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Fault Interpretation of the Groningen area supra-Zechstein Overburden

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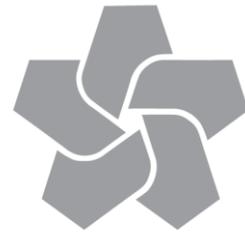
General Introduction

Emphasis of geological modelling has traditionally been on the reservoir formations; the Rotliegend sandstone and also the immediately overlying Zechstein formation (Ref. 1 and 2). However, for the prediction of ground motion and the determination of the hypocentre of an earthquake, the full rock column from the reservoir up to the surface and also down below the reservoir is important. In reports on the models used for Ground Motion Prediction this so-called overburden (rock above the reservoir) and to a lesser extent the underburden (rock below the reservoir) are discussed (Ref. 3 and 4).

Especially during the workshop on the maximum magnitude earthquake (Ref. 5 and 6), the faults in the overburden and underburden were discussed. In this report, the faults in the formations above the Zechstein are presented and discussed.

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Assurance	Internal NAM			

Fault interpretation of the Groningen area supra-Zechstein Overburden



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Nederlandse Aardolie Maatschappij B.V.

Shell UPO

Fault interpretation of the Groningen area supra-Zechstein Overburden

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1 Executive summary

A comprehensive Groningen field overburden fault interpretation has been carried out to assess the possible relation between recorded seismic events and overburden faults. This supra-Zechstein overburden fault interpretation shows that most of the larger fault structures are related to halokinesis of the Zechstein evaporites. Projecting the outline of the gas-water contact of the Groningen field onto the top Zechstein horizon shows that the largest salt structures are positioned at the periphery of the Groningen gas field. Consequently, this is also the area where a relatively high density of faults is found. In the crestal part of the field, no salt structures of significance are observed and therefore also no associated overburden faults.

Areas with a Zechstein time thickness of less than a 75ms appear to have the highest chance of linkage between sub_ and supra_Zechstein faulting. Such a limited thickness mainly occurs in the eastern part. Soft-linked faulting is observed in the southeast and northeast. In the southeast two overburden faults are closely associated with sub-Zechstein faults. The eastern 'curved shaped' fault aligns with a mapped sub-Zechstein Pre-Saalian reactivated fault. The western N-S orientated fault aligns with a mapped sub-Zechstein post-Rotliegend fault. Both faults can be traced up into the North Sea formation, but the area where soft-linked faulting is observed is outside the Groningen gas field closure. In the northeast, two north dipping faults are associated with thick-skinned faulting, of which the most northern fault shows soft-linked faulting corresponding to a sub-Zechstein pre-Saalian reactivated fault. These faults extend into upper Triassic - Jurassic deposits.

By integrating the fault interpretation with isochore maps it becomes clear that the dominant structural features of the study area were present as of mid-to late Triassic times, and continued to evolve since. The supra-Zechstein fault orientations align with the main sub-Zechstein fault trends. This is an indication that reactivation of sub-Zechstein faults controlled the shaping of the Zechstein salt structures and thereby indirectly also the overburden fault structures. Upper Triassic and Jurassic thickness maps show the expression of an erosional event in middle-late Jurassic times, in most places eroding down into lower Triassic deposits. Deposits in the lower Cretaceous are followed by thick deposits in the upper Cretaceous honouring a NW-SE trend, in which the NW-SE orientated 'salt-pillow' grabens show thinner deposits than the rest of the study area. This is an indication of a salt pulse at this stage. Halokinesis locally continued into the Paleogene and Neogene, primarily in the eastern part of the study area.

The seismic quality of the upper 300ms make it impossible to give a decisive answer to whether faults extend to surface. Projecting the fault - upper North Sea horizon intersections onto the present-day elevation map indicates that these faults have no discernible expression at surface.

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2 Introduction

Recent seismic events in the area of the Groningen gas field have triggered renewed interest in the presence of faults in the Groningen field overburden. It has been suggested that there is a possible relation between the seismic events and overburden faults. Therefore, a new seismic fault interpretation of the reprocessed R-3136_Groningen 3D seismic cube has been made focusing on supra-Zechstein formations. A possible relation between sub- and supra-Zechstein faults has also been investigated. The results are presented in this report.

3 Objectives, input data and methods

3.1 Objectives

The key objectives were:

- To generate a supra-Zechstein overburden fault interpretation, with emphasis on faults running from top Zechstein into the North Sea Group formations.
- To assess a possible relation between faults in the overburden and sub-Zechstein faults.

As the study mainly focused on formations and structures above the top Zechstein, all supra-top Zechstein formations will be regarded as overburden. The study area (Figure 1) is covered by a 50 x 50km seismic cube that is composed of multiple surveys. Figure 1 displays the top Zechstein horizon with the outline of the gas-water contact of the Groningen field projected onto it..

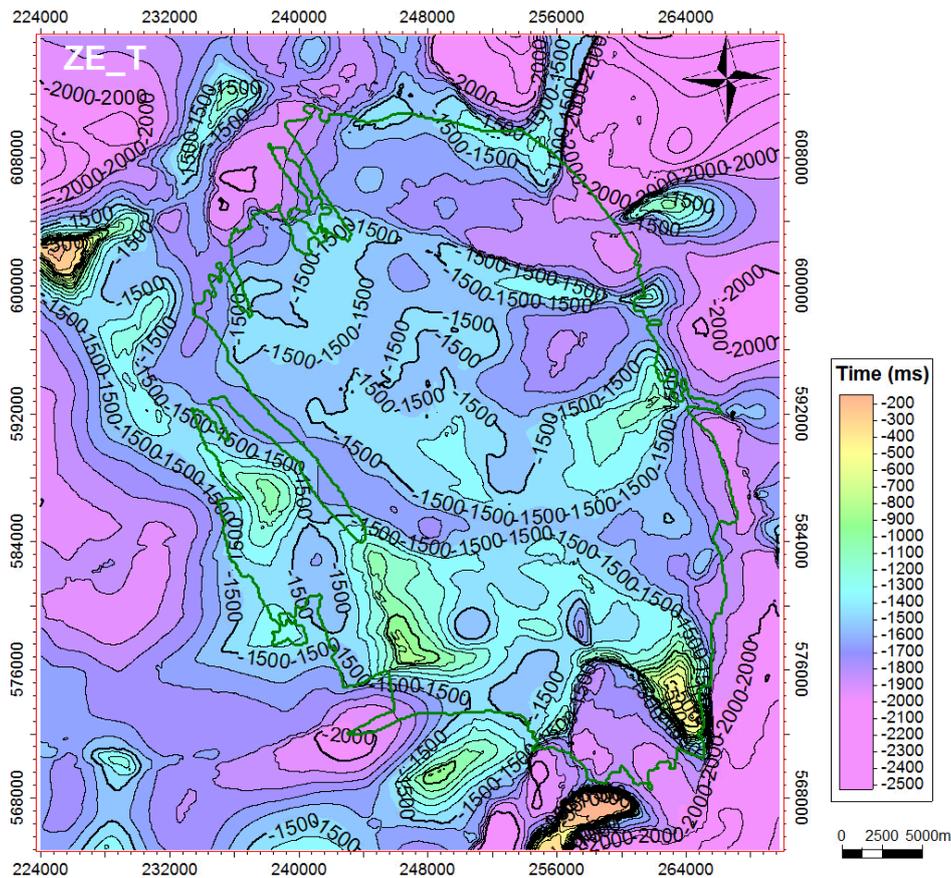


Figure 1: TWT map of the top Zechstein horizon, with the outline of the gas-water contact of the Groningen field in green.

