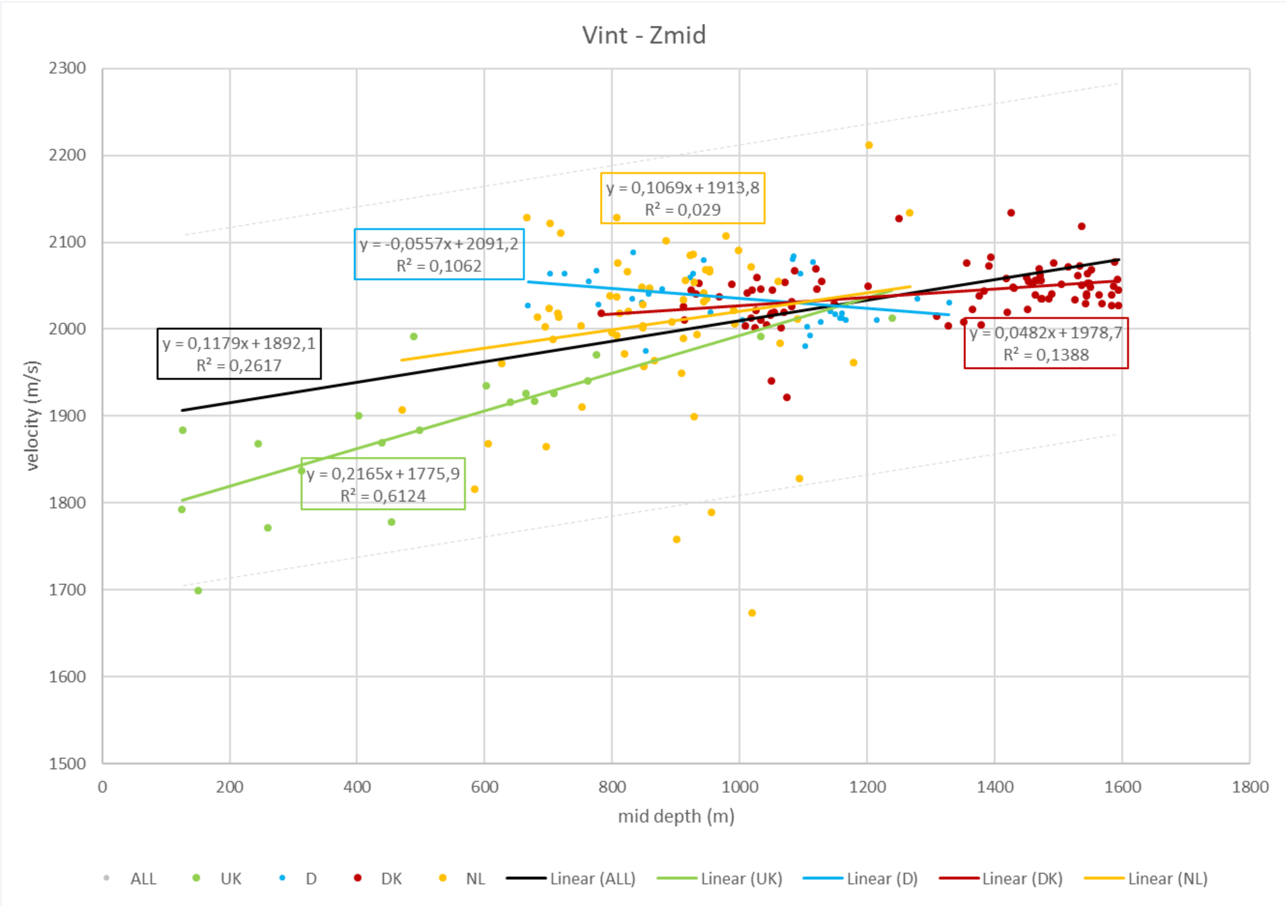
The final results of the determination of the K-factor per lithostratigraphic unit are listed in Table 1.

Lithostratigraphic unit	Code	K-factor	V0	R^2	#
Cenozoic	N	0,118	1892	0,26	209
Upper Cretaceous	CK	0,595	2424	0,66	195
Lower Cretaceous	KN	0,207	2623	0,14	143
Upper Jurassic	S	0,203	2237	0,18	103
Lower + Middle Jurassic	AT	0,448	1824	0,79	52
Triassic	TR	0,115	3116	0,10	48
Zechstein	ZE	not determined			
Upper Rotliegend	RO	0,081	3887	0,01	48
Carboniferous	DC	0,277	3251	0,4	23

Table 1

The following paragraphs show -per modeled lithostratigraphic unit- a Vint-Zmid diagram with the national datasets in separate colors with each a separate regression line. The black regression line is valid for the whole dataset. K-factor, global V0, R-squared and the number of TZ-pairs are also presented in a table. The last three tables show the same parameters for the structural elements.

Cenozoic (N)



N all	K	V0	R2	#
ALL	0,118	1892	0,26	209
NL	0,107	1914	0,03	65
UK	0,217	1776	0,61	20
D	-0,056	2091	0,11	34
DK	0,048	1979	0,14	90
VELMOD-3	0,284	1788	0,30	-

