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A harmonized cross-border velocity model

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GENERAL INTRODUCTION

The GeoERA research project ”3D Geomodeling for Europe (3DGEO-EU)” aims to show on the example of cross-border pilot areas (work packages 1 - 3) how harmonization across the borders can be established and maintained with the progress of the national models. The pilot area of work package 3 (WP3) spans thereby the offshore cross-border North Sea area between the Netherlands, Germany and Denmark. In this region, the partners the Netherlands Organization for Applied Scientific Research (TNO, NL), the Geological Survey of Denmark and Greenland (GEUS, DK) and the Federal Institute for Geosciences and Natural Resources (BGR, GER) intent to integrate existing national (and regional) geomodels into a harmonized, consistent cross-border geomodel of the North Sea area.

The following report will provide information about the production of a harmonized cross-border velocity model covering main parts of the UK, Danish, German and northern part of the Dutch North Sea. This velocity model will be used for time-depth conversion of the main seismic interpreted time horizons that have been selected by the project partners for harmonization purposes.

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1 Harmonization of velocity models

1.1 Introduction

Work package 3 (WP3) of the GeoERA research project "3D Geomodeling for Europe (3DGEO-EU)" aims to integrate existing national (and regional) geomodels into a harmonized, consistent cross-border geomodel of the North Sea area between the Netherlands, Germany and Denmark. During an initial cross-border comparison of national horizon models in the time-domain, several discrepancies in distribution and thickness of certain stratigraphic intervals became apparent along the national borders (see for details Deliverable 3.1 "State of the Art Report"). A closer evaluation of these discrepancies and their revision was an important first step in the process towards a harmonized, consistent cross-border geomodel and the related work is summarized in deliverables D3.3 to D3.6.

Beside the removal of existing disparities in the national horizon models observed in the time domain, the establishment of a transnational velocity model for the time-depth conversion in the study area is a further essential step to ensure successful harmonized cross-border 3D models in WP3. Prior to the project, velocity models for time-depth conversion were largely built separately by each partner (Arfai et al., 2014; Groß, 1986; Japsen, 1993; van Dalfsen et al., 2006) and these models differ partly considerable, especially in the deeper graben systems where the rock intervals are not supported by drilling data. The enormous impact of differences in the current national velocity models on the time-depth conversion is highlighted in Figure 1 by the cross-border comparison of horizon models between offshore Germany and the Netherlands and impressively shows the need for harmonization. Differences in main seismic horizons observed here in the time domain (Figure 1a) partly increase or decrease after time-depth conversion (Figure 1b), depending on the differences in the national velocity models used for this conversion.

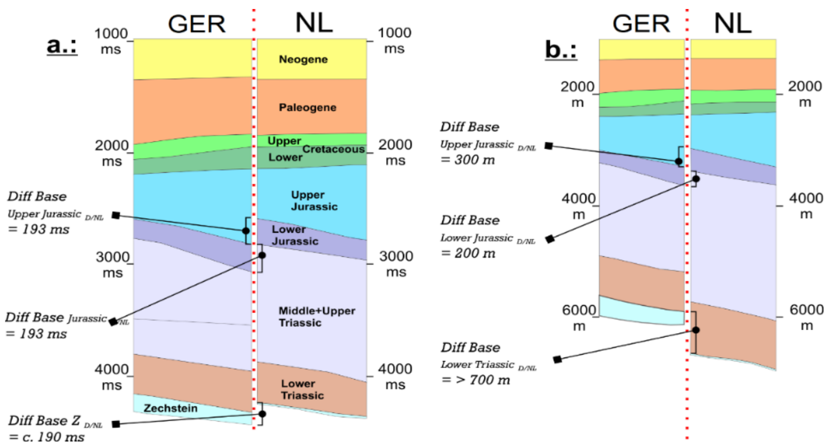


Figure 1: Cross-border comparison of horizon models between offshore GER and NL in the southeastern Entenschnabel in time (a) and depth (b) domain. (a) Differences in TWT are mainly the result of differences in seismic stratigraphic concepts or structural interpretation. Concerning the GER/NL offshore border region, major differences are visible for the Mesozoic to Paleozoic. (b) Differences observed in TWT interpretation may be increased or decreased by time-depth conversion, depending on differences in the velocity model used for conversion. Note increase in vertical difference in the Lower Triassic after depth conversion.

For the Entenschnabel region covering the northwestern part of the German North Sea sector and adjacent areas in Denmark and the Netherlands (Figure 2), a first 3D depth model was built during July 2018 to March 2019 in WP3 (see Deliverable D3.2) and was needed as input model within the GARAH-project. This generalized model is based on 8 seismically interpreted horizons and was time-depth converted by a first developed cross-border velocity model for this region. Due to the limited number of well velocity data used for the initial velocity model and its restriction to the Entenschnabel region, there is a general need to refine the existing model to improve its reliability, as well as to extend it to the other WP3 working areas for time-depth conversion (Figure 2). Information about the construction of a harmonized and improved cross-border velocity model covering the study area is given in the subsequent chapters.

1.2 Selection study area

For 3DGEO-EU WP3 the following three working areas were defined in the North Sea: the Dutch-German offshore border area, the Entenschnabel region and the Horn Graben region (see the dotted polygons indicated in Figure 2). The development of a velocity model and its reliability depends strongly on the availability of velocity data in wells, as these are important to establish velocity-stratigraphy relationships. Beside the intention to integrate a large number of representative well velocity data the partners have decided to select the extent of the study area needed for a transnational velocity model on such a manner that the three working areas have been covered and that the present structural elements are very well covered. The corresponding area of the transnational velocity model is indicated in Figure 2 (see red polygon) and covers main parts of the UK, Danish, German and northern part of the Dutch North Sea.

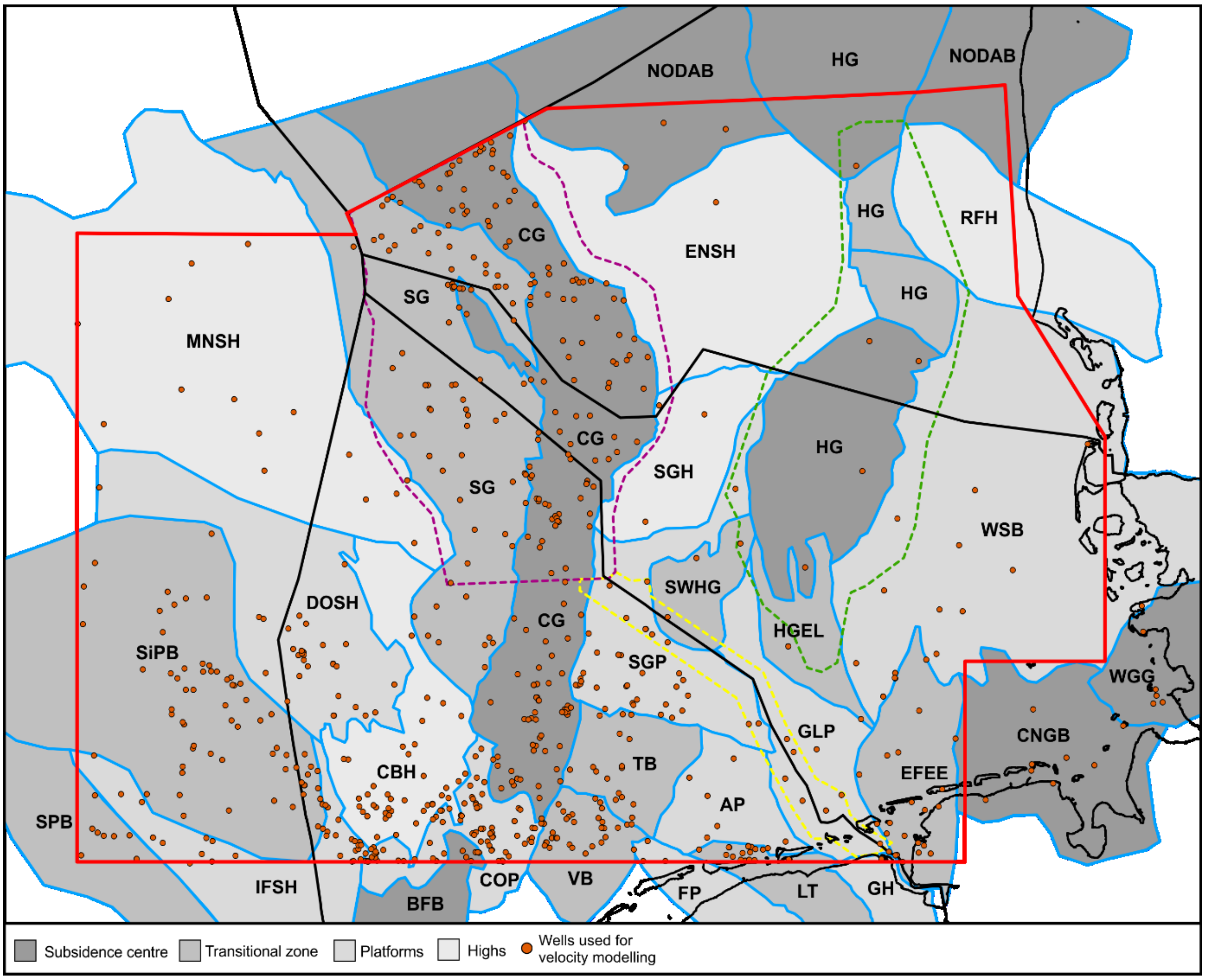


Figure 2: Preliminary map of main structural elements in the area of the UK, Dutch, German and Danish North Sea sectors showing the location of the wells used for generation of the trans-national velocity model. Study area for the trans-national velocity model is indicated by red polygon. Working areas defined in the North Sea for 3DGEO-EU WP3 are marked by dotted lines (yellow= NL-GER offshore border area / purple = Entenschnabel region / green = Horn Graben region).

Abbreviations of main structural elements: SG = Step Graben / CG = Central Graben / ENSH = East North Sea High / HG = Horn Graben / RFH = Ringkøbing-Fyn High / MNSH = Mid North Sea High / SGH = Schillgrund High / SGP = Schillgrund Platform / SWHG = southwestern branch Horn Graben / HGEL = southern branch Horn Graben – Ems Lineament / WSB : West Schleswig Block / GLP = G- and L-Platform / EFEE = East Frisia – Ems Estuary Region / CNGB = NW part of the Central North German Basin / WGG – Western branch Glückstadt Graben / DOSH = Dogger Shelf / CBH = Cleaver Bank High / COP = Central offshore Platform / VB = Vlieland Basin / TB = Terschelling Basin / BFB = Broad Fourteens Basin / FP = Friesland Platform / AP = Ameland Platform / LT = Lauwerszee Trough / GH = Groningen High / SIPB = Silver Pit Basin / SPB = Sole Pit Basin / IFSH = Indefatigable Shelf / NODAB = Norwegian-Danish Basin.

2 METHODS FOR VELOCITY MODEL BUILDING

In the following chapter the velocity modelling methods applied and tested in the project for the time-depth conversion of seismic interpreted horizons selected for harmonization will be shortly described. In general, 8 key stratigraphic horizons have been selected by the project members for harmonization purposes (Table 1):

Table 1: Key stratigraphic horizons selected for harmonization and corresponding lithostratigraphic interval codes.

No	Horizon	Code
1	Near Mid Miocene Unconformity	NU
2	Near base Cenozoic	N
3	Base Upper Cretaceous	CK
4	Near base Lower Cretaceous	KN
5	Near base Upper Jurassic	S
6	Near base Lower Jurassic	AT
7	Near base Lower Triassic	RN+RB
8	Base Zechstein	ZE

In the Horn Graben region, which is mainly dominated by Triassic clastic strata up to 6 km thick (Kilhams et al., 2018), GEUS and BGR agreed to include 3 additional Triassic horizons to address this fact. These includes the Top Grabfeld Formation, the Near base Middle Triassic and the Near base Volpriehausen Formation.