3.2 Input data

3.2.1 Seismic data

For the seismic interpretation the R3136_15UnrPrDMkD_Full_T_Rzn_RMO_Shp_AVC seismic cube was used. It consists of an area of approximately 2700 km² of 3D seismic, covered by several (partially overlapping) surveys, acquired in the early 1990's (Wervelman, R., 2015) and will be used for 3D seismic interpretation. The interpretation was conducted in the time domain, with a full-stack seismic cube. Figure 2 shows the same seismic line of the near-stack cube and the full-stack cube. With the focus on mapping larger faults and less on small subtle faults, quality discrepancies between the near-stack and the full-stack cube were assessed to be trivial and therefore the full-stack cube was used.

Overall the seismic imaging quality of the supra-Zechstein is considered to be of good quality, except for the northeastern area where no data is present. The upper ~300ms are assessed to be uninterpretable because the 500x500m receiver-transmitter grid introduces a dominant acquisition direction as artifacts in the upper part of the overburden, losing its interference with depth.

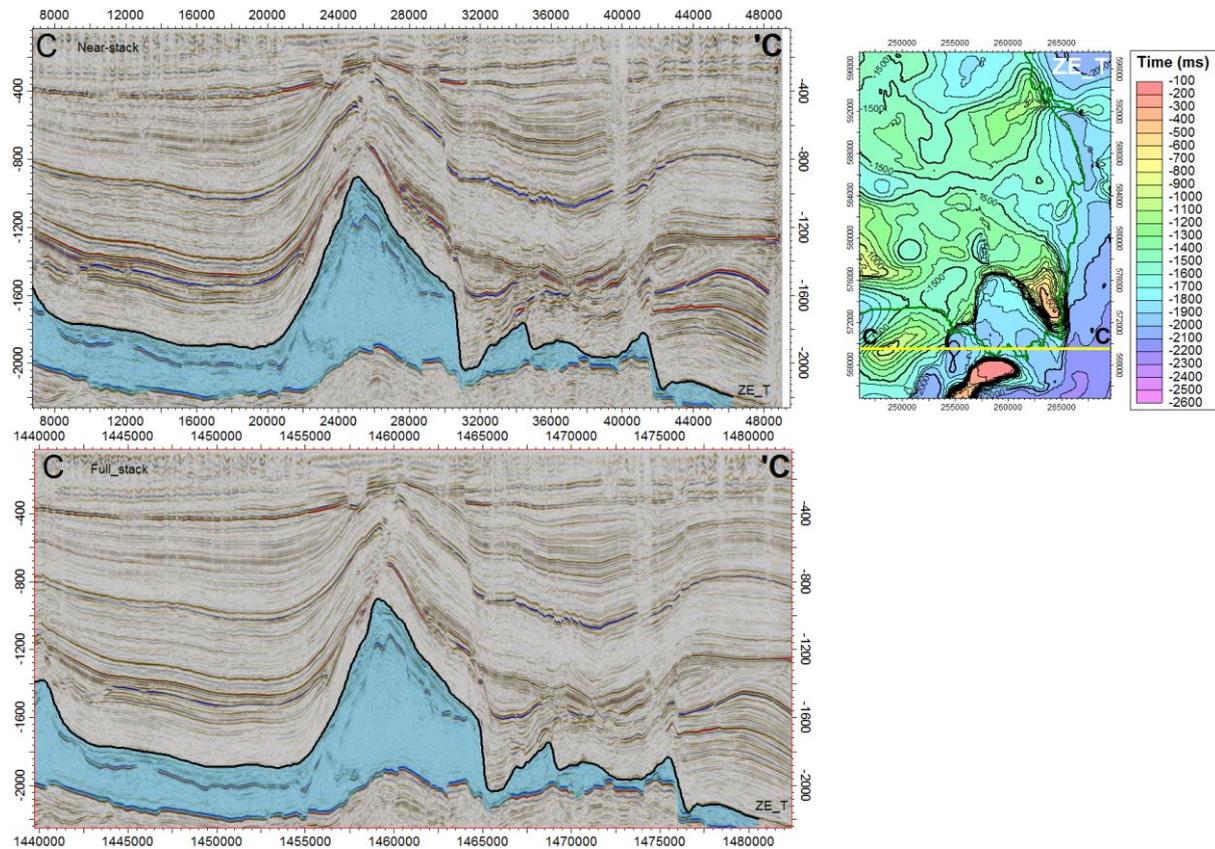


Figure 2: Seismic line of the near-stack (upper) and the full-stack (lower) seismic cube.

3.2.2 Horizon data

Table 1 contains the horizons used for the interpretation. Figure 3 displays the lithostratigraphic column and the associated markers.

Horizons	Corresponding markers
Base Upper North Sea	NU_B

Base Lower North Sea	NS_B
Base Chalk	CK_B
Base Rijnland	KN_B
Base Altena	AT_B
Top Röt	RNRO_T
Top Zechstein	ZE_T

Table 1: List of horizons provided and their corresponding markers.

3.3 Methods

3.3.1 Seismic interpretation

With the top Zechstein evaporites as the base level of interest, the main Zechstein topographic irregularities were the initial focus areas. By initially scanning through seismic lines perpendicular to the major salt structures the major faults of the area were identified. These were mapped through manual picking.

This was followed by assessing the possibility of using volume attributes to better identify faults. Both SOF semblance and semblance processing was applied on the dataset, followed by both active and passive Petrel Ants extraction. This showed that the specific data set is not suitable for these attributes, because of the acquisition artifacts in the upper ~300ms. It was attempted to filter out these artifacts in ant tracking by setting the stereonet option to filter out between 90 and 70 degrees. The upper 300ms of seismic data can be considered uninterpretable because of these artifacts.

Horizon/surface attributes proved to be more effective than the mentioned volume attributes. Use was made of the following attributes:

- Horizon/surface probes (sculpting). This is an irregular probe that follows one horizon. The probe was aligned vertically to the center of the horizons with a thickness of 40ms.
- The traditional dip and dip-azimuth attributes.

3.3.2 Fault-horizon intersection maps

A workflow was created in Petrel to derive the fault-horizon intersections. This workflow creates clean fault sticks from the interpreted fault sticks and converts them into a surface. Then it crops the fault surfaces and smoothens the horizons and faults surfaces. Intersections are then created from the fault surfaces and the horizons. The output is a set of fault-horizon intersection polygons that can be projected onto horizon and isochore maps. These maps were used to determine the areas with high fault density and through which formations the faults were active.