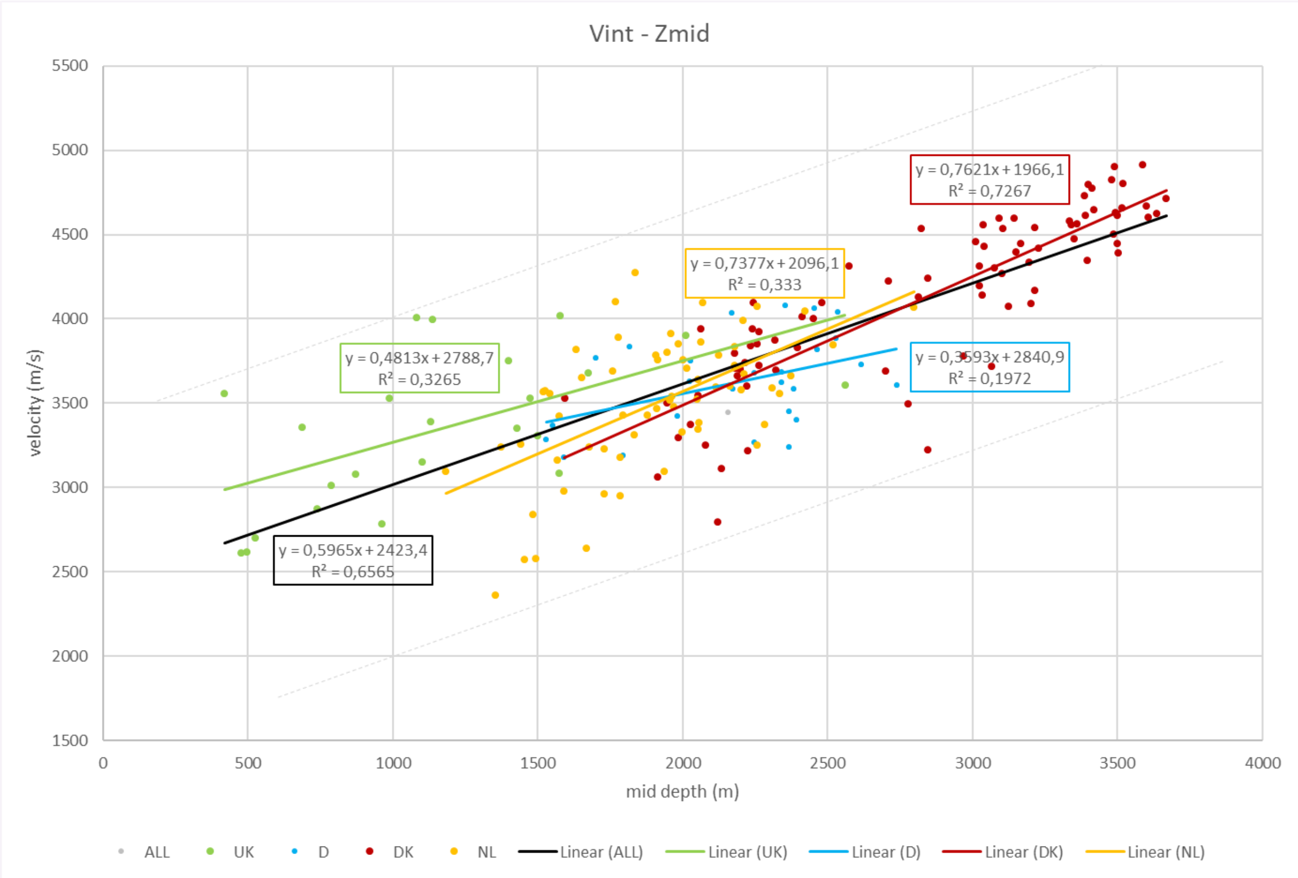
N mnsh	K	V0	R2	#
ALL	0,234	1766	0,51	27
NL	0,246	1757	0,20	9
UK	0,229	1768	0,65	18
D	-	-	-	-
DK	-	-	-	-

N cg	K	V0	R2	#
ALL	0,041	1999	0,05	96
NL	0,160	1904	0,08	31
UK	-	-	-	-
D	0,049	2017	0,10	13
DK	0,079	1945	0,02	52

N sg	K	V0	R2	#
ALL	0,096	1901	0,02	77
NL	0,117	1877	0,03	25
UK	-	-	-	-
D	0,037	1974	0,05	17
DK	0,080	1923	0,12	35

The following wells are considered outliers: A12-01 (NL), A15-01 (NL), A17-01 (NL), B13-01 (NL)

Upper Cretaceous (CK)



CK	K	V0	R2	#
ALL	0,595	2424	0,66	195
NL	0,738	2096	0,33	64
UK	0,481	2789	0,33	23
D	0,359	2841	0,20	26
DK	0,762	1966	0,73	82
VELMOD-3	0,889	2257	0,74	-

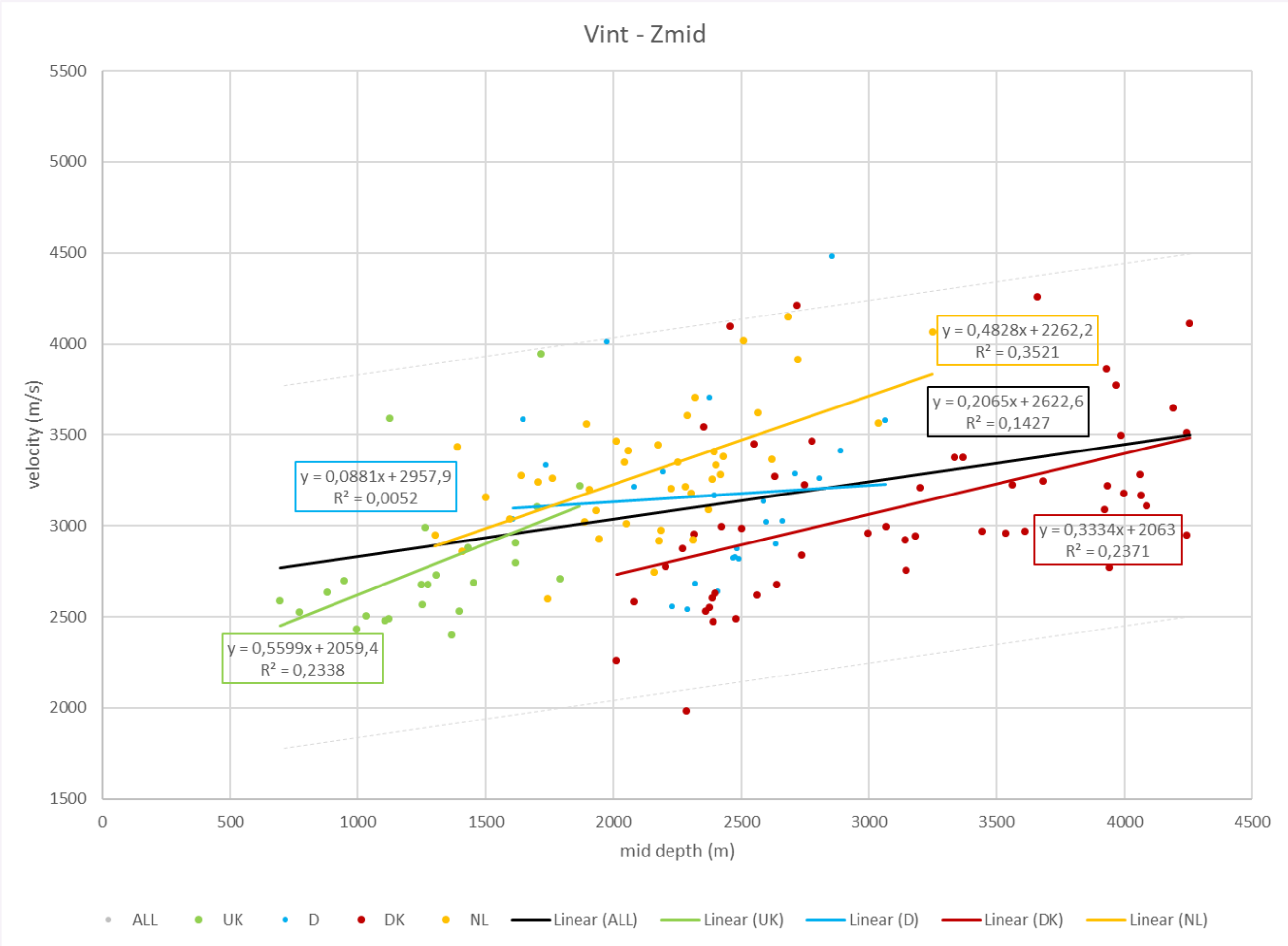
CK mnsh	K	V0	R2	#
ALL	0,530	2735	0,43	32
NL	0,842	2179	0,47	9
UK	0,481	2789	0,33	23
D	-	-	-	-
DK	-	-	-	-