2.1 V_0-K layer cake velocity model

For the time-depth conversion of the Cenozoic to Mesozoic units a V_0-K layer cake velocity model based on the V_{int} – Z_{mid} method (Robein, 2003) combined with local parameter calibration at boreholes is adopted. In this type of model, it is generally assumed that the acoustic velocity of a unit increases linearly with depth under the influence of burial and compaction and can be described by the following equation:

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

$V(x,y,z)$ = 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

Interval velocities (V_{int}) versus mid depths (Z_{mid}) plotted in Figure 3 for 8 main lithostratigraphic groups in the Netherlands clearly show the general increase of velocity with depth typical for the Cenozoic and Mesozoic units in the study area. Furthermore, from this figure it could be concluded that values per interval could be grouped or characterized by a certain dip (K value) and a certain V_0 value. Accordingly, the K-factor of the velocity function can be obtained per lithostratigraphic unit by means of plotting a set of (Z_{mid},V_{int}) pairs in a scatterplot and calculating the linear least squares fit to the data:

$$V_{int}(Z_{mid}) = V_0 + K \cdot Z_{mid}$$

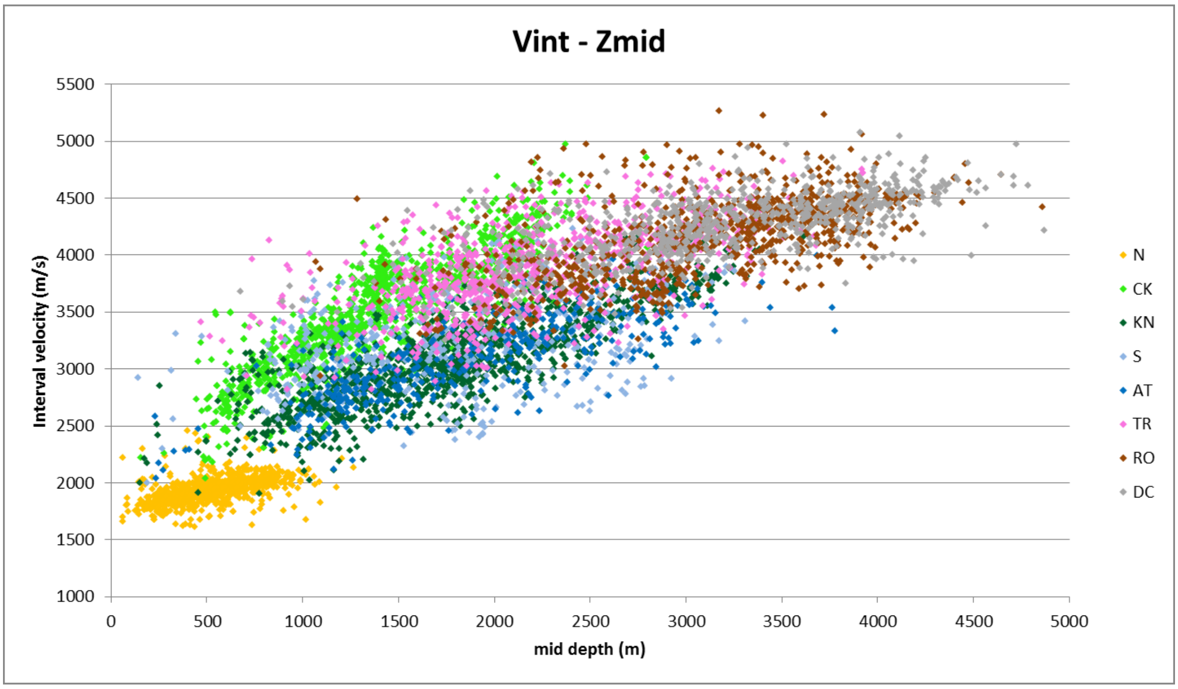


Figure 3 Interval velocity V_{int} vs mid depth Z_{mid} for 8 main lithostratigraphic groups in the Netherlands (VELMOD-3.1, 2017). From this figure could be clearly concluded that there is a general increase of velocity with depth but also that the values per interval could be grouped or characterised by a certain dip (K value) and a certain V_0 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.

On the basis of the global parameterization of K, the local parameter V_0 can be determined at borehole locations by 2 different methods:

1) "*Local V_0_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 V_0_rms*" calibration based on the least square error of all velocity data points per well with regard to the velocities derived from the V_0-K model.

An example of the difference between the two methods is visualized in Figure 4. Although the *Local V_0_basefit* calibration results in a zero depth error at the base of the stratigraphic interval, the *Local V_0_rms* calibration gives the smallest average depth error over the complete stratigraphic interval.
The velocity model D3.7 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 V_0_basefit* calibration were used for the construction of regional V_0 distribution maps.

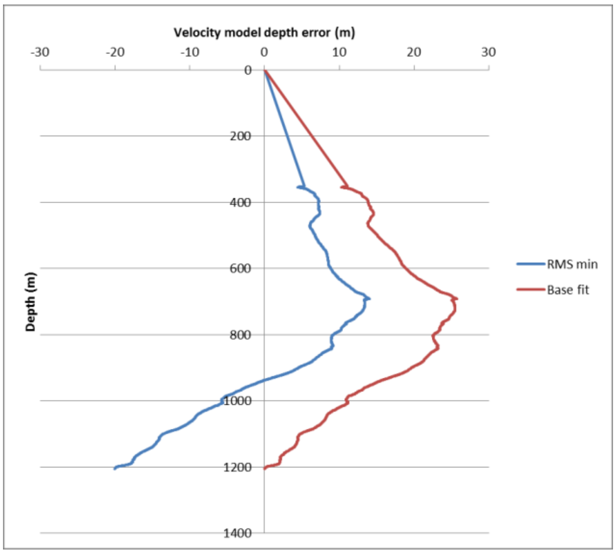


Figure 4 *Depth error of Local V0 model (basefit and rms) estimates at the Dutch well KDK-01. Shown depth error is the difference between modelled velocity and instantaneous velocity from sonic log.*

2.2 V_{int}-DeltaT model

In contrast to the Cenozoic and Mesozoic layers the Zechstein interval velocity is not a function of depth. The lithology of the Zechstein Group 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. For this project the Zechstein velocities are modelled based on an interval velocity - thickness (or ΔT) relation (see Figure 5). In general, layers with limited thickness show the relative high abundance of high velocity carbonate layers and in regions with diapirs and thick halite layers an average interval velocity of 4500 m/s was used in accordance to Kombrink et al, 2012.

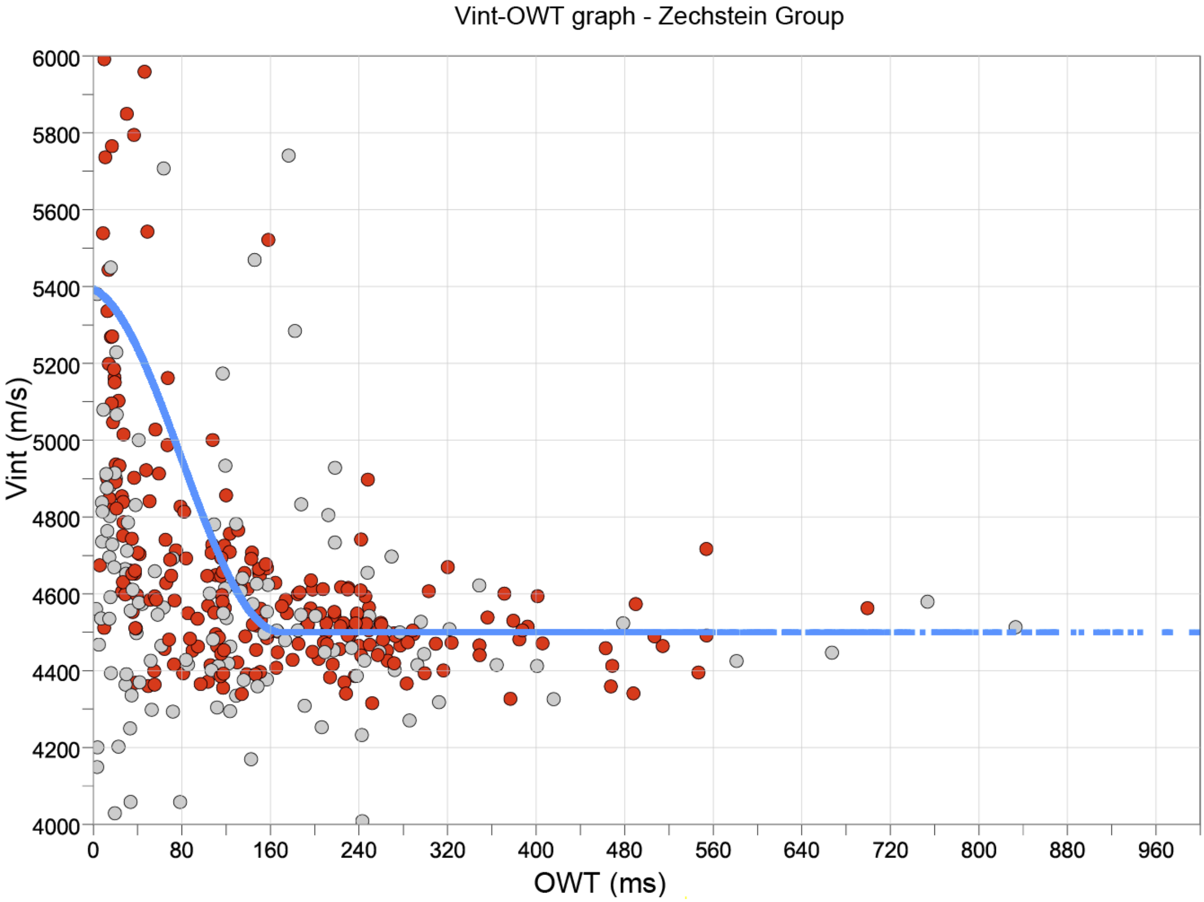


Figure 5 *Interval velocity V_{int} in relation to thickness (ΔT-ZE in ms OWT=One-Way-Time) for Zechstein Group. Red dots show V_{int} -values of the wells selected for the Zechstein velocity grid based on criteria discussed below.*

For this project the following workflow was used:

- a provisional grid of V_{int} is built based on the travel times from seismic interpretation:
  - $V_{int}prov = 4500$ m/s if $\Delta TZE \geq 170$ ms
  - $V_{int}prov = 4950 + (450 \cdot \cos(\Delta TZE + 10))$ if $\Delta TZE < 170$ ms
- The final V_{int}-grid was obtained by kriging the difference ($V_{int}prov - V_{int}borehole$) at borehole locations, and by subtracting the kriged differences from the $V_{int}prov$-grid. In this step a factor was included to minimize hard breaks in the difference grid. The minimum V_{int}-value in the final velocity grid was constrained to 4300 m/s (only outside the study area lower velocities exist in clastic facies at the edges of the Southern Permian Basin).

3 PROCESSING OF WELL VELOCITY DATA

For building the velocity model the velocity data from wells have to be gathered, controlled for quality and have to be filtered on various criteria.

3.1 Gathering velocity data

Most of the gathered velocity data are velocity data retrieved from (calibrated) sonic logs and from data gathered by well-shoots. In total the velocity data of 724 wells have been gathered (see Table 2 and Figure 2) from the Danish, Dutch and German project-partners, the UK velocity data were retrieved from the SPBA-project (Doornenbal and Stevenson, 2010).

Table 2: Number of wells with velocity data per country.

Country	Number of wells
DK	102
GE	95
NL	440
UK	87
Total	**724**

Originally the velocity data, gathered from the 4 different countries, were subdivided in 24 stratigraphical intervals from Upper North Sea Group (NU) to pre-Zechstein intervals. 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 (North Sea Supergroup or Cenozoic)
- AT1 and AT2 are merged to AT
- RN (RN1 and RN2) and RB are merged to TR (Lower and Upper Germanic Triassic groups)

Also most of the countries didn't gather the velocity data for pre-Zechstein intervals.

Finally, 7 main stratigraphical intervals have been selected for building the transnational velocity model: N, CK, KN, S, AT, TR and ZE (see Table 3):

Table 3: Seismically interpreted horizons and the used lithostratigraphic interval codes.

No	Horizon	Code
1	Near base Cenozoic	N
2	Base Upper Cretaceous	CK
3	Near base Lower Cretaceous	KN
4	Near base Upper Jurassic	S
5	Near base Lower Jurassic	AT
6	Near base Lower Triassic	TR
7	Base Zechstein	ZE

3.2 QC of velocity data

A general first rough QC was executed on the gathered data such as:

- Well-names: in some cases wells with same name exist in Germany and Denmark.
- Coordinates: typing errors in x- and y-coordinates
- Overlapping intervals: errors in depth-values were retrieved and corrected.
- For UK the Upper Jurassic groups (S) and the Lower + Middle Jurassic groups (AT) had the same values. It has been investigated which data were S and which were belonging to AT, only for the wells within blocks 48 and 49 couldn't made a decision.

3.3 Filtering of velocity data

For the Cenozoic to Triassic intervals (N, CK, KN, S, AT, TR) the following filtering criteria have been applied:

- Data with interval velocity lower than 1500 m/s and higher than 7000 m/s were discarded from analysis
- Thin intervals (OWTitv < 5 ms) were discarded
- NOT_UP_TO_TOP for N in the Netherlands were discarded, because sonic logs are starting in the middle of the interval
- NOT_DOWN_TO_BASE_NOT_UP_TO_TOP for NL wells were discarded
- NOT_DOWN_TO_BASE and OWTitv<50ms for AT (3 wells) and TR (11 wells) were not selected

For the Zechstein Group (ZE) a total of 240 (out of 399) wells have been selected based on the following criteria:

- V_{int} < 4300 m/s were discarded
- Thin intervals (OWTitv < 5 ms) were discarded
- Data originating from not-calibrated sonic logs (SOURCE='son') of the Dutch wells were discarded.
- Íntervals 'NOT_DOWN_TO_BASE' and V_{int}>4650m/s were discarded

4 RESULTS

4.1 K-factor determination and evaluation

The region defined by the project partners for the cross-border velocity model covers main parts of the UK, Danish, German and northern part of the Dutch North Sea (Figure 2). An important aspect in determining the K-factor in such a large area is to evaluate whether a single K-value per lithostratigraphic unit can be regarded as valid for the whole study area or whether regionalized K-values are more suitable for the velocity model due to varying burial and compaction histories of sediments in different parts of the study area.