4 Geological setting

The study area is located in the NE Netherlands, southern Permian basin and comprises the overburden of the Groningen high. With a 100 Tcf GIIP the Groningen high contains one of the largest gas reservoirs of the world (Dijksman, 2009), The Rotliegend sandstones (middle Permian) form the reservoir (A. Sluijk, K. van Ojik, M. de Keijzer, J. Graaf, J. Steenbrink, 2011). The reservoir is sealed by late Permian Zechstein evaporites. Triassic to lower-Cretaceous sequences are poorly developed on the Groningen high, reflecting a structural elevation during this time (van Gent, 2010). Late Cretaceous Chalk, Chalky limestones and relatively dense limestones form the Chalk group (van Gent, 2010). This stage is associated with regional tectonic inversion, of which the intensity varied from basin to basin (de Jager, 2003). Inversion of the Groningen high is thought to be relatively mild (de Keijzer, M., 2008). Above the Chalk interval, sedimentary

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sequences ranging between 800-1800m of predominantly siliciclastic Paleogene and Neogene deposits make up the North-Sea super group (van Gent, 2010).

Multi-phase salt movement of the Zechstein evaporites has influenced the younger deposits and tectonics in the study area. It has resulted in folded structures, thin and thick-skinned faults, uplift and erosion of younger sediments and syn-tectonic deposits. Figure 3 displays the main tectonic phases and formations.

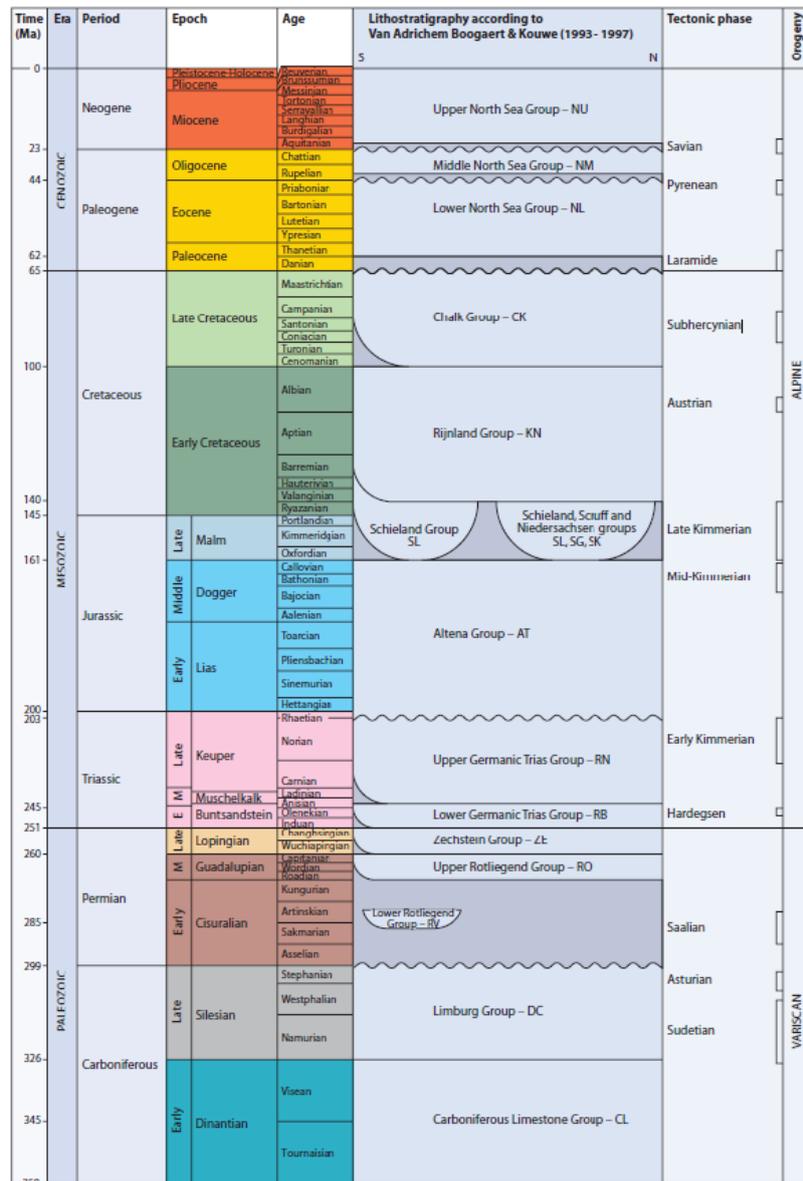


Figure 3: Geological time scale (Grandstein, 2004) and lithostratigraphic column (van Adrichem Boogaert H. , 1993-1997) showing main tectonic phases.

5 Salt tectonics

5.1 The Zechstein group

The Zechstein group was deposited in the Southern Permian Basin and consists of five dominantly evaporitic cycles (Geluk, 2000) (Figure 4). In the study area only the Z1-Z4 cycles are found.

The first evaporitic cycle (Z1) forms an E-W trending anhydrite platform in the central Netherlands (van Adrichem Boogaert H. , 1983). The study area is located on the slope to basin facies and wells show a 50m thick layer of anhydrite deposited continuously in the study area. The second (Z2) and third (Z3) cycle generally contain the thickest halite intervals that respectively reach thicknesses of up to 600m and 300m (ten Veen, 2012). It should be noted that due to halokinesis salt thicknesses found in the study area are not representative for the depositional thickness. The Z4 salt is deposited locally in isolated depocentres (ten Veen, 2012).

Since it is the thickness and presence of mechanically ductile salt that plays a role in halokinesis and decoupling, the salt should be separated from the rest of the Zechstein group. To get an estimation of the actual presence and thickness of salt to determine if thick-skinned faults can potentially be present the 50 m Z1 anhydrite is subtracted from the Zechstein group.