CK cg	K	V0	R2	#
ALL	0,719	2112	0,64	88
NL	0,924	1793	0,33	30
UK	-	-	-	-
D	0,664	2274	0,69	11
DK	0,811	1831	0,69	47

CK sg	K	V0	R2	#
ALL	0,861	1589	0,71	71
NL	0,895	1634	0,57	23
UK	-	-	-	-
D	0,627	1842	0,07	14
DK	0,660	2289	0,41	34

The following wells are considered outliers: 369400 (D), 733602 (D), 151573 (D), F06-01-S1 (NL), B17-03 (NL)

Lower Cretaceous (KN)



KN	K	V0	R2	#
ALL	0,207	2623	0,14	143
NL	0,483	2263	0,35	42
UK	0,560	2059	0,23	24
D	0,088	2958	0,01	25
DK	0,333	2063	0,24	52
VELMOD-3	0,536	2133	0,69	-

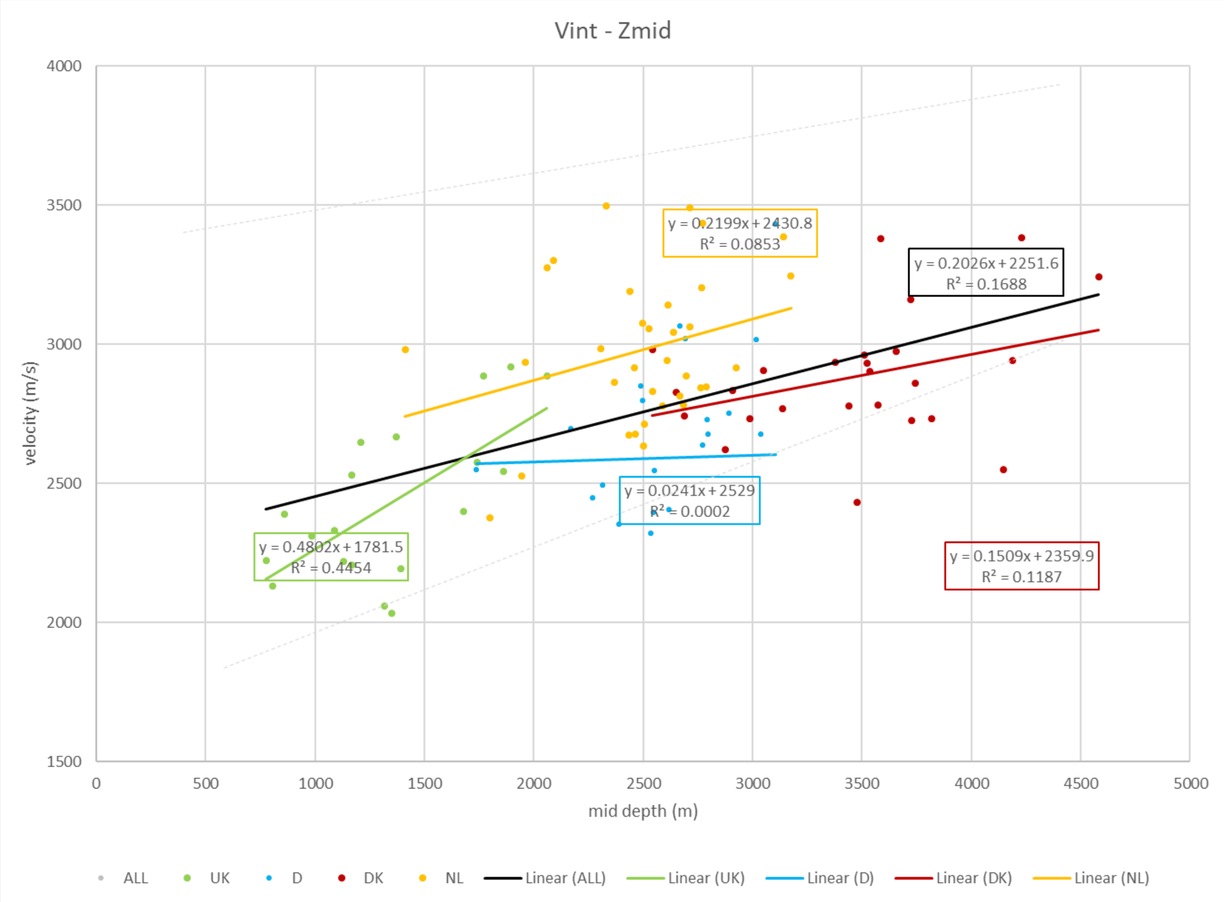
KN mnsh	K	V0	R2	#
ALL	0,587	2020	0,36	28
NL	0,420	2360	0,38	6
UK	0,598	2000	0,23	22
D	-	-	-	-
DK	-	-	-	-