In order to determine and evaluate different K-factors a V_{int}-Z_{mid} graph - per modelled lithostratigraphic unit (N, CK, KN, S, AT and TR) - were compiled and V_{int}-Z_{mid} relations were analyzed

- for the whole study area
- per country
- per structural element
- per structural element type (subsidence center, high, transition and platform) or a combination of structural element types
- per combination of structural elements for example Central Graben + Step Graben

The derived K-factor, global V_0, R-squared, the number of V_{int}-Z_{mid}-pairs, mean Z_{mid}, mean V_{int} and mean OWT are summarized in Tables 5-7. The R-squared (R^2) is a number between 0 and 1 and is determined by least-square analyses. The R-squared has been subdivided (see Table 4) from very weak (red), weak (rose), moderate (yellow), strong (green), very strong (blue) to exceptionally strong (white). These colors for R-squared have been used in all tables that are presented in this report. In general, it can be assumed that a very good linear relationship exists between V_{int} and Z_{mid} if the R-squared is greater than 0.5.

Table 4: R, R-squared ($R^{2)}$, explained variance and its explanation.

R	R^2	explained variance	explanation
<0,3	<0,1	<10%	very weak
0,3-0,5	0,1-0,25	10-25%	weak
0,5-0,7	0,25-0,5	25-50%	moderate, reasonable
0,7-0,85	0,5-0,75	50-75%	strong
0,85-0,95	0,75-0,9	75-90%	very strong
>0,95	>0,9	>90%	exceptionally strong

Table 5: Results of V_{int}-Z_{mid} analysis for the whole study area including and excluding DK=Denmark. The values for TR are without region SPB=Sole Pit Basin.

	Whole study area							Whole study area without DK						
Code	K	V_0	R^2	#	Z_{mid}	V_{int}	OWT	K	V_0	R^2	#	Z_{mid}	V_{int}	OWT
N	0,16	1852	0,51	368	812	1979	799	0,27	1787	0,62	269	655	1962	644
CK	0,62	2582	0,65	539	1881	3754	175	0,77	2361	0,63	444	1696	3673	187
KN	0,37	2342	0,32	481	2263	3190	59	0,58	1973	0,61	418	2156	3224	56
S	0,09	2769	0,03	212	2794	3020	152	0,60	1588	0,36	144	2468	3061	135
AT	0,35	2129	0,62	94	2638	3056	69	0,47	1874	0,77	77	2419	3021	71
TR	0,42	2721	0,54	287	2394	3724	168	0,45	2659	0,61	275	2375	3737	166

At first K values have been determined for the whole study area based on all available wells (see Table 5). It could be concluded that the velocity data of KN and S do not have a good linear relationship between V_{int} and Z_{mid}, but if the Danish wells are discarded then the results are much better. Because the aim of the project was to build a velocity model crossing national borders, however, the subdivision of the dataset per country was not preferred. Also the subdivision in structural element(s) following the generalized map shown in Figure 2 was examined, but did not result in clear linear relations because in many cases a too low number of wells were present within a structural element.

Further the structural elements were grouped into different structural element types i.e. subsidence center, high, transition and platform or a combination of structural element types. For the Chalk Group (CK) the results are very promising (Figure 6), but for the other intervals it was rather disappointing (Table 6).

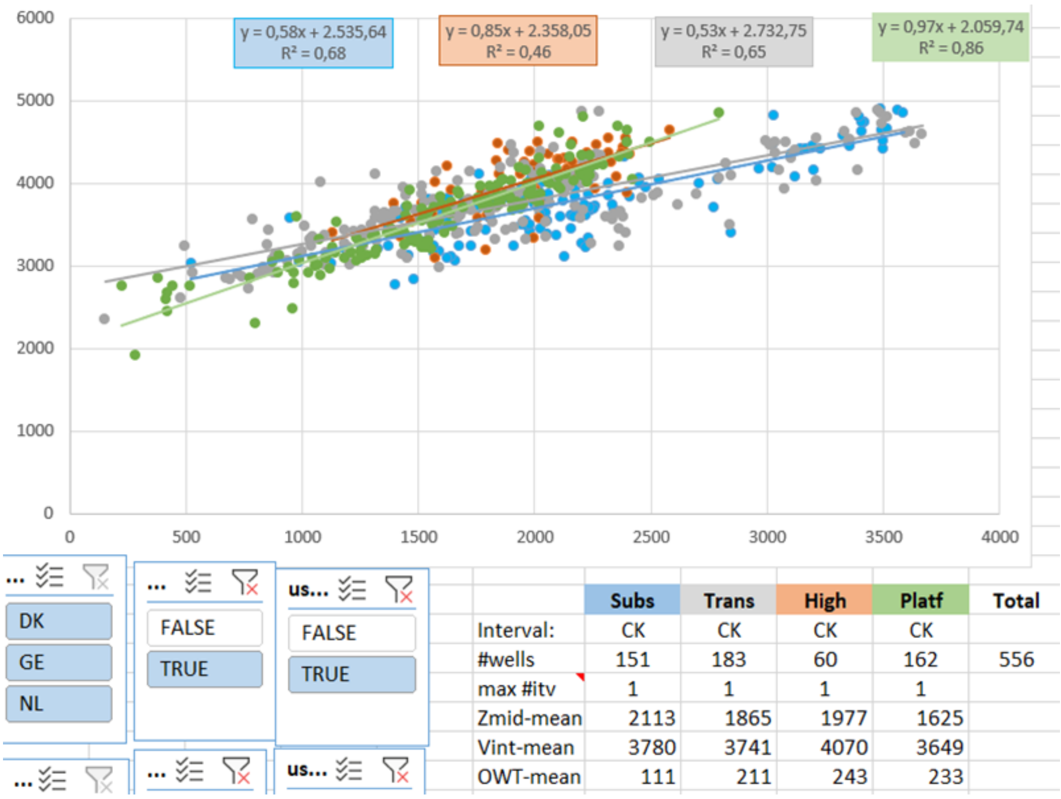


Figure 6: V_{int}-Z_{mid} graph for Chalk Group

Table 6: Results of V_{int}-Z_{mid} analysis per structural element type (subsidence center, transition, high, platform) and combinations of structural element types (subsidence+transition and high+platform).

	Subsidence							Transition							High							Platform						
Code	K	V_0	R^2	#	Z_{mid}	V_{int}	OWT	K	V_0	R^2	#	Z_{mid}	V_{int}	OWT	K	V_0	R^2	#	Z_{mid}	V_{int}	OWT	K	V_0	R^2	#	Z_{mid}	V_{int}	OWT
N	0,08	1948	0,19	133	981	2024	963	0,16	1840	0,52	135	786	1966	871	0,30	1744	0,53	35	752	1973	922	0,31	1767	0,63	82	572	1945	583
CK	0,58	2535	0,68	151	2113	3765	111	0,53	2734	0,65	183	1865	3730	211	0,85	2358	0,46	60	1977	4036	243	0,97	2060	0,86	162	1625	3638	233
KN	0,11	2739	0,03	125	2388	3009	68	0,36	2404	0,41	154	2142	3164	68	0,66	1791	0,81	50	2581	3490	47	0,60	2014	0,75	169	2152	3301	49
S	0,06	2756	0,02	126	2644	2905	199	-0,04	3332	0,01	65	3101	3201	98	0,59	1539	0,75	12	2212	2840	32	0,26	2676	0,13	13	2707	3385	33
AT	0,31	2260	0,41	67	2770	3154	82	0,31	2195	0,63	28	1827	2767	160														
TR	0,36	2643	0,40	22	2864	3672	273	0,33	2978	0,42	123	2252	3722	315	0,70	1723	0,80	11	2284	3331	57	0,50	2591	0,71	138	2382	3774	166

	Subsidence+Trans								High+Platform						
Code	K	V_0	R^2	#	Z_{mid}	V_{int}	OWT		K	V_0	R^2	#	Z_{mid}	V_{int}	OWT
N	0,14	1865	0,50	252	897	1991	930	without WGG	0,29	1733	0,60	117	626	1953	684
CK	0,54	2779	0,65	334	1977	3746	166		0,98	2068	0,82	222	1720	3745	236
KN	0,23	2581	0,14	279	2252	3095	68		0,60	2004	0,76	219	2250	3344	49
S	0,07	2804	0,02	191	2800	3006	164		0,67	1470	0,69	25	2469	3123	32
AT	0,36	2082	0,65	89	2653	3050	80	without WGG,BFB							
TR	0,29	3027	0,35	145	2344	3715	308		0,52	2512	0,67	149	2375	3742	158

When the V_{int}-Z_{mid} relations per structural element were analyzed, it was concluded that for both the Central Graben (CG) and the Step Graben (SG) most of the lithostratigraphic intervals resulted in bad linear relations. Further in general lower velocities occur in area inside CG+SG in comparison with the values outside CG+SG for all intervals (Figures 9-12). So it was decided to divide the study area in 2 parts: (i) 'CG+SG' and (ii) the area 'Outside CG+SG'.

From Figures 7-12 and Table 7 it could be concluded that

- for the area 'Outside CG+SG' the results of K and V_0 for all intervals are comparable with the VELMOD-3.1 results and have better linear relations (R^2), than the VELMOD-3.1 results (see Figures 7-12: dashed lines for VELMOD3.1 results and solid black lines for results 'Outside CG+SG').
- for the area 'CG+SG' the intervals N, KN and S have very weak, AT and TR have reasonable linear relations and only CK has a strong linear relation. The intervals N, KN and S display a K value close to 0 with corresponding low correlation coefficients. This is probably due to the non-compaction of the sediments, where trapped (or not yet drained) pore fluids are hindering the compaction (Japsen, 1998).

Table 7: Results of V_{int}-Z_{mid} analysis for VELMOD-3.1 (2017), the global results for the whole study area and the regionalized results for the areas 'Outside CG+SG' and 'CG+SG'. The values for S in the VELMOD-3.1 project are for the region VB/TB/SG only (see Figure 10). The values for TR are without region SPB=Sole Pit Basin.

	VELMOD-3.1				Whole study area				Outside CG+SG				CG+SG			
Code	K	V_0	R^2	#	K	V_0	R^2	#	K	V_0	R^2	#	K	V_0	R^2	#
NU	0,44	1761	0,32	660	0,35	1792	0,55	163	0,40	1777	0,39	114	0,31	1814	0,28	49
NLM	0,24	1779	0,32	757	0,15	1856	0,21	244	0,24	1767	0,26	159	0,03	2019	0,01	85
N	0,28	1788	0,30	1075	0,16	1852	0,51	368	0,32	1758	0,65	211	0,02	2003	0,05	157
CK	0,89	2257	0,74	1160	0,62	2582	0,65	539	0,91	2216	0,78	351	0,64	2365	0,72	188
KN	0,54	2133	0,69	1225	0,37	2342	0,32	481	0,59	1988	0,74	340	0,20	2539	0,09	141
S	0,52	1609	0,47	458	0,09	2769	0,03	212	0,65	1661	0,68	55	0,07	2713	0,03	157
AT	0,44	2259	0,59	419	0,35	2129	0,62	94	0,58	1771	0,93	18	0,26	2392	0,34	76
TR	0,37	3046	0,38	817	0,42	2721	0,54	287	0,49	2584	0,67	257	0,31	2758	0,26	30

For the Cenozoic interval (see Figure 7) the results for the area 'CG+SG' nicely show the effect of undercompaction on the general velocity depth trend and demonstrates that a single K value for the Cenozoic interval is not the best approach. Within a "main depocenter region" (= 'CG+SG'), where the sediments are characterized by undercompaction, it is better to assume a constant V_{int} or a velocity trend with a much smaller K value than the region outside the main depocenter. Also for the Chalk interval the results show a clear difference in velocity-depth trend for the areas inside and outside the main depocenter region (Figure 8). So the regionalized K values (inside / outside CG+SG) have the preference for N and CK intervals

In the area inside "CG+SG" a poor velocity-depth correlation has been found for the older Mesozoic intervals (KN, S, AT, TR), which could be caused by the following effects:

a) The facies distribution of Ryazanian sediments is changing from deep marine shales in the Danish sector, clastic facies in the middle to shallow marine shales in the south of our study area (see figure Zwaan, 2018). These facial changes are roughly corresponding with our strong discrepancies in the velocity values. Presumably the other Lower Cretaceous and Upper Jurassic units show similar facial changes.
b) The strongly differential uplift during Late Cretaceous basin inversion in the CG+SG region are causing differences in compaction and thus in velocity for older Mesozoic strata. These uplift differences could clearly explain the low correlation coefficient for Mesozoic strata.
c) Differences in formation pressure

Also for the S-interval a bad correlation (R^2= 0.03, see Table 7) was found in the depocenter region. The wells with thick Upper Jurassic have a similar impact on the determination of K values than wells that drilled only thin intervals. This was confirmed by a test discarding wells with thin Upper Jurassic strata (<50, 100 or 200ms), which did not result in more realistic K-values (or a better correlation).