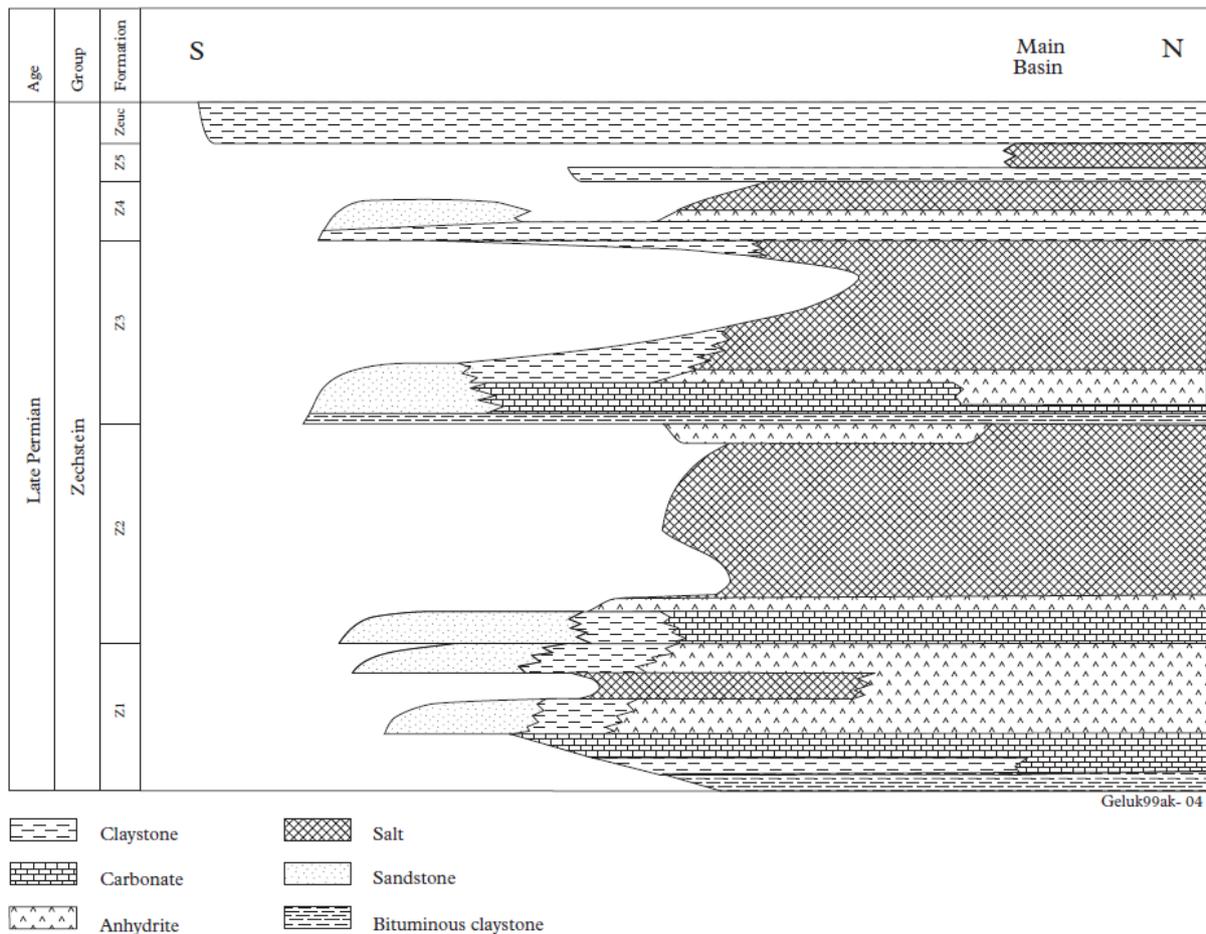


Figure 4: Zechstein group Z1-Z5 formations. Zechstein facies in the Netherlands, from South to North (Geluk, 2000).

5.2 Salt structures

It is broadly recognised that most faults in the Northern and Eastern Netherlands supra-Zechstein formations are related to salt movements (van Gent, 2010). The level of halokinesis seen in the study area (Fig. 4) is similar to that seen more regionally / a cross the Southern Permian Basin (Fig. 3).

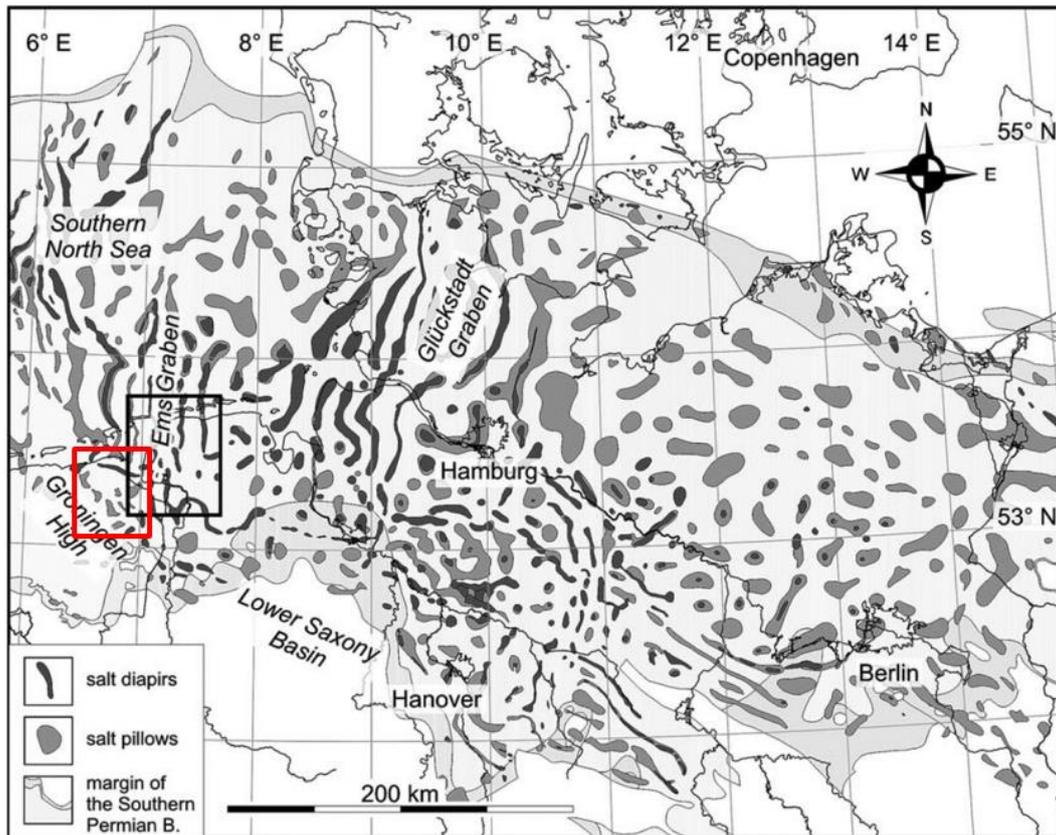


Figure 5: Map showing the distribution of salt diapirs and pillows. The study area is located inside the red rectangle and projected on a map from (Mohr, 2005) of the central part of the Southern Permian Basin.

The study area includes 12 major salt structures (Figure 7). Distinction will be made between salt pillows and salt diapirs (Figure 6). A positive salt structure produced by thickening of the salt without piercement of the overburden will be referred to as a salt pillow (van der Es, J.S., 1995). A salt diapir describes a salt feature where active piercement of the overlying sequence has taken place (van der Es, J.S., 1995). Local salt structures can be named after their shape: wall or arch.

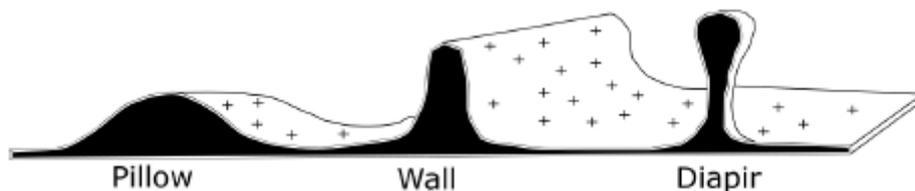


Figure 6: Conceptual image of the distinguished positive salt structures observed in the study area.