KN cg	K	V0	R2	#
ALL	0,012	3067	0,00	61
NL	0,055	3266	0,01	17
UK	-	-	-	-
D	0,154	3112	0,03	11
DK	0,228	2309	0,09	33

KN sg	K	V0	R2	#
ALL	0,273	2633	0,10	50
NL	1,091	1056	0,60	19
UK	-	-	-	-
D	1,060	175	0,88	10
DK	-0,032	3733	0,00	21

The following wells are considered outliers: Elly-2 (DK), A08-01 (NL), A12-01 (NL)

Upper Jurassic (S)



S	K	V0	R2	#
ALL	0,203	2251	0,17	102
NL	0,220	2431	0,08	36
UK	0,480	1782	0,45	19
D	0,024	2529	0,00	22
DK	0,151	2360	0,12	26
VELMOD-3	0,520	1609;2120;2557	0,47;0,22;0,34	-

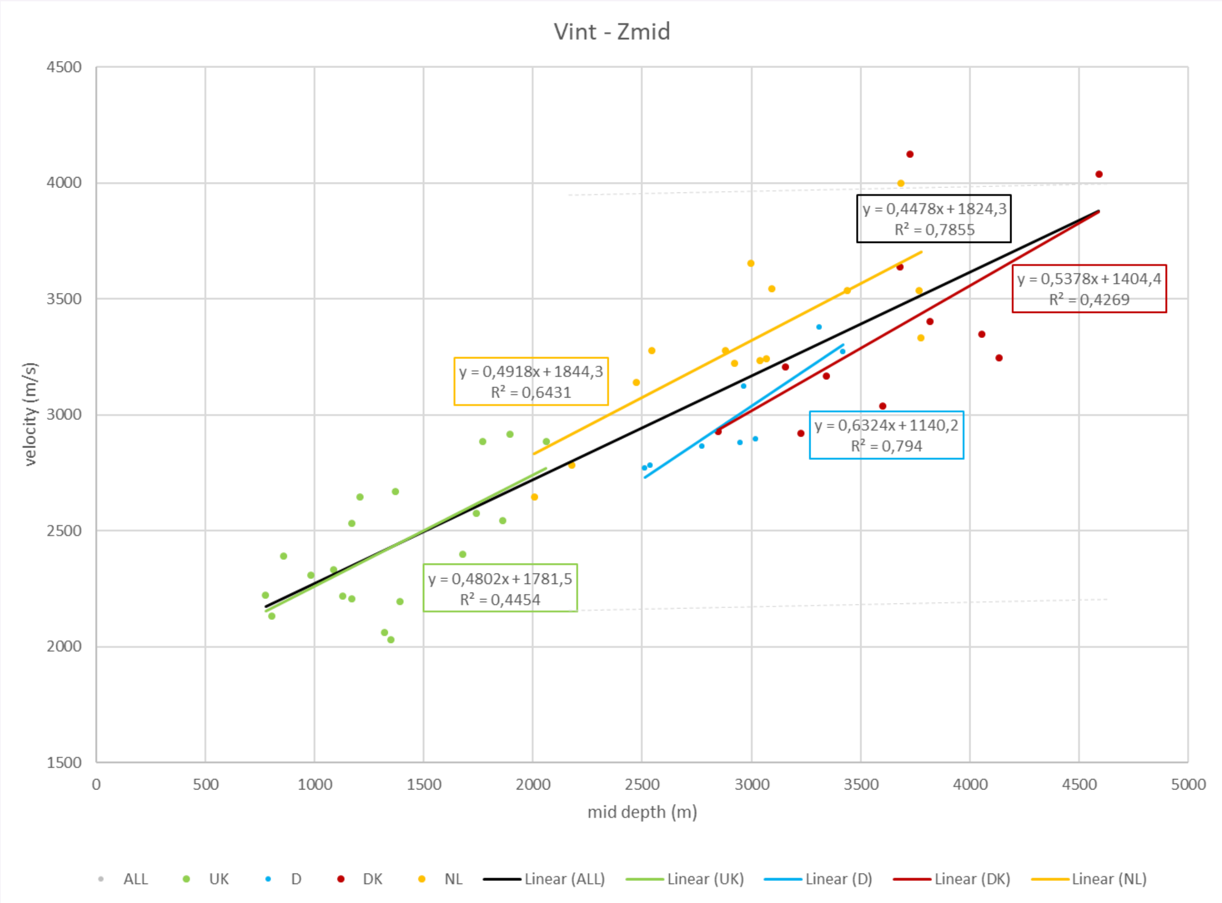
S mnsh	K	V0	R2	#
ALL	-	-	-	-
NL	-	-	-	-
UK	0,489	1767	0,44	18
D	-	-	-	-
DK	-	-	-	-

S cg	K	V0	R2	#
ALL	0,123	2534	0,10	51
NL	0,128	2566	0,05	25
UK	-	-	-	-
D	0,417	1740	0,41	8
DK	0,183	2278	0,17	18

S sg	K	V0	R2	#
ALL	0,027	2793	0,00	26
NL	0,375	2345	0,17	8
UK	-	-	-	-
D	0,666	855	0,30	11
DK	0,189	2147	0,08	7

The following wells are considered outliers: F11-03 (NL), A12-02 (NL), CLEO-1 (DK), 877047 (D), 42/13-1 (UK)

Lower + Middle Jurassic (AT)



AT	K	V0	R2	#
ALL	0,448	1824	0,79	52
NL	0,492	1844	0,64	14
UK	0,480	1782	0,45	19
D	0,632	1140	0,79	8
DK	0,538	1404	0,43	11
VELMOD-3	0,436	2259	0,59	-