Global K value for KN, S, AT and TR intervals

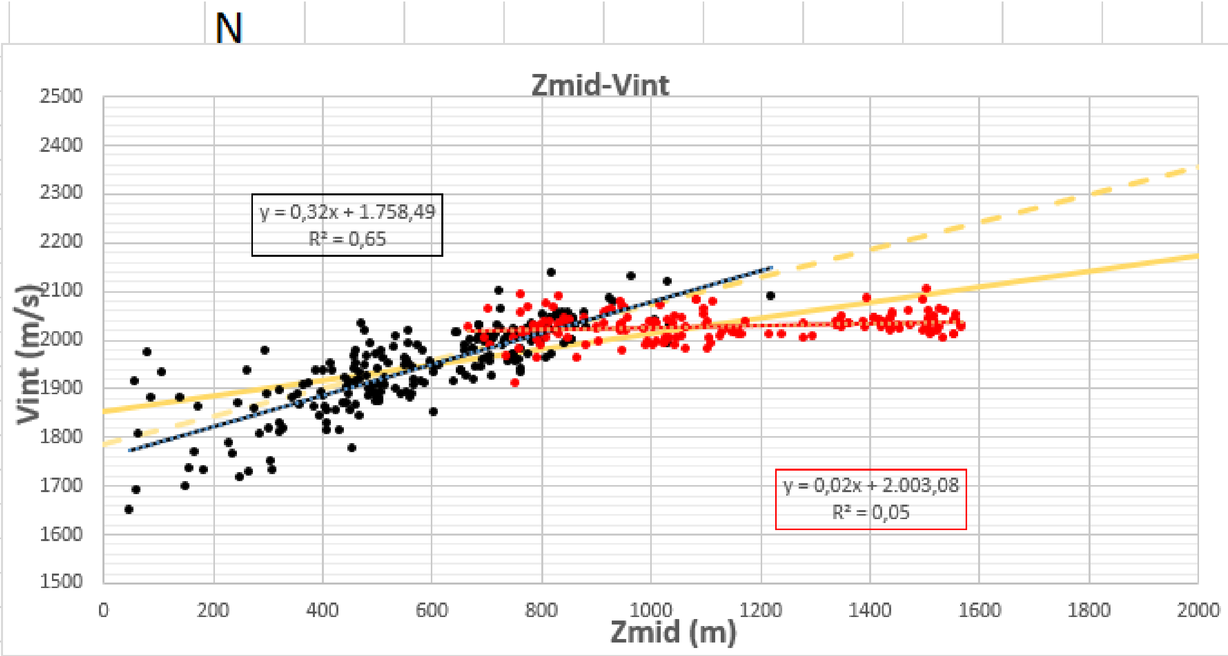
During Early Cretaceous rifting the subsidence decreased steadily. In addition, large parts of the flanks of the Central Graben also appear to have subsided at this time and some boreholes along the Schillgrund High and Platform also show comparable or higher thicknesses than in the depocenter. Furthermore during this time interval (KN) no strong depth trends were present along the borders of the depocenter, thus a hard division between inner and outer depocenter is probably not clearly applicable.

The Jurassic intervals (S and AT) are only or mainly present within the depocenter, so for these intervals there is no need to make a subdivision in inside/outside depocenter. For the Triassic interval only 30 wells are available within the region "inside CG+SG" to determine the K value, whereas "outside CG+SG" 257 wells could be used (Figure 12). Because of this low number of wells it was decided to choose for the TR interval one global K (K=0,42; Table 7) for the whole study area.

Because of the above reasons it was concluded that no clear division between inside and outside depocenter could be made for the KN, S, AT and TR intervals and thus a global K value for the whole study area was preferred.

Summarizing the following K values will be used (Table 7):

- regionalized K values (inside / outside CG+SG) for N and CK intervals
- global K value (whole study area) for KN, S, AT and TR intervals



	Outside	CG+SG
Interval:	N	N
#wells	211	157
max #itv	1	1
Zmid-MIN	47	668
Zmid-mean	577	1128
Zmid-MAX	1220	1568
Vint-MIN	1651	1910
Vint-mean	1943	2028
Vint-MAX	2139	2105
OWT-mean	569	1108

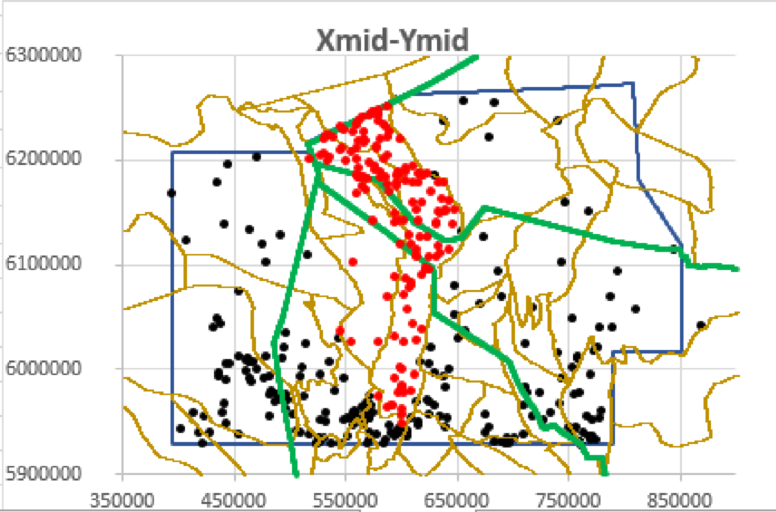
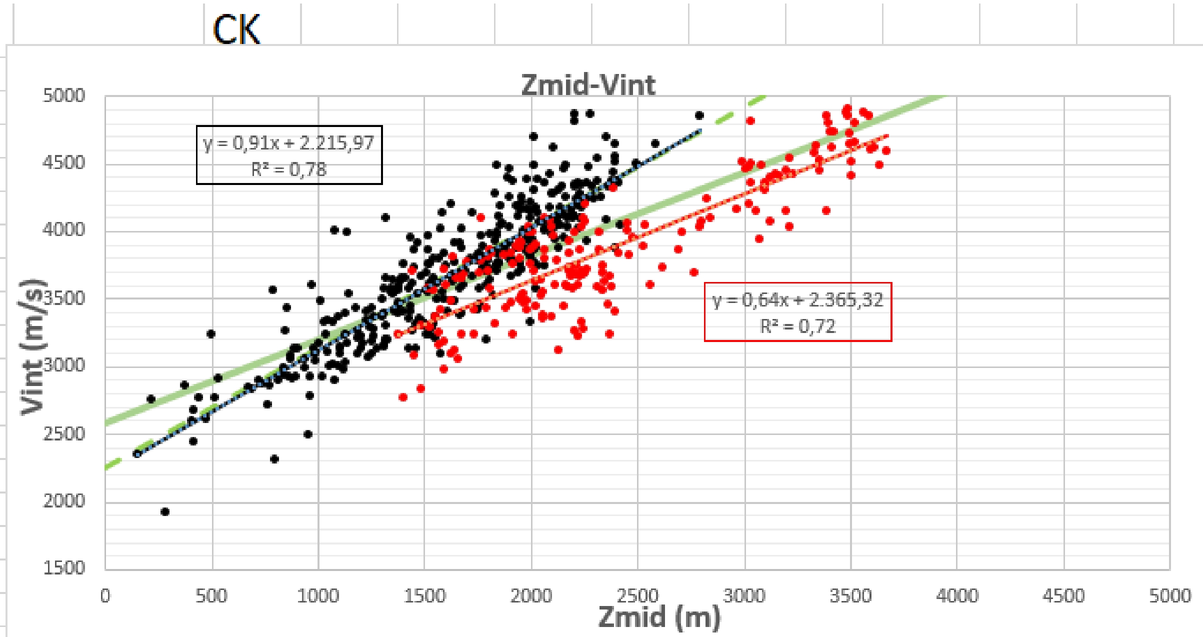


Figure 7: V_{int}-Z_{mid} relation for North Sea Supergroup (N). The study area has been subdivided in 2 parts: 'CG+SG' (Central Graben + Step Graben, see red dots) and the area 'Outside CG+SG' (black dots). For the area 'Outside CG+SG' there is a strong linear relation and for the area 'CG+SG' there is a very weak linear relation. It should be highlighted that the results of the VELMOD-3 project (yellow dashed line) and the results for the area 'Outside CG+SG' (black solid line) are comparable. The result for the whole study area (see Table 5) is indicated by the yellow solid line (K=0,16 and V_0=1852 m/s and R^2=0,51).



	Outside	CG+SG
Interval:	CK	CK
#wells	351	188
max #itv	1	1
Zmid-MIN	154	1373
Zmid-mean	1624	2362
Zmid-MAX	2793	3667
Vint-MIN	1921	2771
Vint-mean	3691	3871
Vint-MAX	4866	4905
OWT-mean	213	104

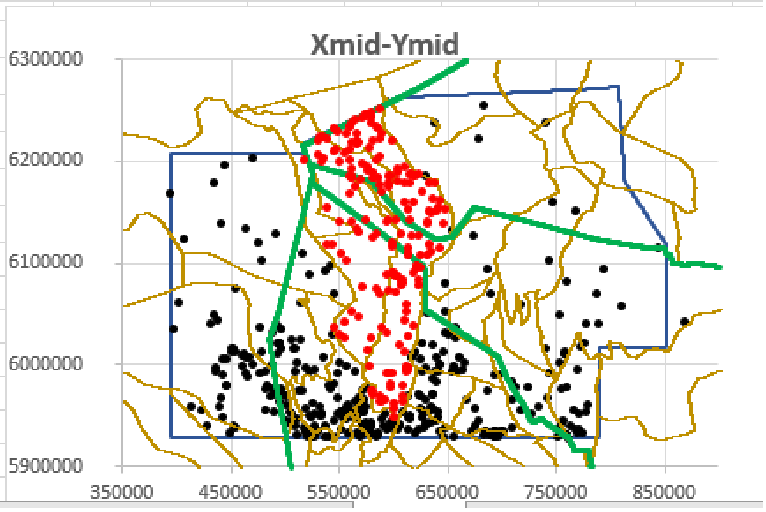
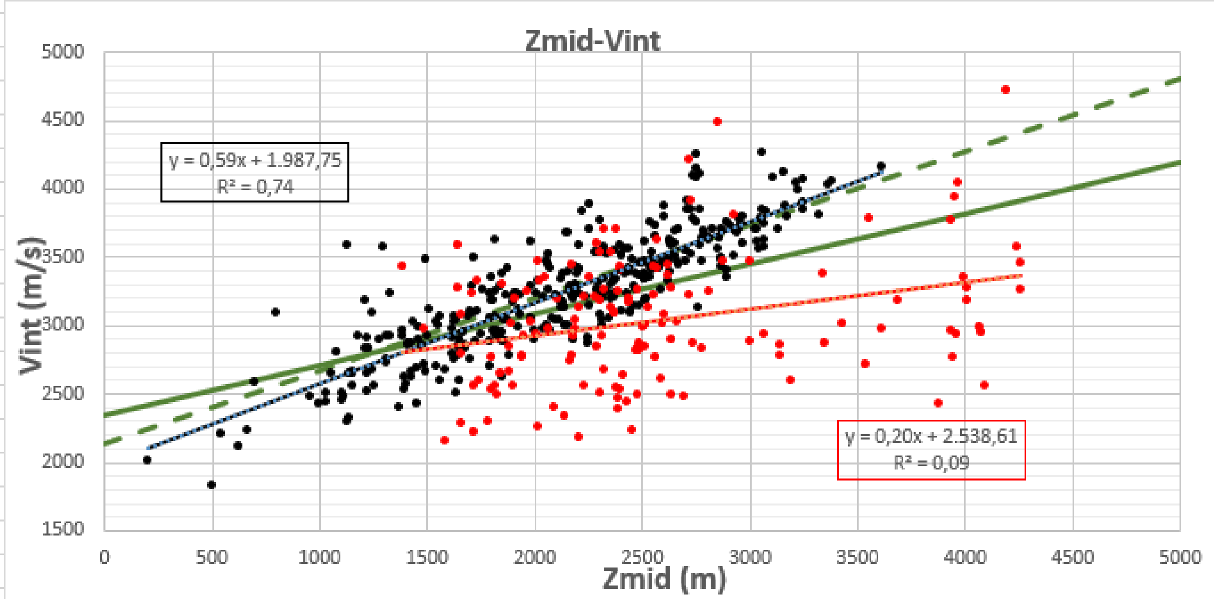


Figure 8: V_{int}-Z_{mid} relation for the Upper Cretaceous (CK=Chalk Group). The study area has been subdivided in 2 parts: 'CG+SG' (Central Graben + Step Graben, see red dots) and the area 'Outside CG+SG' (black dots). Both for the area 'Outside CG+SG' as for the area 'CG+SG' there is a strong linear relation. It should be highlighted that the results of the VELMOD-3 project (light green dashed line) and the results of this project for the area 'Outside CG+SG' (black solid line) are comparable. The result for the whole study area (see Table 5) is indicated by the light-green solid line (K=0,62 and V_0=2582 m/s and R^2=0,65).