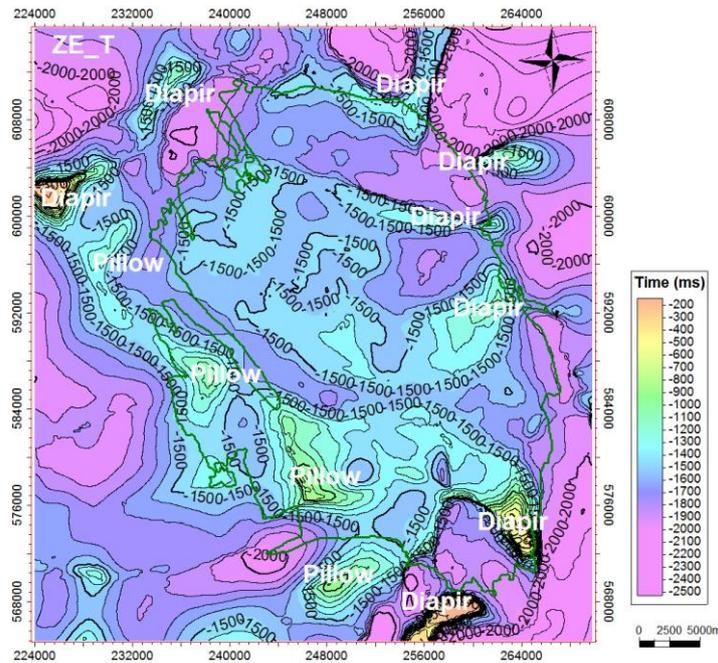


Figure 7: A map of the top Zechstein horizon identifying the major salt structures in the study area. Distinction is made between salt pillows and salt diapirs.

The timing of the growth of the salt structures differs from area to area, but periods of accelerated pulses are known. These are generally associated with times of increased tectonic activity (van der Es, J.S., 1995). Zechstein salt movement initiated following deposition of the Buntsandstein, during periods of extension in the middle-late Triassic (early Kimmerian) (van der Es, J.S., 1995). This is followed by an erosional event in the middle-Jurassic caused by thermal doming (mid Kimmerian) (van der Es, J.S., 1995). Late Jurassic – early Cretaceous rifting (late Kimmerian) divides the area into rapidly subsiding basins and more quiescent platform areas (van der Es, J.S., 1995). At the end of the late Cretaceous structural inversion affects most basin areas (van der Es, J.S., 1995). Subsidence is resumed in the Tertiary and the sedimentation of thick marine and fluvial sediments is interrupted by several erosional events which are believed to be related to late inversion pulses and eustatic sea level changes (van der Es, J.S., 1995).

In Chapter 7 thickness maps are integrated with the fault interpretation. These give an indication whether the structural features in the study area align with this.

The distribution and orientation of the interpreted overburden faults strongly coincides not only with the Zechstein salt structures, but also with the main sub-Zechstein faults (Figure 25, Figure 26). This indicates that the formation of overburden faults is evoked by the formation of Zechstein salt structures, which in turn appears to be initiated by sub-Zechstein fault movement.

Salt movement in an area like the southern Permian basin is controlled by an interplay of several factors including the weakening of the overburden by active faulting, consequent differential loading induced by fault controlled accommodation space generation and the buoyant behaviour of salt (van Winden, 2015).

Faults associated with this salt movement can be categorized as follows:

1. Hard-linked faults: faults above and below the salt cover are in direct contact at seismic resolution. Because the Zechstein group (Figure 4) is not solely made up of halite, but also contains a 50m thick continuous anhydrite layer at the base (Z1) it can be assumed that when the Zechstein thickness is less than 50m thick no halite is present and hard linked faults can be present. (referred to as '3' in Figure 8).
2. Soft-linked faults: Faults above and below the salt cover are spatially related, but they are not connected. This is dependent on the ratio between the basement fault offset and the salt thickness. A quantitative fault distribution analysis shows that faults are only able to penetrate salt with a

depositional thickness of < 300m (ten Veen, 2012). This thickness will be used to give an indication whether thick-skinned or thin-skinned is likely to be present(referred to as '2' in Figure 8).

3. Non-linked faulting: Faults above and below the salt cover are completely decoupled by thick salt. (referred to as '1' in Figure 8).

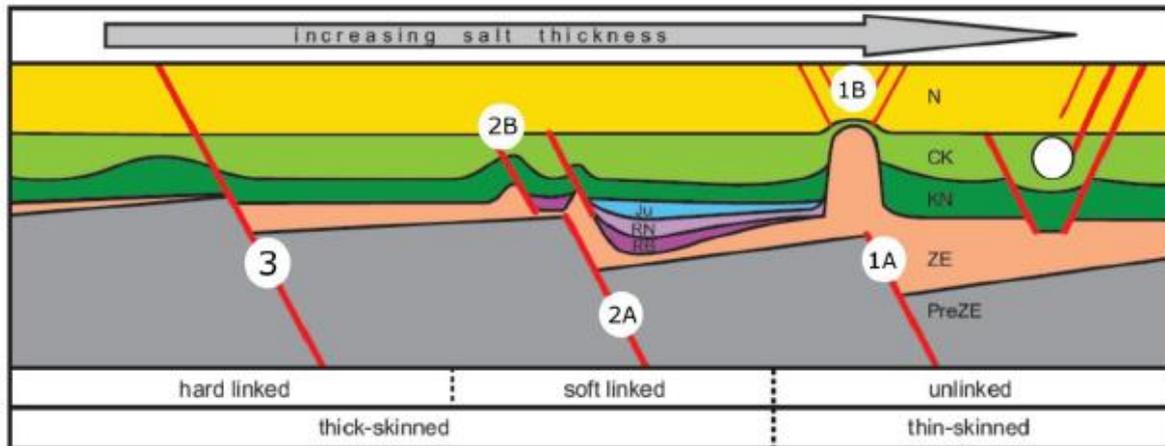


Figure 8: Linking of faults below and above a salt cover (van Winden, 2015). 1) Non-linked fault. 2) Soft-linked fault. 3) Hard-linked fault.

These different types of faults show there is a close relationship between salt thickness and structural style. The thickness map of the Zechstein (Figure 9) gives an indication of which areas are more prone to have either hard linked, soft linked or unlinked faults.

Figure 9 shows two versions of the isochore map of the Zechstein group, with the right map marking all areas where the thickness is less than 10 ms green and areas with a thickness of less than 75 ms yellow. The 10ms threshold was chosen because a 50m thick anhydrite layer corresponds to approximately 10ms, assuming a velocity of 5900m/s. The 75ms threshold was distinguished because this corresponds to 300m of salt at a velocity of 4500m/s and around 50m of anhydrite at 5900 m/s.