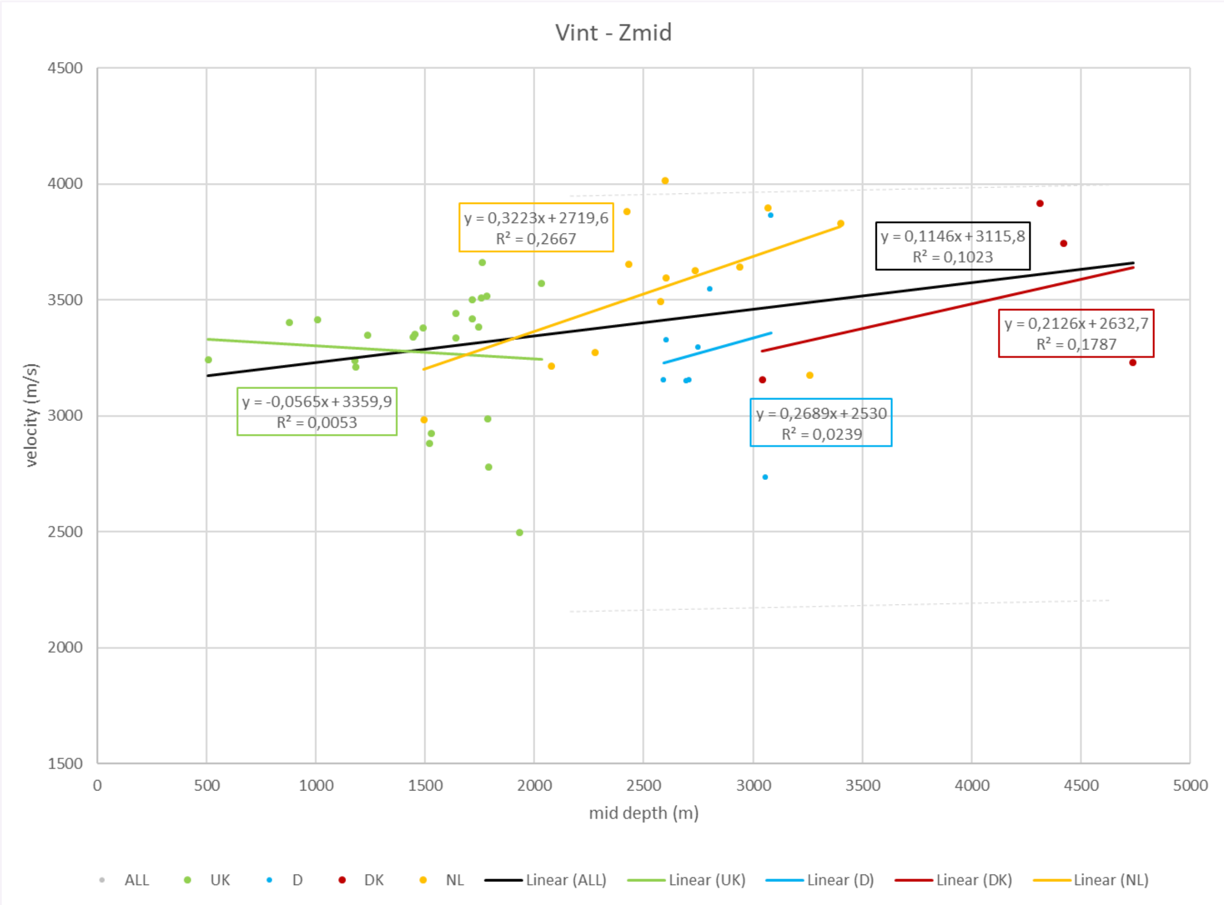
AT mnsh	K	V0	R2	#
ALL	-	-	-	-
NL	-	-	-	-
UK	0,489	1767	0,44	18
D	-	-	-	-
DK	-	-	-	-

AT cg	K	V0	R2	#
ALL	0,446	1867	0,47	28
NL	0,492	1844	0,64	14
UK	-	-	-	-
D	0,754	779	0,79	5
DK	0,592	1241	0,47	9

AT sg	K	V0	R2	#
ALL	-	-	-	6
NL	-	-	-	8
UK	-	-	-	-
D	-	-	-	4
DK	-	-	-	2

The following wells are considered outliers: 131124 (D), 211159 (D), 42/13-1 (UK)

Triassic (TR)



TR	K	V0	R2	#
ALL	0,115	3116	0,10	48
NL	0,322	2720	0,27	13
UK	-0,057	3360	0,01	23
D	0,269	2530	0,02	8
DK	0,213	2633	0,18	4
VELMOD-3	0,374	3046	0,38	-

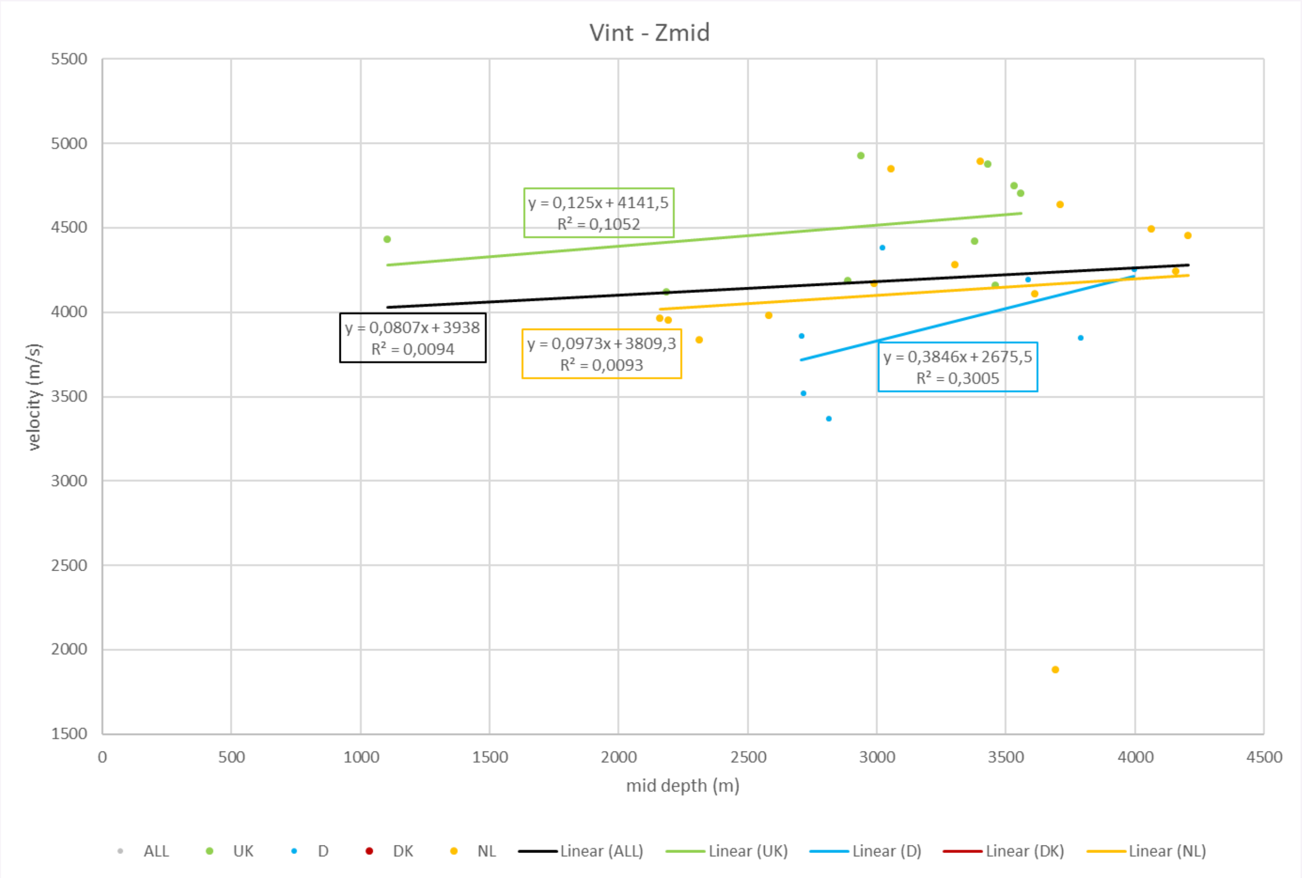
TR mnsh	K	V0	R2	#
ALL	0,301	2765	0,07	22
NL	-	-	-	3
UK	0,011	3240	0,00	19
D	-	-	-	-
DK	-	-	-	-