KN



	Outside	CG+SG
Interval:	KN	KN
#wells	340	141
max #itv	1	1
Zmid-MIN	204	1388
Zmid-mean	2140	2557
Zmid-MAX	3614	4258
Vint-MIN	1829	2155
Vint-mean	3253	3039
Vint-MAX	4263	4718
OWT-mean	55	68

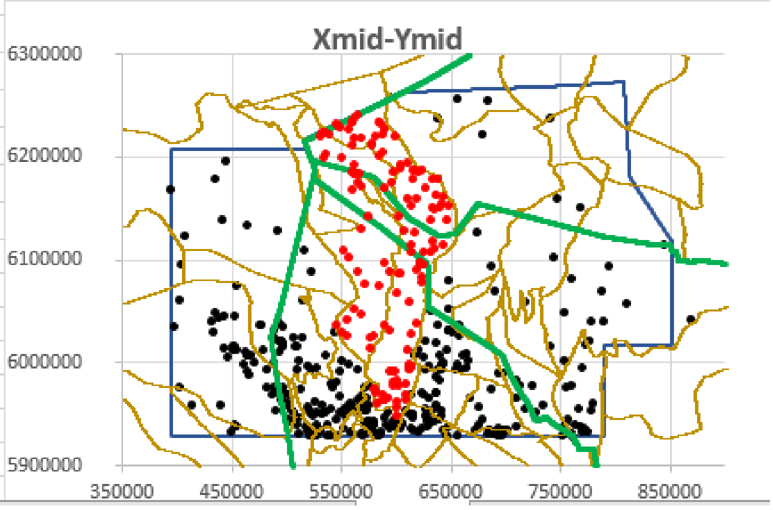
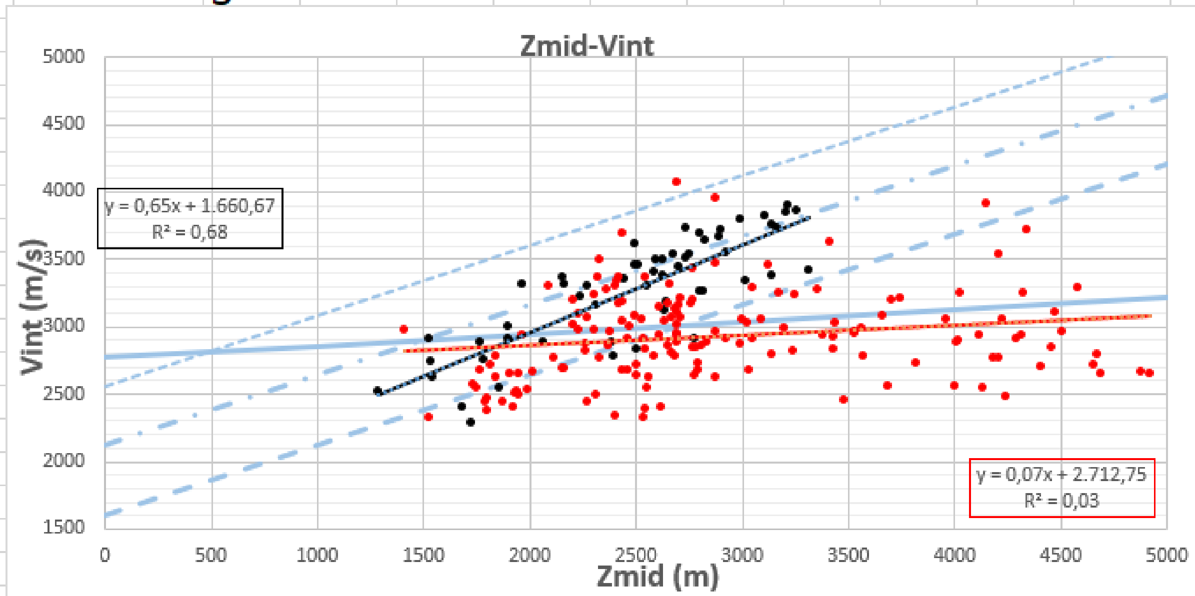


Figure 9: V_{int}-Z_{mid} relation for the Lower Cretaceous (KN=Rijnland Group). The study area has been subdivided in 2 parts: CG+SG (Central Graben + Step Graben, see red dots) and the area 'Outside CG+SG' (black dots). For the area outside CG+SG there is a strong linear relation and for the area 'CG+SG' there is a very weak linear relation. It should be highlighted that the results of the VELMOD-3 project (dark green dashed line) and the results of this project for the area 'Outside CG+SG' (black solid line) are comparable. The result for the whole study area (see Table 5) is indicated by the dark-green solid line (K=0,37; V_0=2342 m/s and R^2=0,32).

S



	Outside	CG+SG
Interval:	S	S
#wells	55	157
max #itv	1	1
Zmid-MIN	1282	1410
Zmid-mean	2491	2900
Zmid-MAX	3311	4918
Vint-MIN	2286	2321
Vint-mean	3278	2929
Vint-MAX	3900	4073
OWT-mean	64	183

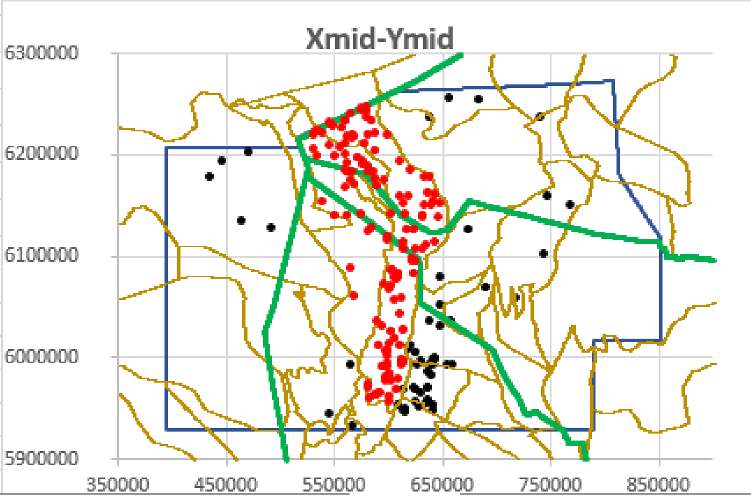
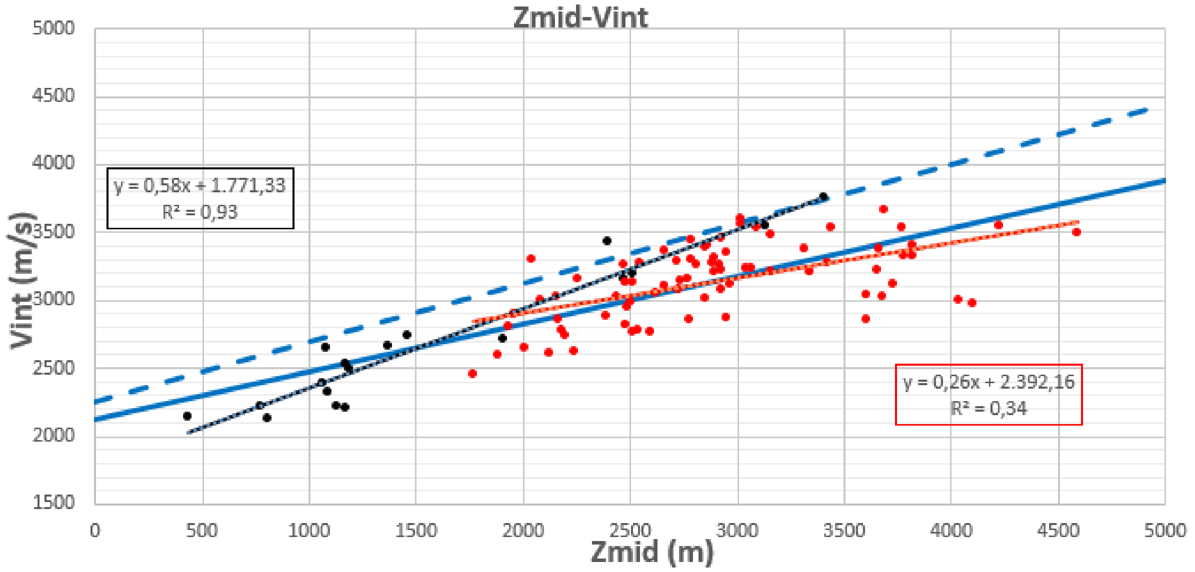


Figure 10 V_{int}-Z_{mid} relation for Upper Jurassic groups (S). The study area has been subdivided in 2 parts: 'CG+SG' (Central Graben + Step Graben, see red dots) and the area 'Outside CG+SG' (black dots). For the area 'Outside CG+SG' there is a strong linear relation and for the area 'CG+SG' there is a very weak linear relation. The results of the VELMOD-3 project are indicated with three 3 light-blue dashed lines for 3 different basin areas (CG, VB/TB/SG and all other basins in the south of the NL) with same K-value (0,52), but different regionalized V_0 values (1609, 2120 resp. 2557 m/s). It should be highlighted that the results for the basin region VB/TB/SG (middle light-blue dashed line) and the results of this project for the area 'Outside CG+SG' (black solid line) are comparable. The result for the whole study area (see Table 5) is indicated by the light-blue solid line (K=0,09; V_0=2769 m/s and R^2=0,03).

AT



	Outside	CG+SG
Interval:	AT	AT
#wells	18	76
max #itv	1	1
Zmid-MIN	432	1763
Zmid-mean	1586	2888
Zmid-MAX	3401	4590
Vint-MIN	2132	2459
Vint-mean	2697	3140
Vint-MAX	3758	3668
OWT-mean	61	71

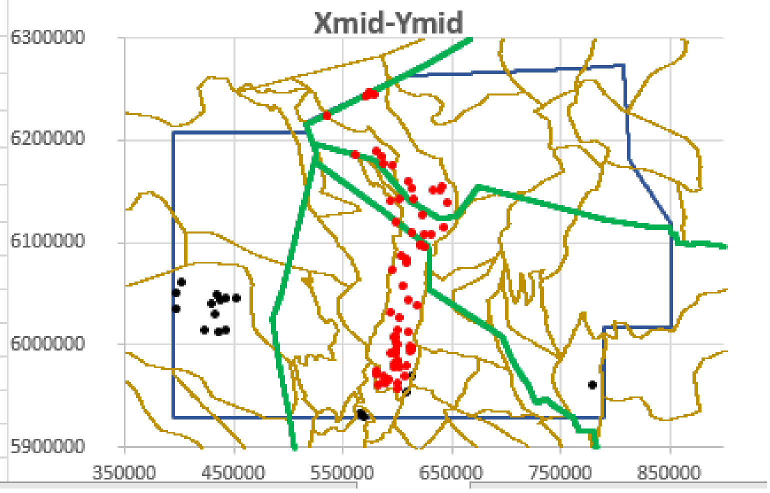
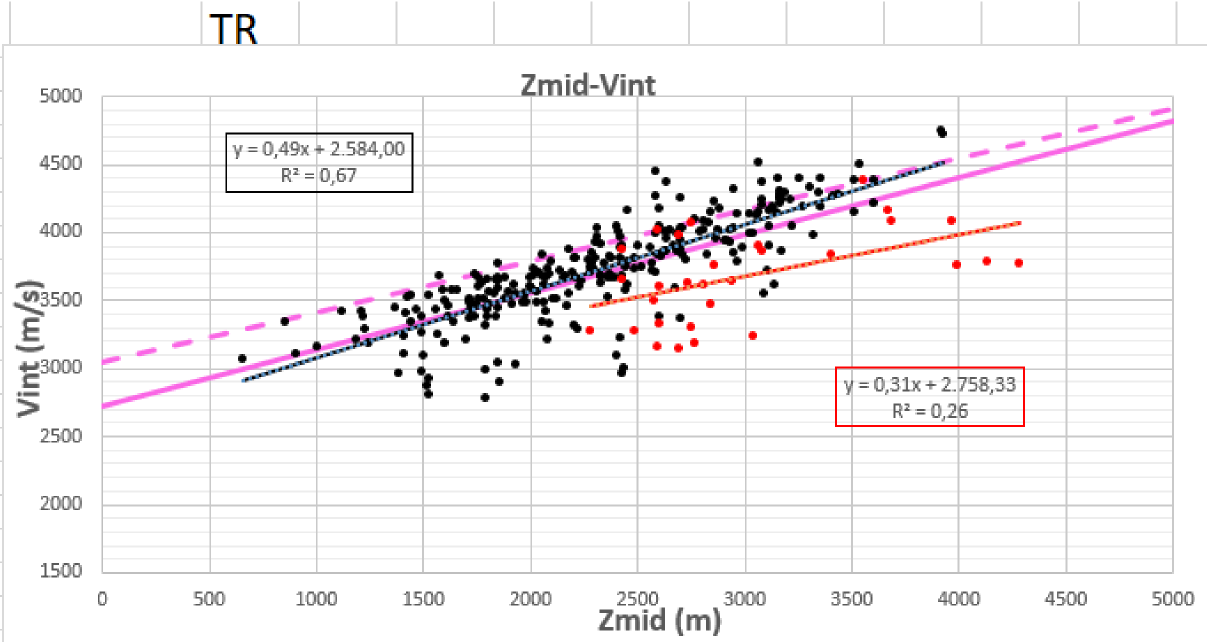


Figure 11 V_{int}-Z_{mid} relation for Lower + Middle Jurassic groups (AT). The study area has been subdivided in 2 parts: 'CG+SG' (Central Graben + Step Graben, see red dots) and the area 'Outside CG+SG' (black dots). For the area 'Outside CG+SG' there is a very strong linear relation and for the area 'CG+SG' there is a reasonable linear relation. It should be highlighted that the results of the VELMOD-3 project (dark blue dashed line) and the results of this project for the area 'Outside CG+SG' (black solid line) differs, but the time-depth conversion within this project will focus only on the Entenschnabel region. The result for the whole study area (see Table 5) is indicated by the dark-blue solid line (K=0,35; V_0=2129 m/s and R^2=0,62).