Hard linked faults are not expected in the study area as thicknesses of the Zechstein group of less than 10 ms (approximately 50m of anhydrite) is not observed. Zechstein thicknesses less than a 75ms (approximately 300m of salt and 50 m of anhydrite) are mainly found in the eastern part of the study area, and soft linked faults would be expected there. With the major part of the study having significant salt thickness (area coloured red in Figure 9), unlinked faults are expected for most of the study area. See Section 6 for further details on the overburden fault interpretation and relations to the Zechstein.

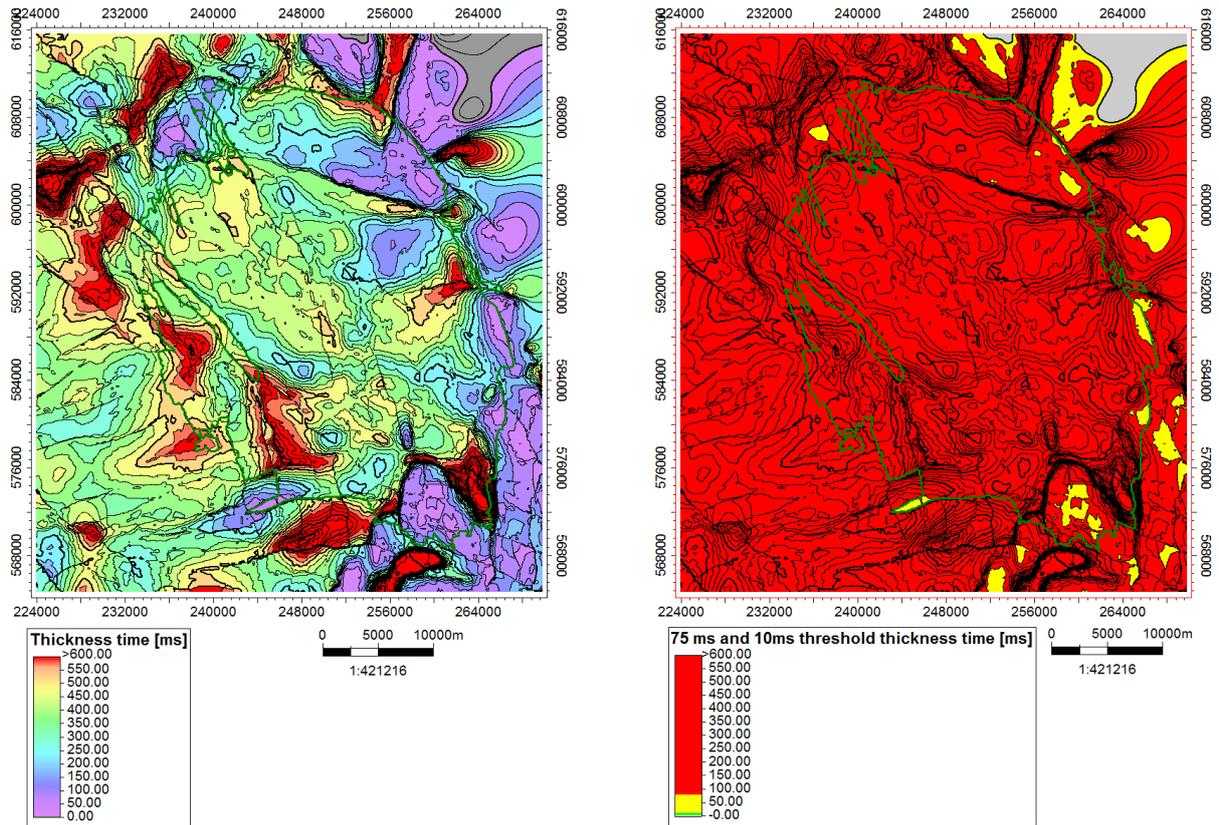


Figure 9: Isochore maps of the Zechstein group. Left map shows the thickness of the Zechsteinn from 0->600 ms and the right map marks Zechstein Thickness between 0 and 10ms green, 10-75 ms yellow and thickness greater than 75ms red. Areas where no data was present are coloured grey.

6 New fault map of the supra-Zechstein overburden

Figure 10 displays map views of the result of the seismic fault interpretation. This chapter displays the fault interpretation by means of a series of fault maps and seismic sections.

The fault maps show fault intersections in red, intersecting the various horizons. The outline of the gas-water contact of the Groningen gas field is projected onto the maps in green. The map in the upper right corner displays the top Zechstein. This applies to all fault intersection maps.

The seismic lines will have the Zechstein group overlain by a blue transparent layer. The black lines on the seismic lines show the horizons and the coloured lines show the interpreted faults. The map in the upper right corner displays the top Zechstein map zoomed in to the specified study area and seismic lines marked yellow and the gas-water contact of the Groningen gass field projected onto the horizon in green.

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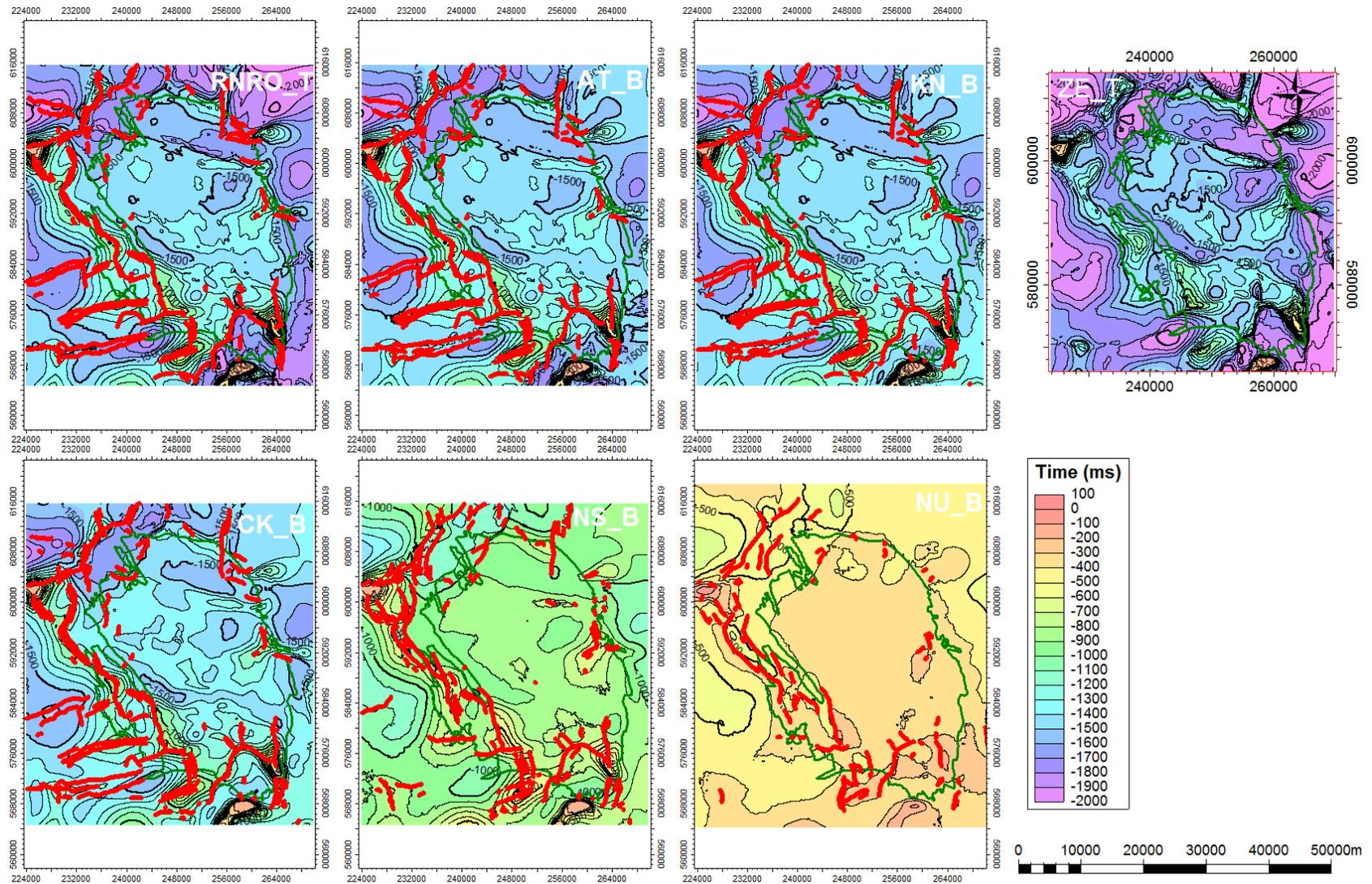