TR cg	K	V0	R2	#
ALL	-	-	-	-
NL	-	-	-	-
UK	-	-	-	-
D	-	-	-	-
DK	-	-	-	-

TR sg	K	V0	R2	#
ALL	0,106	3135	0,09	45
NL	0,100	3340	0,02	10
UK	-0,057	3360	0,01	23
D	0,269	2530	0,02	8
DK	0,213	2633	0,18	4

The following wells are considered outliers: Elly-1 (DK), 877047 (D), 797445 (D)

Upper Rotliegend (RO)



RO	K	V0	R2	#
ALL	0,081	3938	0,01	28
NL	0,097	3809	0,01	14
UK	0,125	4142	0,11	9
D	0,385	2675	0,30	5
DK	-	-	-	-
VELMOD-3	0,309	3209	0,31	-

Carboniferous (DC)

DC	K	V0	R2	#
ALL	0,277	3251	0,40	23
NL	0,370	2985	0,74	5
UK	0,193	3417	0,20	17
D	-	-	-	1
DK	-	-	-	-
VELMOD-3	0,261	3427	0,44	-

(ii) Production of $V_0(x,y)$ grids

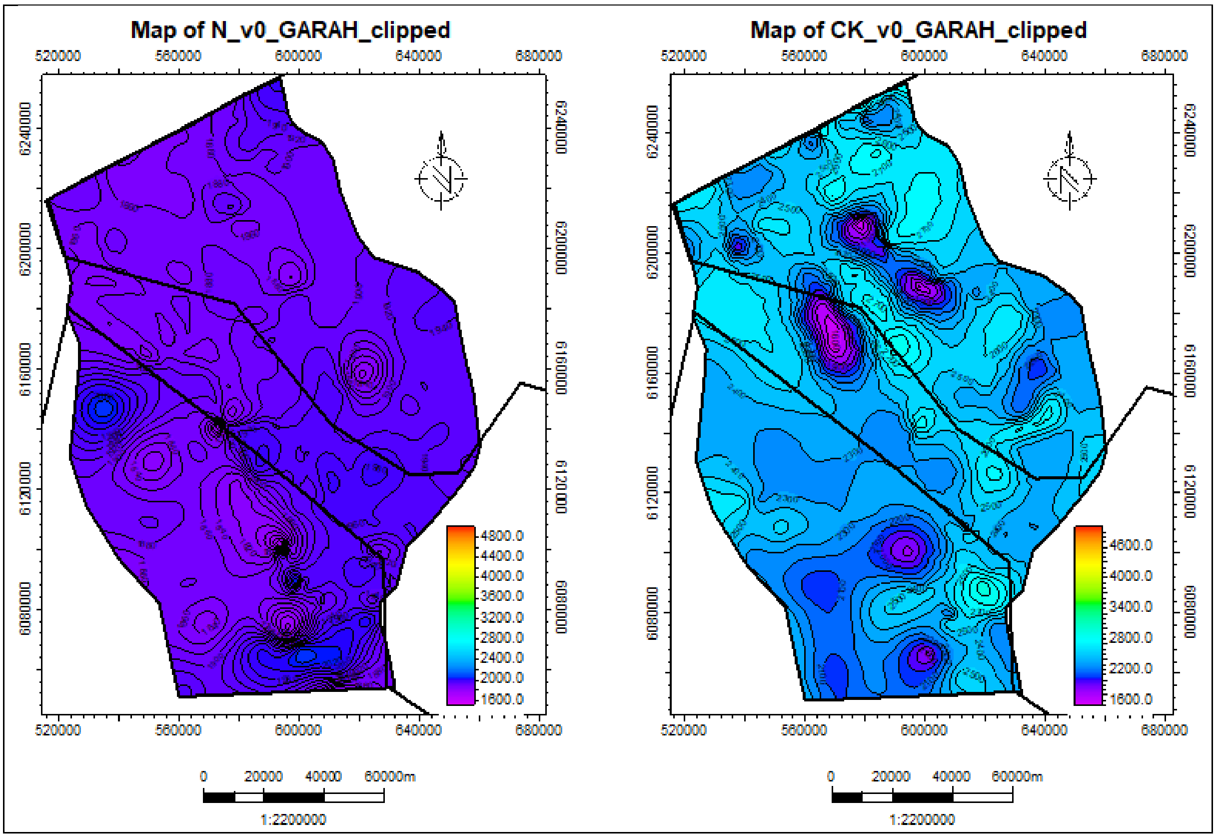
Per lithostratigraphic unit the location dependent $V_0(x,y)$ values at borehole locations have to be computed using the determined K-factor for this lithostratigraphic unit (Table 1) by:

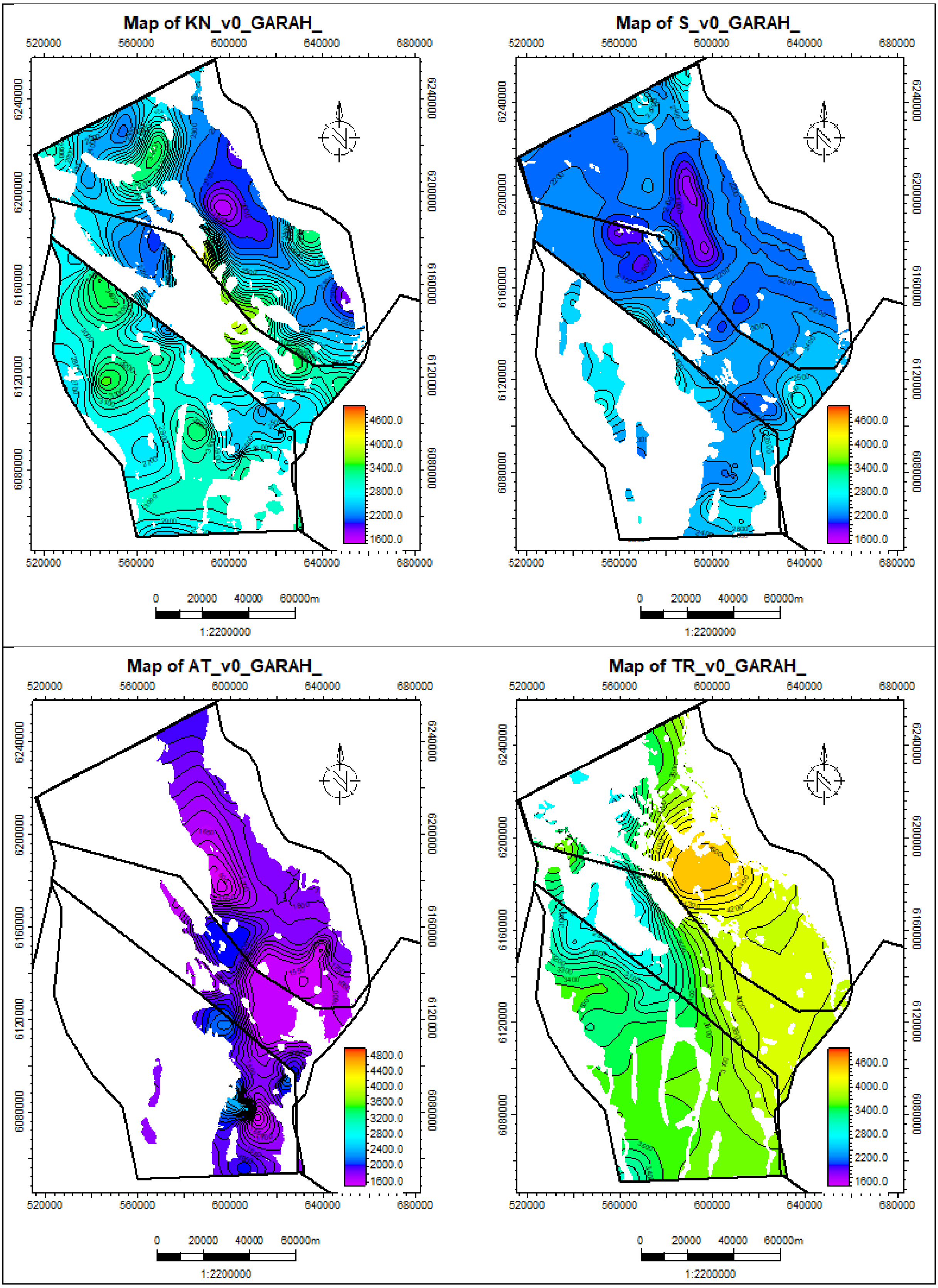
$$V_0(x,y) = K\cdot [z_b - z_t\cdot \exp(K\cdot \Delta T)] \cdot [\exp(K\cdot \Delta T) - 1]^{-1}$$

These V_0-values have been gridded at 250x250 m grid resolution using a kriging gridding algorithm in the Dutch sector. In the German and Danish area V_0-values have been resampled to 500x500 m grid resolution following several gridding steps. Triangulation of German and Danish V_0-values, resulting in a mesh with sharp edges, served as a constraint for remeshing the intermediate result. This grid in turn was smoothed and served as a constraint for an interpolation with DSI (Discrete smooth interpolator) to obtain a final smoothed surface for the German and Danish area. To prevent mismatches at the Dutch German border steering points obtained from the smoothed German-Danish grid have been included in kriging V_0-values of the Dutch sector. A final merge and resampling has been executed at 250x250 m grid resolution. Prior to gridding V_0-values have been checked for anomalous velocities and anomalous values have been removed from the gridding input. An anomalous velocity could be caused by geological reasons for example:

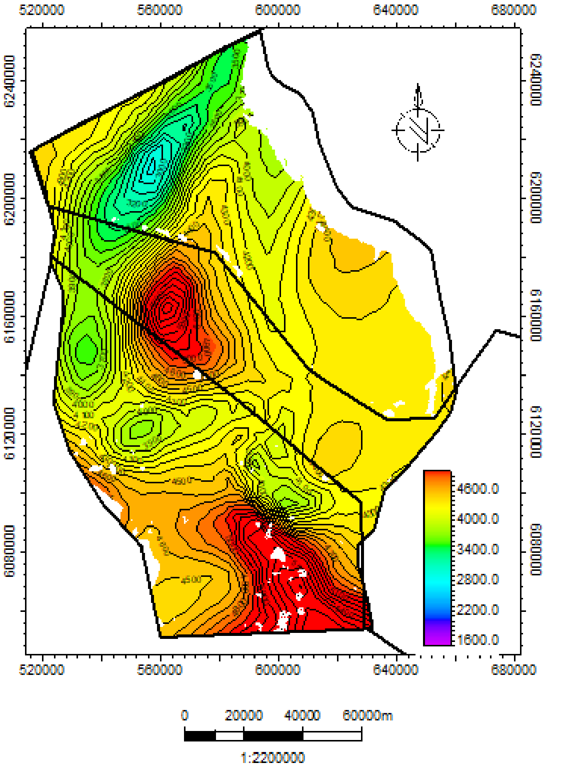
- well drilled on top of a saltdome: the younger lithostratigraphical units above the saltdome have been moved to shallower depths, which means relative higher velocity on shallower depth.
- stratigraphical unit is truncated (unconformity) so only a part of the complete stratigraphical unit is present.