	Outside	CG+SG
Interval:	TR	TR
#wells	257	30
max #itv	1	1
Zmid-MIN	655	2277
Zmid-mean	2322	3010
Zmid-MAX	3923	4280
Vint-MIN	2778	3153
Vint-mean	3729	3678
Vint-MAX	4755	4388
OWT-mean	164	197

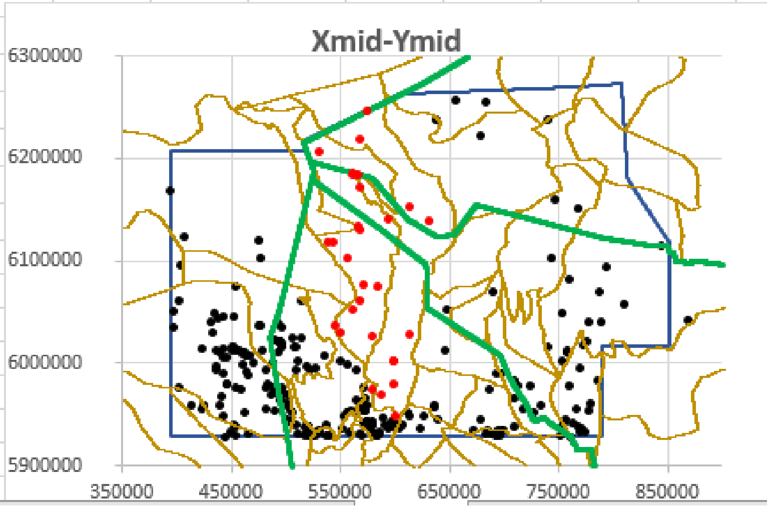


Figure 12 V_{int}-Z_{mid} relation for Triassic groups (TR). The study area has been subdivided in 2 parts: 'CG+SG' (Central Graben + Step Graben, see red dots) and the area 'Outside CG+SG' (black dots). For the area 'Outside CG+SG' there is a strong linear relation and for the area 'CG+SG' there is a reasonable linear relation. It should be highlighted that the results of the VELMOD-3 project (purple dashed line) and the results of this project for the area 'Outside CG+SG' (black solid line) are comparable. The result for the whole study area (see Table 5) is indicated by the purple solid line (K=0,42; V_0=2721 m/s and R^2=0,54).

In areas with very thick Triassic succession such as the Horn Graben, it will be preferred to include a cap velocity in order to prevent unrealistic velocities.

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

Per lithostratigraphic unit the location dependent $V_0(x,y)$ values at borehole locations have computed using the determined regionalized K-factor for the areas 'Outside CG+SG' and 'CG+SG' (Table 7) by:

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

<u>Filtering of V_0-data</u>

Before gridding the V_0 values have been controlled on the following criteria:

- Thin intervals (< 5 ms) were discarded
- V_0 value should range between a minimum and maximum value for each lithostratigraphic unit (see V_0-MIN and V_0-MAX in Table 8). These values were manually determined using the V_{int}-Z_{mid}-graphs for each lithostratigraphic unit (Figures 7-12). In total for all lithostratigraphic units the V_0 lies between 1100 and 4000 m/s.
- if COVERAGE (or OWTitv) was 'NOT_UP_TO_TOP' or 'NOT_DOWN_TO_BASE_AND_NOT_UP_TO_TOP', for the Dutch wells, many V_0 values have been discarded (213 records). In these cases the OWT-interval is not covering the whole interval for that lithostratigraphic unit and then in general the calculated V_{int} values for the whole interval are not corresponding with the V_{int} values used for the V_{int}-Z_{mid} analysis.
- For UK the Upper Jurassic groups (S) and the Lower+Middle Jurassic groups (AT) had the same values. It has been investigated which data were S and which were belonging to AT, only for wells within blocks 48 and 49 a decision couldn't be made.

In total 406 V_0 values (out of 2366) have been discarded by using the above mentioned criteria.

Table 8: *The regionalized results per lithostratigraphic unit for the whole study area, the areas 'Outside CG+SG' and 'CG+SG', including the V_0-MIN and V_0-MAX values that have been used to discard V_0 values*

	Whole study area						Outside CG+SG						CG+SG					
Code	K	V_0	R^2	#	V_0-MIN	V_0-MAX	K	V_0	R^2	#	V_0-MIN	V_0-MAX	K	V_0	R^2	#	V_0-MIN	V_0-MAX
N	0,16	1852	0,51	368	1610	2100	0,32	1758	0,65	211	1610	1980	0,02	2003	0,05	157	1890	2100
CK	0,62	2582	0,65	539	1550	3050	0,91	2216	0,78	351	1550	3050	0,64	2365	0,72	188	1550	3050
KN	0,37	2342	0,32	481	1300	4000	0,59	1988	0,74	340	1450	3050	0,20	2539	0,09	141	1300	4000
S	0,09	2769	0,03	212	1100	3900	0,65	1661	0,68	55	1100	2600	0,07	2713	0,03	157	2050	3900
AT	0,35	2129	0,62	94	1400	2850	0,58	1771	0,93	18	1400	2200	0,26	2392	0,34	76	1800	2850
TR	0,42	2721	0,54	287	1790	3650	0,49	2584	0,67	257	1790	3650	0,31	2758	0,26	30	2100	3200

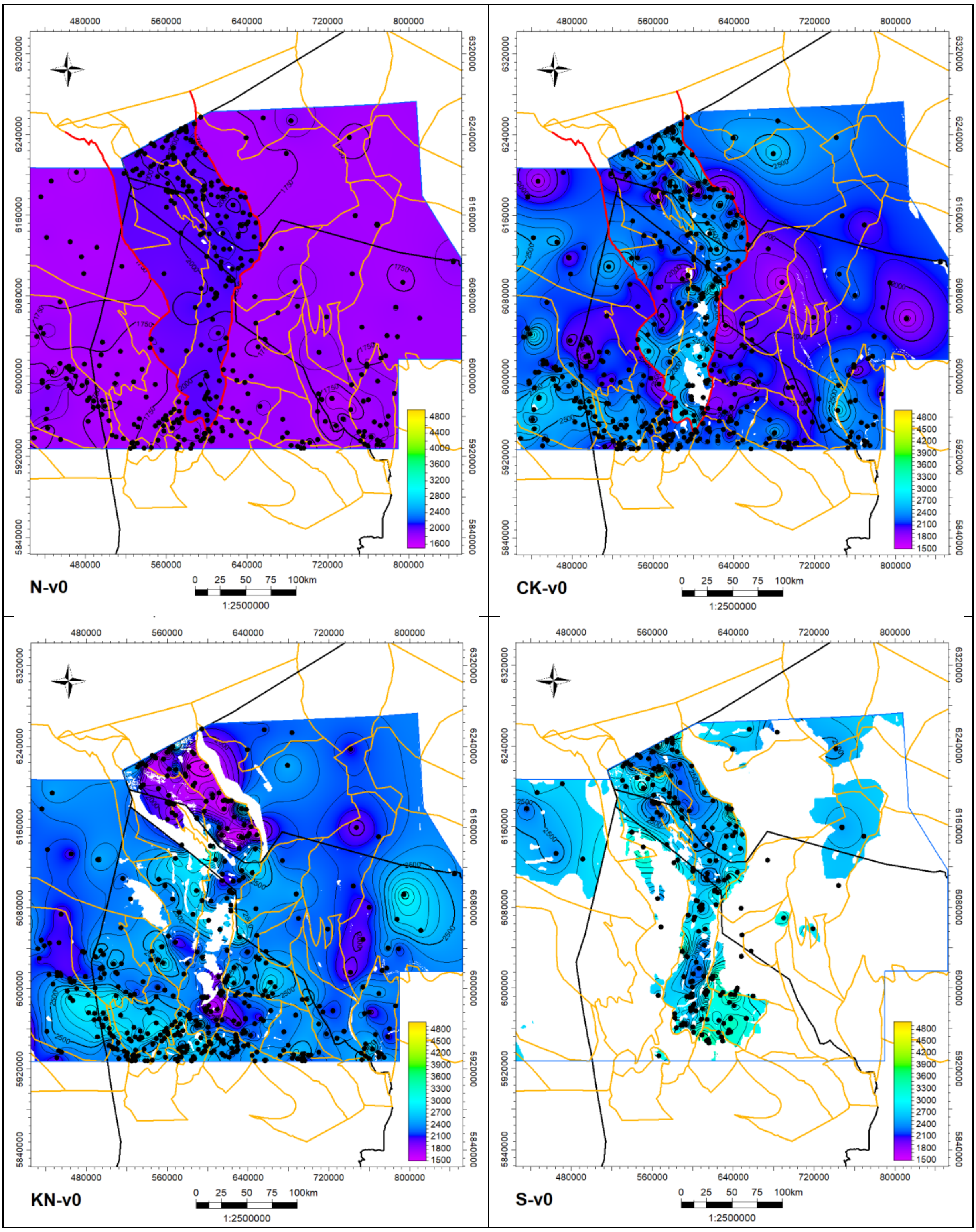


Figure 13: *a) V_0 map for N, b) V_0 map for CK, c) V_0 map for KN and d) V_0 map for S.*

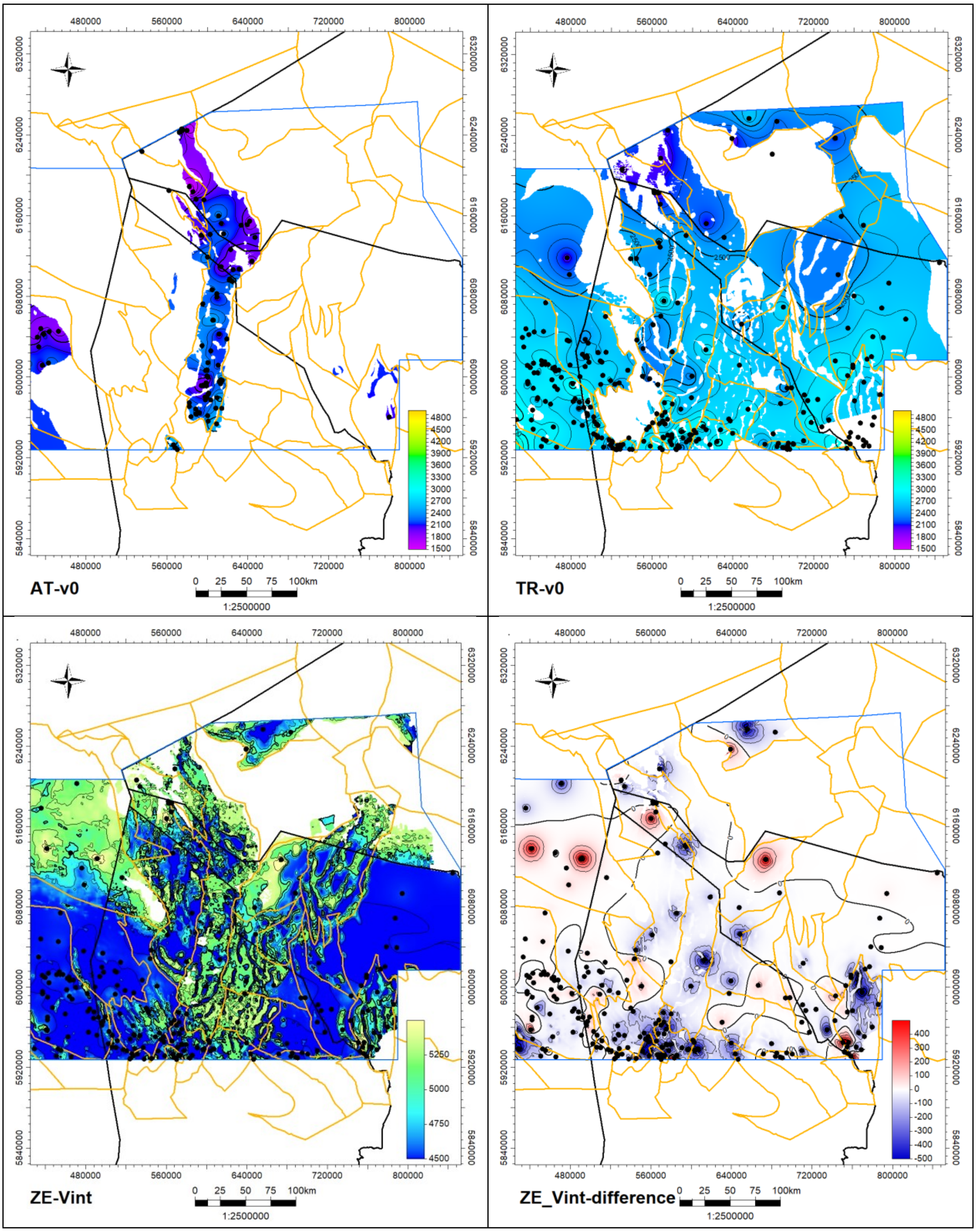


Figure 14: a) V_0 maps for AT, b) V_0 map for TR, c) V_{int} map for ZE, d) V_{int}borehole-V_{int}provisional difference map for ZE.