Figure 10: Fault intersection maps of the entire study area.

To facilitate the Rotliegend reservoir fault interpretation the area was divided into structural domains (SD). This was done by (Structural Evolution of the Groningen West-Periphery; de Keijzer, M., 2008) on the Groningen Western Periphery and later applied on the entire Groningen field (Visser, C., 2012).

However, extrapolating these structural domains to the overburden and using them to describe the overburden fault interpretation is not straightforward because the Zechstein evaporites acted as a detachment level (Coward, 1995).

Therefore the area is divided and described on the basis of the different salt structure and five different sub-areas are distinguished (Figure 11):

1. The northwest: Two NE-SW orientated salt diapirs.
2. The north-northeast: One arch-shaped salt diapir and one E-W orientated salt diapir.
3. The center-east: One salt wall diapir and one salt diapirs.
4. The southeast: Two NE-SW orientated salt diapirs.
5. The west-southwest: Four NW-SE orientated salt pillows.

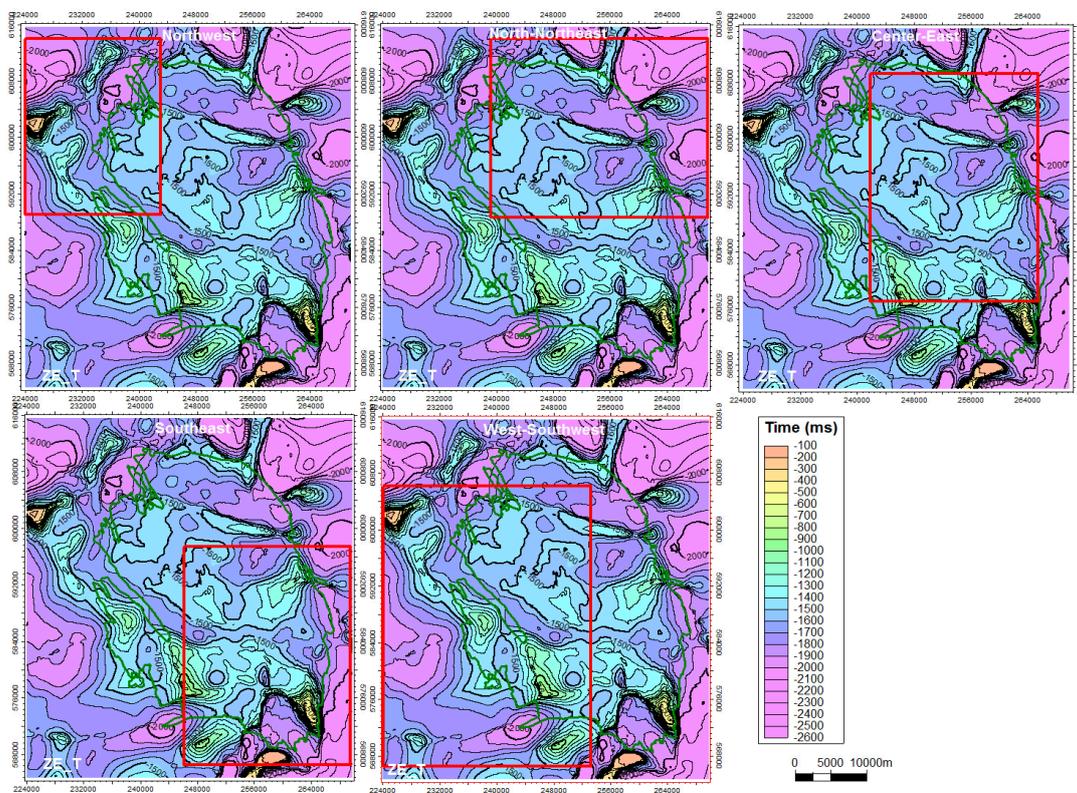


Figure 11: Maps showing the outline of the five areas of interest used to describe the fault interpretation marked in red and projected onto the top Zechstein horizon. Outline of the gas-water contact projected onto the map in green.

6.1 The northwest

In the northwest two salt diapirs are present with a SW-NE orientation. The most northern structure runs from NE-SW and has a collapse graben on top extending from the northern diapir to the southern diapir. The extensional graben faults run from the top Zechstein into the upper North Sea formation. The major normal fault dips towards the southeast. The graben terminates in the northeast against a normal fault. This is shown in cross-section A-A of Figure 13. Another collapse graben strikes NW-SE and crosses the major NE-SW graben. This graben extends into the Cretaceous Chalk formation, but is absent in the North Sea formations. Cross-section B-B in Figure 13 shows the NW-SE trending collapse graben

The southern diapir has a collapse graben running of its southern flank and a graben parallel to it that is associated with a salt pillow south of the diapir (Figure 12). Cross-section D-' D in Figure 13 shows both these collapse grabens. Its orientation is in line with the en echelon shaped fault system and the salt pillows running NW-SE and south of the diapir.

In this part of the study area, a Zechstein thickness less than a 75ms is only found east of the northern diapir (Figure 9). Crossline E-'E in Figure 13 shows that this basin appears to be related to salt depletion into the adjacent salt diapir. No soft-linked faults are observed in this area, only unlinked faults.