V_0-values have been modeled for the entire Cenozoic interval, which implies that the near base Neogene and near base Paleogene horizons have been depth converted with the V_0-grid and K-factor for the Cenozoic unit.

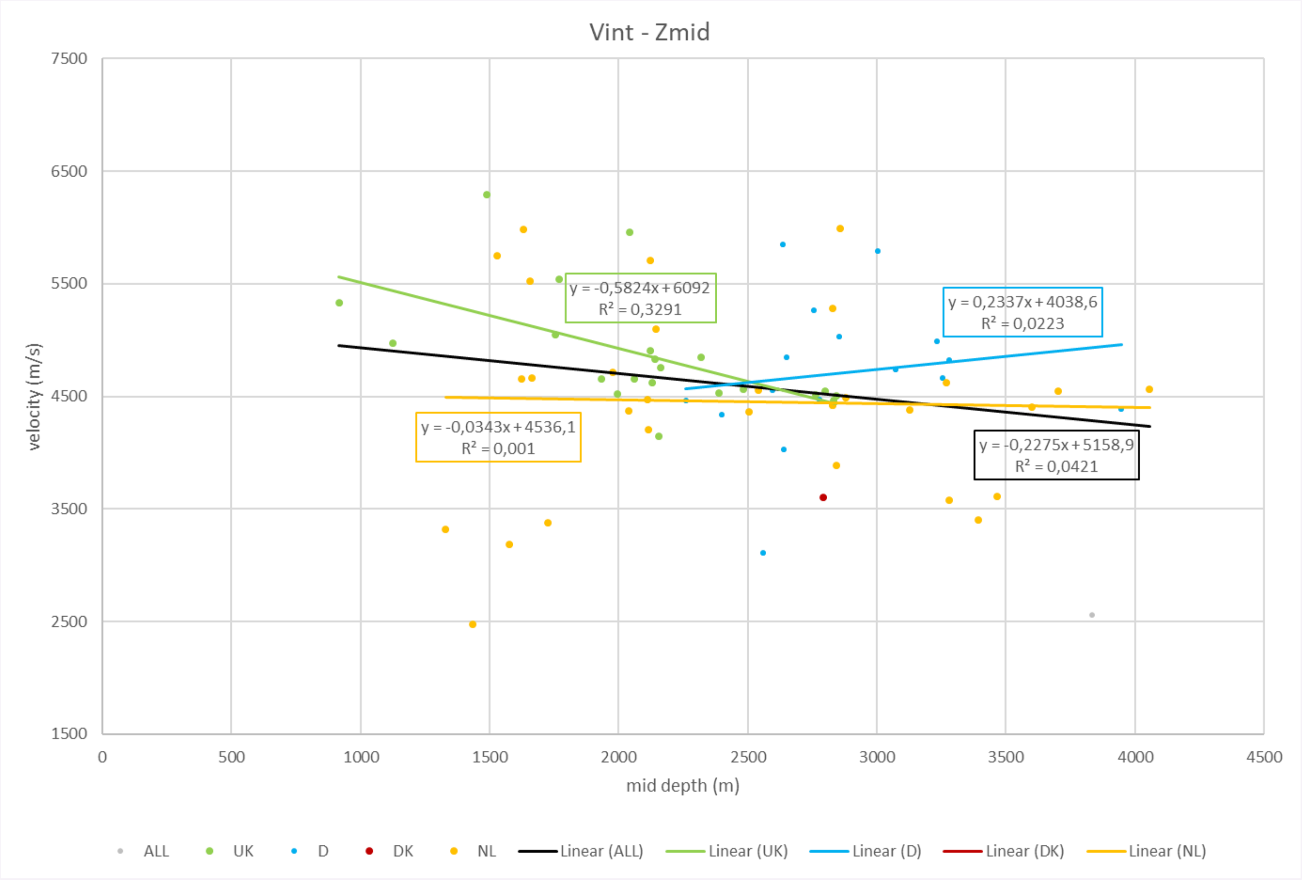



Map of KN_v0_GARAH_
Map of S_v0_GARAH_
Map of AT_v0_GARAH_
Map of TR_v0_GARAH_
520000
560000
600000
640000
680000
6240000
6200000
6160000
6120000
6080000
4600.0
4000.0
3400.0
2800.0
2200.0
1600.0
4800.0
4400.0
3600.0
3200.0
2400.0
2000.0
0
20000
40000
60000m
1:2200000

Map of ZE_vint_GARAH_



(iii) Velocity model for the Zechstein (ZE)



In contrast to the near base Neogene to base Triassic horizons the Zechstein horizon has been depth converted by using interval velocities of the Zechstein unit.

The lithology of the Zechstein in general consist of anhydrite, halite and/or carbonate. The lithological composition of the interval is the most dominant factor for the interval velocity. The influence of compaction on the interval velocity is considered very minor.
Zechstein interval velocity is modelled based on velocity - thickness (or ΔT) relation. In general, layers with limited thickness show the relative high abundance of high velocity carbonate layers (Kombrink et al, 2012).
See the Velmod-3.1 report[1] as published on the NLOG-portal[2]

In the Dutch area a base level of 3000 m/s has been used to eliminate low-velocity values because the Zechstein unit predominantly consists of high velocity carbonates and halite. In VELMOD 1-3 velocity model for the Dutch on- and offshore Zechstein velocities are based on interval velocities and a correlation between V_{int} and ΔT–data in the wells. For the GARAH-model an average interval

[1] https://www.nlog.nl/sites/default/files/2018-11/060.26839%20R11014%20with%20erratum%20page%2067%20Doornenbal-final.sec_.pdf
[2] https://www.nlog.nl/velmod-31

velocity of 4500 m/s was used in regions with diapirs and thick salt. Outside these areas well-interval velocities-Values have been interpolated.