Several methods of constructing the velocity maps were evaluated along with defining the filtering criteria of V_0 values; i.e. kriging vs. convergent gridding, marking the CG+SG using a polygon vs. no polygon. Kriging was selected as the best candidate gridding operator because the least over- or undershoot effect was observed in the gridding result in areas with a strong gradient related to diverging velocities in nearby wells. The effect of each choice for potential edge effects was tested by using the previously constructed GARAH time model in depth conversion (D3.2). These preliminary test results suggest that edge effects due to using the CG+SG outline polygon will be limited in the final depth output.
The V_0 maps selected were constructed with a kriging algorithm (simple kriging, exponential type, sill 1, range 80 km, nugget 0.001) and using a 250X250 grid increment.
For the N and CK horizons, subsets from the selection of well velocity data were created for gridding the area outside CG+SG and the area inside CG+SG, in correspondence with the variable K-value. In a final step these 2 grids were merged into a full area grid (Figure 13a,b). The deeper horizons KN-TR were gridded without a boundary polygon (Figures 13c,d and 14a,b).

Triassic cap velocity for deep basin(s) (Figure 14b)
In areas with very thick Triassic succession it will be preferred to include a cap velocity in order to prevent unrealistic high velocities. For the model area it is decided to integrate a cap velocity of 5000 m/s into the Petrel workflow. This cap value is supported by the graph in Figure 12 and from other basin areas (Schnabel et.al, 2021).

Outlier on the TR V_0-map (Figure 14b)
On the V_0-map the R1-well in the German Horn Graben seems to be an outlier because only the upper Triassic and parts of the Mid Triassic was drilled and will not represent the whole Triassic of this area. It was decided to take an average V_0 for the German part of the Horn Graben by using the R1 and Danish wells of this area.

V_{int} map for ZE (Figure 14c,d)
Chapter 3.2 describes the workflow for constructing the Zechstein V_{int}-grid. It was explained that the final Zechstein V_{int}-grid is based on a provisional grid corrected with a difference grid from V_{int}borehole and V_{int}provisional at borehole location. This difference grid was constructed with similar kriging parameters and grid increment as the V_0 velocity grids, but a smaller range (=20) was set. A factor was included to minimize hard breaks in the final velocity grid; Factor= If(OWT >300,1, (1/(1+7*((300- OWT)/300)))) (Figure 14d), and in a final step the minimum value of the V_{int}-grid was clipped at 4300 m/s.

4.3 Subdivision Cenozoic

So far the transnational harmonized velocity model has been built for seven main stratigraphical intervals, i.e. N, CK, KN, S, AT, TR and ZE (Table 3). Because also the Near Mid Miocene Unconformity horizon (NU) has been selected for harmonization purposes during the seismic interpretation phase (Table 1), this NU horizon should be time-depth converted too.

If for td conversion of the NU horizon (=Near Mid Miocene Unconformity) the same method (regionalized K values for inside / outside CG+SG) and parameters will be used as for td conversion of the ‘Near base Cenozoic (N)’, then a distortion in the depth map will be observed along the ‘CG+SG’ boundary (see Section 4.4 and Figure 18a,c). Further the basefit calibration method that was used for the ‘Near base Cenozoic (N)’ horizon only aims a zero depth error at the well base of the complete stratigraphic interval in the gridded horizon. So for intermediate horizons such as the ‘Near Mid Miocene Unconformity’ the basefit method used for N is not suitable.

Because of above reasons, the Cenozoic interval (N) is divided in 2 sub-layers: NU (MSL to Near Mid Miocene Unconformity) and NLM (Near Mid Miocene Unconformity to Near base Cenozoic). For both intervals NU and NLM, a V_{INT}-Z_{MID} analysis was executed (see Figures 16 and 17). All wells with a ‘ COMPLETE’ interval were selected and no further selection criteria were necessary.
The V_{INT}-Z_{MID} analysis (Figures 16 and 17) show the following:

- The results of NU for the region ‘CG+SG’ are lining up with the results for the region ‘Outside CG+SG’ (red resp. black dots in Figure 16). It could be also observed that the results by using the method ‘one K(=0,35) for the whole study area’ shows a strong linear relation.
- The results of NLM show similarities with the results for N (compare Figures 9 and 17): for the area ‘Outside CG+SG’ there is a reasonable linear relation and for area ‘CG+SG’ there is a very weak linear relation.
- The results of NU and NLM are comparable with the VELMOD-3 results (Table 7); for NU for both areas and for NLM for the area “Outside CG+SG’

For the reasons stated above, a V_0 map for NU was created using the method ‘one K(=0,35) for the whole study area’ (Figure 15). Finally, a better depth map without distortion along the ‘CG+SG’ boundary for the ‘Near Mid Miocene Unconformity’ has been produced (Fig.17b).

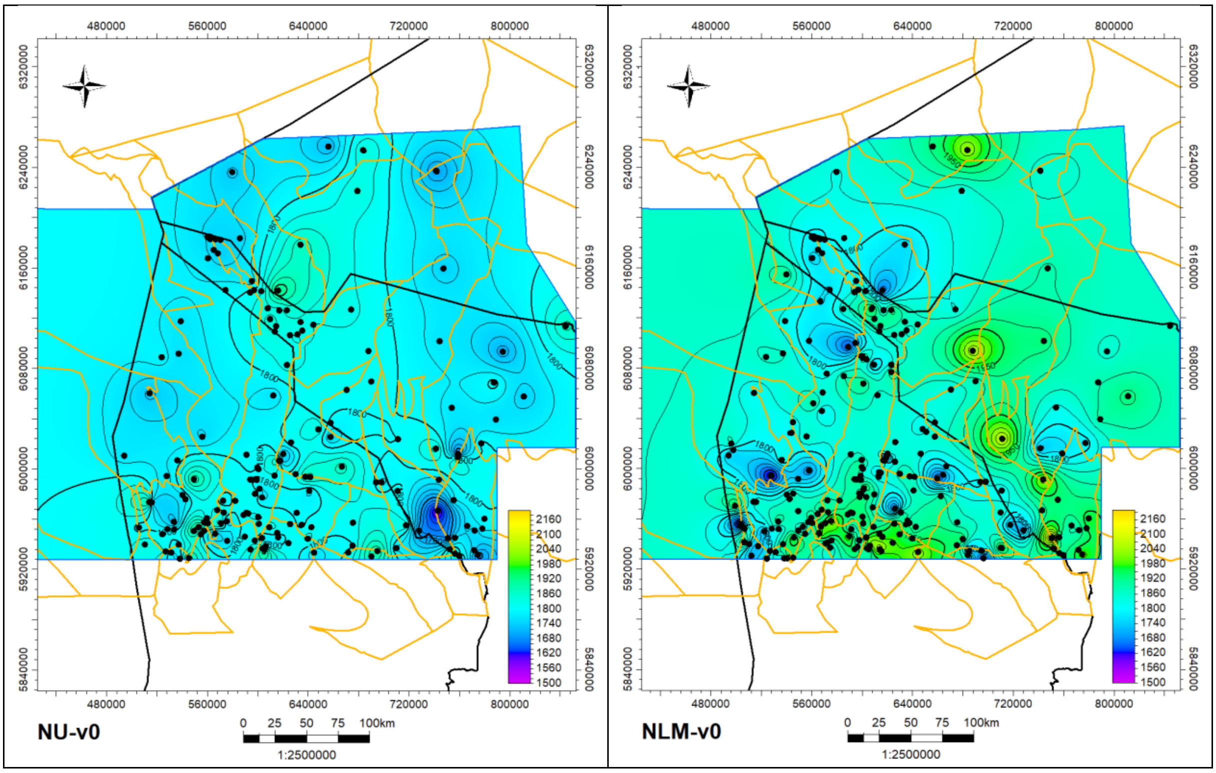
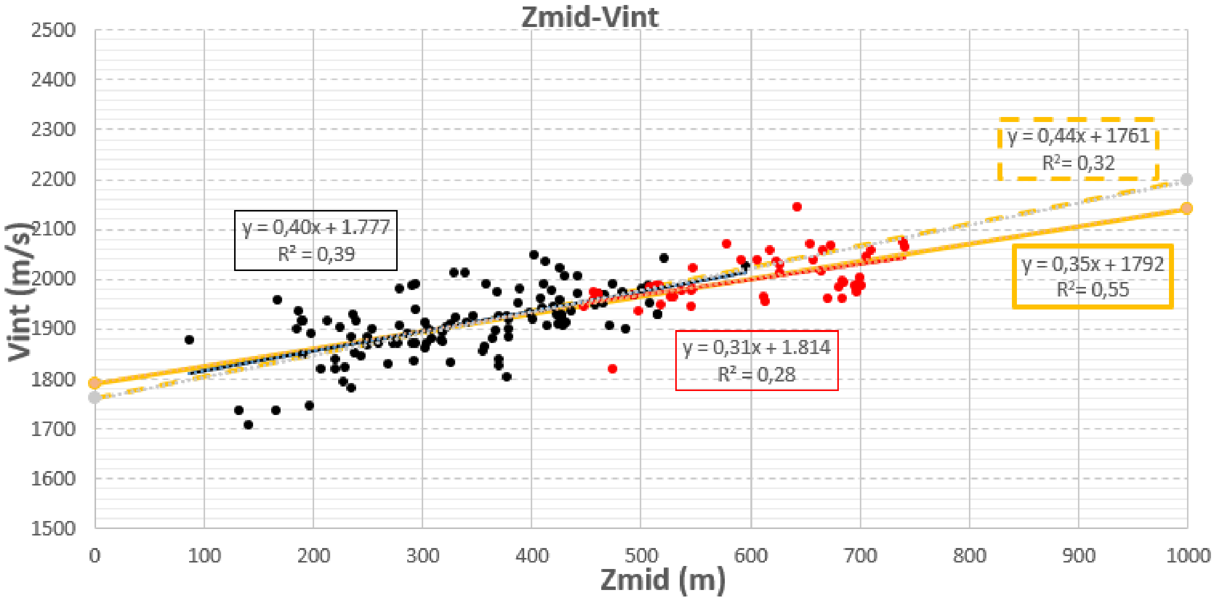


Figure 15: V_0-map for a) ‘Near Mid Miocene Unconformity’ (NU), and b) ‘Near base Cenozoic (NLM)’ by using one K (=0,35, 015 resp.), for the whole study area.

NU



	Outside	CG+SG
Interval:	NU	NU
#wells	114	49
max #itv	1	1
Zmid-MIN	87	448
Zmid-mean	342	602
Zmid-MAX	596	741
Vint-MIN	1710	1820
Vint-mean	1913	2000
Vint-MAX	2050	2146
OWT-mean	346	594

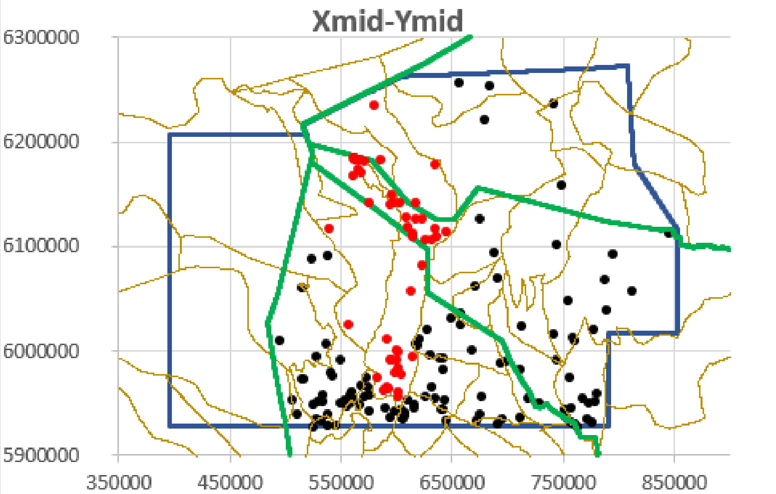
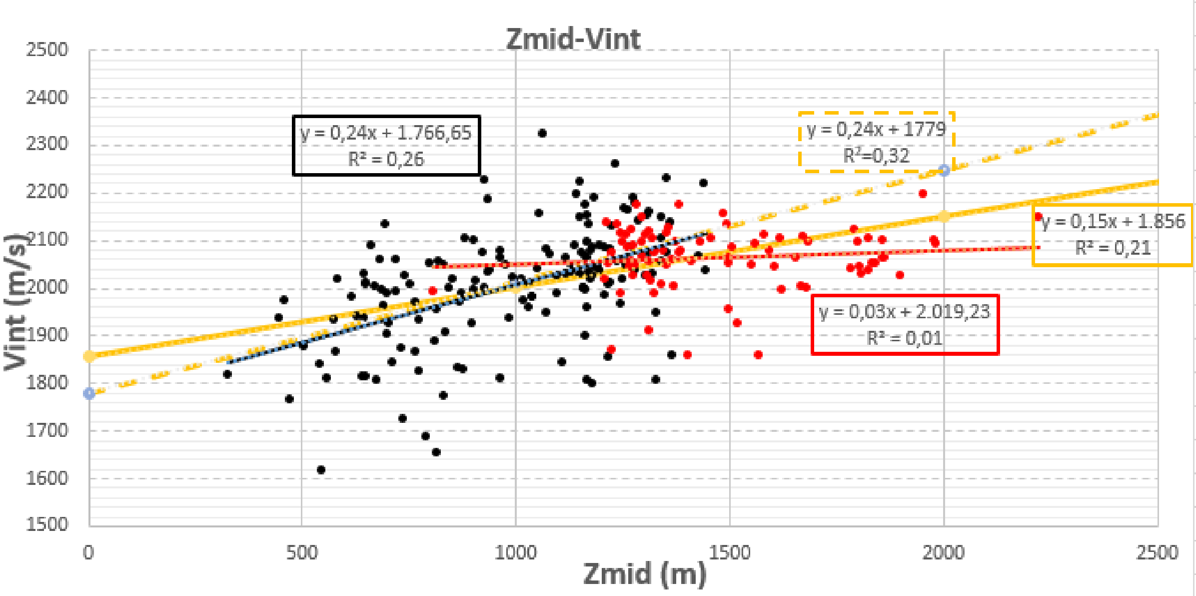


Figure 16: V_{int}-Z_{mid} relation for interval MSL to Near Mid Miocene Unconformity (NU). The study area has been subdivided in 2 parts: 'CG+SG' (Central Graben + Step Graben, see red dots) and the area 'Outside CG+SG' (black dots). For both areas there is a reasonable linear relation. It should be highlighted that the results for the VELMOD-3 project (orange dashed line), the area 'Outside CG+SG' (black solid line), the area 'CG+SG' (red solid line) and the results for the whole study area (orange solid line: K=0,35 and V_0=1792 m/s and R^2=0,55) are all comparable.

NLM



	Outside	CG+SG
Interval:	NLM	NLM
#wells	159	85
max #itv	1	1
Zmid-MIN	327	805
Zmid-mean	997	1479
Zmid-MAX	1442	2220
Vint-MIN	1619	1857
Vint-mean	2007	2064
Vint-MAX	2325	2197
OWT-mean	296	307

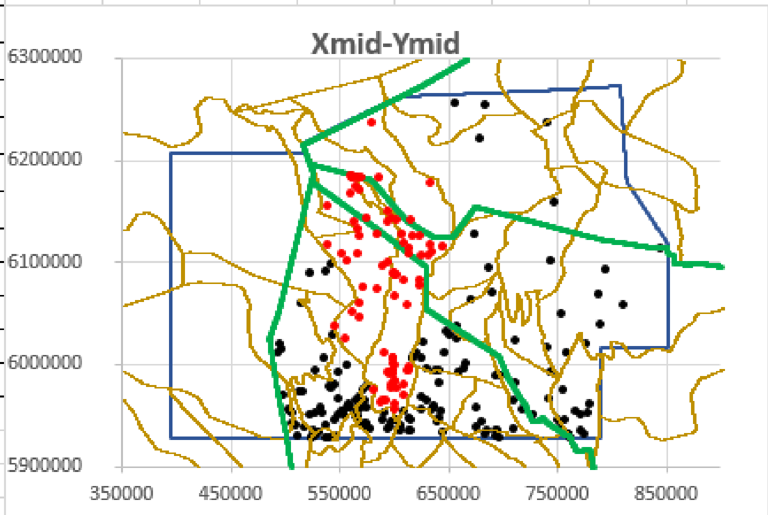


Figure 17: V_{int}-Z_{mid} relation for interval Near Mid Miocene Unconformity to Near base Cenozoic (NLM). The study area has been subdivided in 2 parts: 'CG+SG' (Central Graben + Step Graben, see red dots) and the area 'Outside CG+SG' (black dots). For the area 'Outside CG+SG' there is a reasonable linear relation and for area 'CG+SG' there is a very weak linear relation. It should be highlighted that the results for the VELMOD-3 project (orange dashed line) and for the area 'Outside CG+SG' (black solid line) are comparable.The results for the whole study area is indicated with an orange solid line: K=0,15, V_0=1856 m/s and R^2=0,21.

4.4 Discussion

It is clear that the method using ''regionalized K values for inside/outside CG+SG'' is causing distortion of the final depth output (Figure 18). Depth conversion was initially tested with the 3D depth model of the Entenschnabel region (D3.2) and subsequently conducted with an updated version of the model including reinterpretations discussed in D3.6. The method using 'regionalized K values for inside/outside CG+SG' was used for the Near base Cenozoic and the Base Upper Cretaceous horizons. In the final depth results the edge effect varies spatialy along the CG+SG boundary line because of variations in the velocity grid (Figure 13a,b) and time thickness. At the location of intersection A-A' (Figure 18a-d), a relative strong distortion was observed (base NU: A ~ 55m, A' ~75m; base N: A ~ 40m, A' ~145m; base CK: A ~60m, A' ~265m,). The effect also propagates to deeper horizons due to the top-down successive layer cake depth conversion process. The jump observed in deeper levels compared to the Near base Cenozoic is larger because the Base Upper Cretaceous contributes to the effect. Depending on the structural setting and areal extend of the model, the effect might be acceptable or not. For example, in the eastern part of the CG+SG boundary polygon coincides with the Coffee Soil fault system. Here, the propagated distortion may be easily corrected by smoothing or remodeling the fault gap in depth in this steep dipping fault system offsetting the deeper horizons. However, for the shallower and gradual dipping Near Base Cenozoic and Base Upper Cretaceous horizons the jump is more obvious, even suggesting a fault scarp. As a result, the method seems less acceptable. The Entenschnabel region model area (GARAH) only covers part of the CG+SG area, and is likely not revealing all issues. Therefore, on a more regional scale or even countrywide scale, a more general approach without the need to edit local distortions may be advisable. Although the new velocity data reveals a clear variation inside and outside the CG+SG for the Near base Cenozoic and the Base Upper Cretaceous horizons, to finally conclude if the method is acceptable in further modeling the horizons, a thorough review of the full outcome is advised. This may lead to an iterative process of remodeling the velocity data, depth converting the horizons, including evaluating misties of the well marker depth with the horizon depth. Within the timeframe of this project, this was not possible and further will not discussed here.

For depth conversion of the Zechstein interval, a provisional grid of V_{int} based on the travel times from seismic interpretation and corrected for differences at the well location was used. Although the method attempts to compensate for the relative high abundance of high velocity carbonate layers in relatively thin layers and for the halite velocity (= 4500 m/s) in regions with diapirs and thick halite layers, this Zechstein V_{int} calculation does not prevent a strong pull down effect when modeling salt domes and including salt structures in the time model. The project area includes several large salt domes, over a kilometer thick. In the new model, as for the GARAH model (D3.2), complex multi-z salt structures with overhang or mushroom shapes are modified to a vertical shape. To correct for the pull-down effect, different modelling approaches can be applied. A simple approach is eliminating the distorted Zechstein below the salt structure and reinterpolate within the cutout area, but any trend originally interpreted will be lost. Alternatively, the cutout area may be regridded including the Zechstein time horizon as a trend surface, which is the method applied in the updated GARAH model. However this method may not be available in all modelling software. Finally, a 2 step method may be applied. In the first step, a closed layer cake without salt structures down to the base of the Triassic is used in converting the horizons. Secondly, the depth converted Base Triassic, slightly smoothed in the vicinity of salt structures, can be used as starting point for implementing the interval velocity model for the Zechstein.

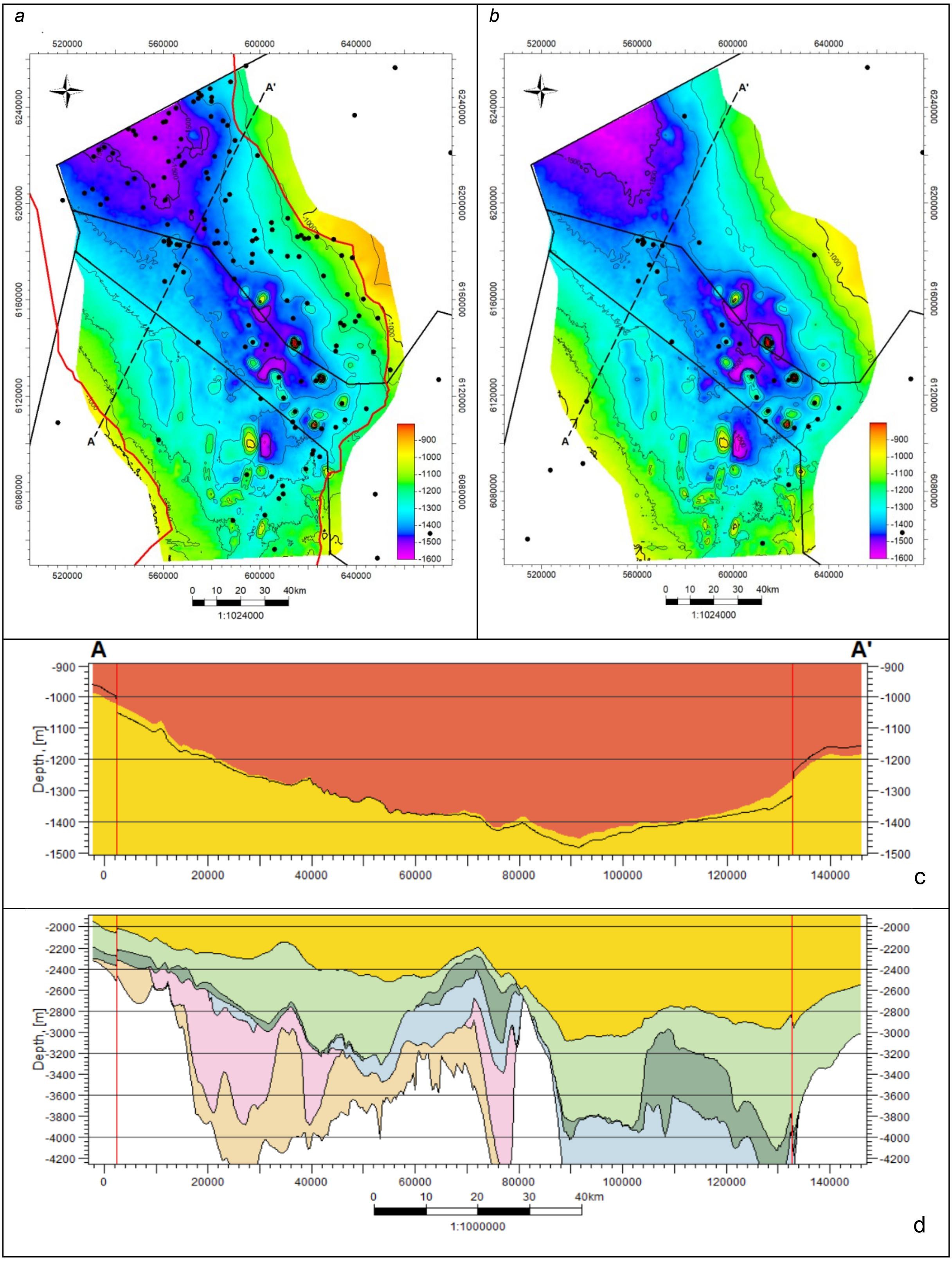


Figure 18: Comparison of depth maps for 'Near Mid Miocene Unconformity' (NU) after td-conversion by using a) the *method for the 'Near base Cenozoic' (N) (regionalized K values for inside/outside CG+SG) and b) the method used for NU: 'one K-value(=0,35) for the whole study area'. Vertical intersections c) and d) along line A-A' illustrate the offset caused by the method inside/outside CG+SG for 'NU (method a =black line, method b=colour shading) and for base N and CK horizons respectively. The red polyline in a) and the vertical red lines in c) and d) mark the CG+SG boundary.*

5 CONCLUSIONS

The velocity model for the study area is created for a minimal lithostratigraphic unit configuration as the dataset appeared to be too limited for a detailed unit configuration. Finally, seven main stratigraphical intervals have been selected for building the transnational velocity model: N, CK, KN, S, AT, TR and ZE.

For the Cenozoic and Mesozoic intervals, it is generally assumed that the acoustic velocity increases linearly with depth under the influence of burial and compaction (V_0-K method).
After analyzing the results of the V_0-K method for the study area as a whole or splitting it in structural elements, structural element types or combination of structural elements finally the following K-values have been used:

- regionalized K values (inside / outside CG+SG) for N and CK intervals and
- a global K value (whole study area) for KN, S, AT and TR intervals

In general, for the Cenozoic and Mesozoic intervals, lower velocities occur within the main depocenter region as the Central Graben + Step Graben (CG+SG), where the sediments are characterized by a more relative faster subsidence, resulting in undercompaction. For the Cenozoic interval, it is better to assume for the main depocenter region a constant V_{int} or a velocity trend with a much smaller K value than the region outside the main depocenter.
Also within the depocenter region ("CG+SG") a poor velocity-depth correlation has been found for the older Mesozoic intervals (KN, S, AT, TR), which could be caused by changes in facies distribution, strongly differential uplift during Late Cretaceous basin inversion and differences in formation pressure.

In contrast to the Cenozoic and Mesozoic layers, the Zechstein (ZE) interval velocity is not a function of depth and compaction. The lithological composition of the interval is the most dominant factor for the interval velocity and the influence of compaction on the interval velocity is considered very minor. For this project, the Zechstein velocities are modelled based on an interval velocity - thickness (or ΔT) relation.

Finally, after subdividing the N interval into two intervals NU and NLM, it could be concluded that for NU a 'global K for the whole study area' gave the best results and that for NLM (similar to the N interval) it is better to assume for the main depocenter region a constant Vint or a velocity trend with a much smaller K value than the region outside the main depocenter.

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