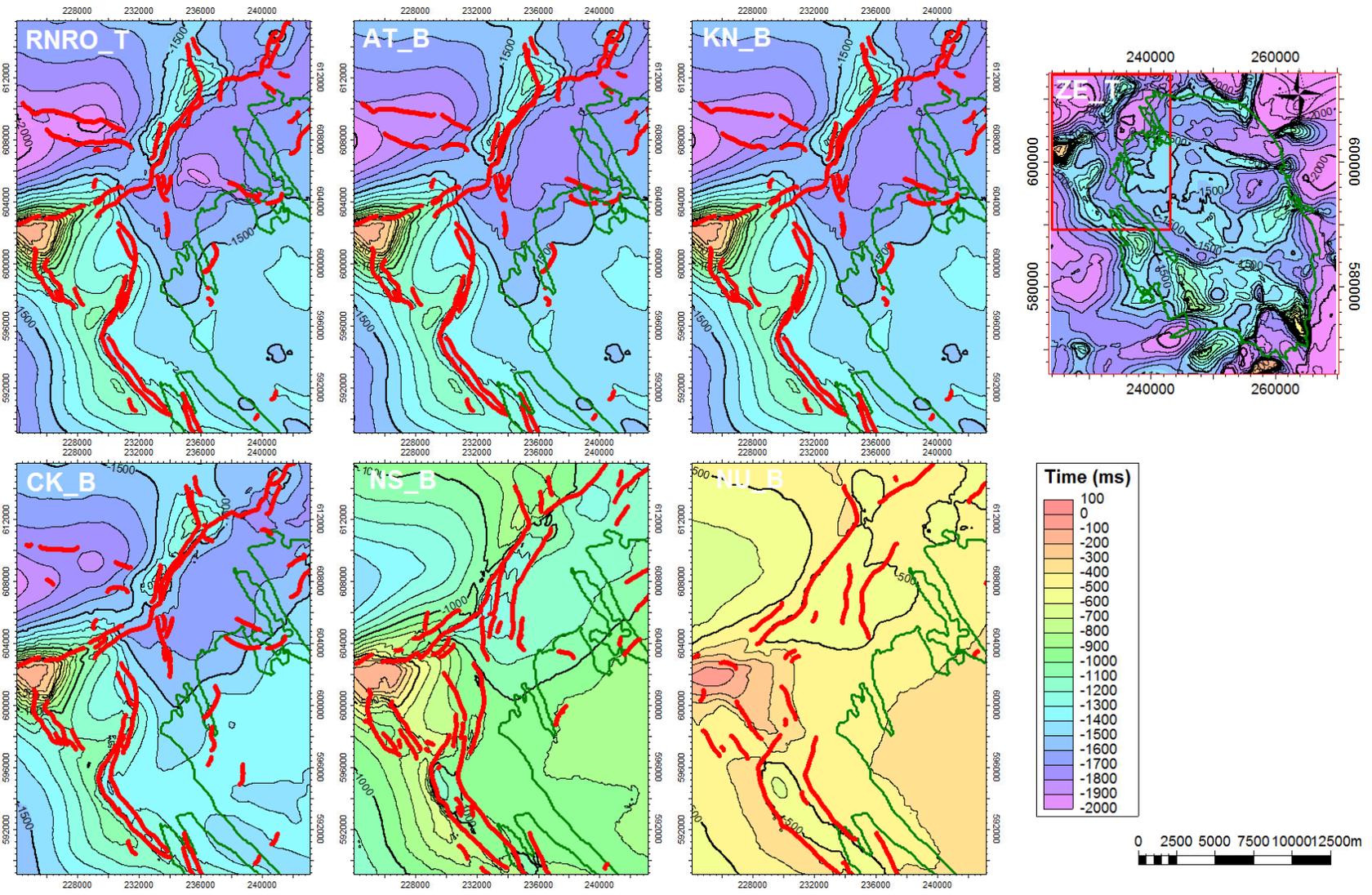


Figure 12: Fault intersection maps of the northwestern sub-area.

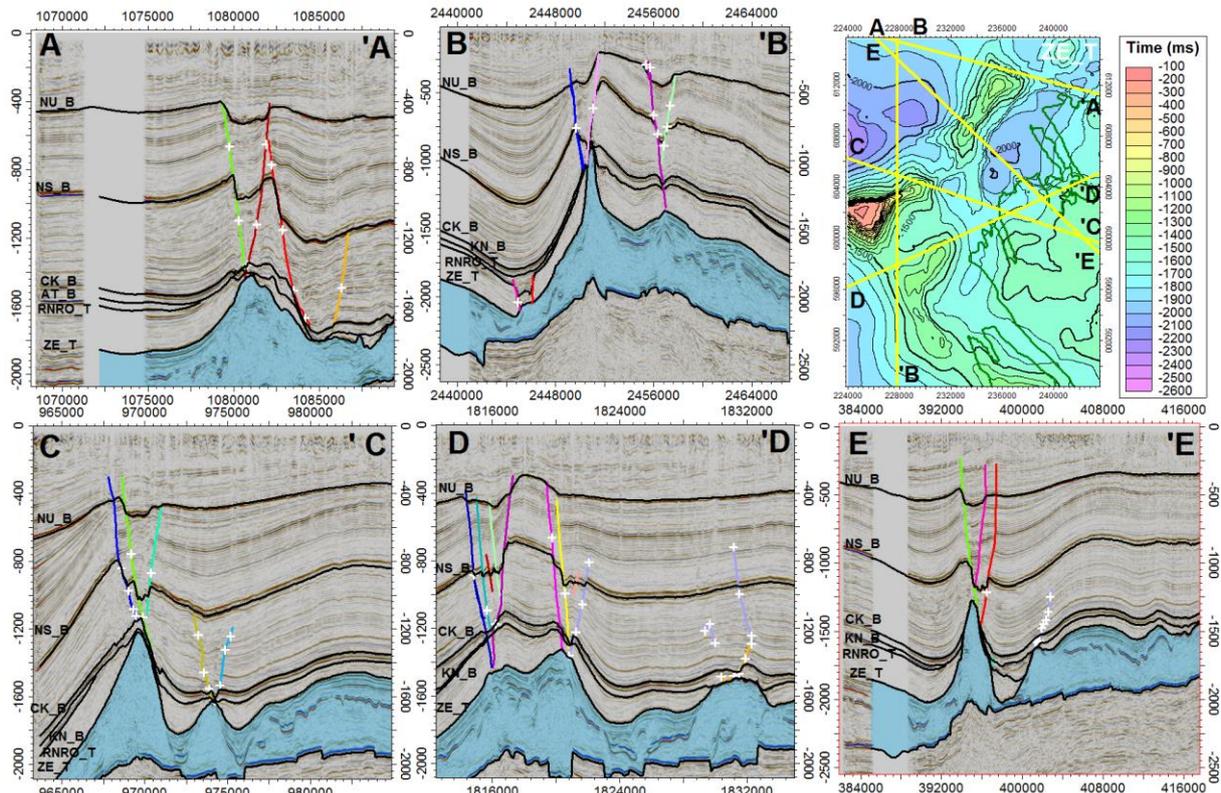


Figure 13: Seismic lines of the northwestern sub-area.

6.2 The north-northeast

Salt structures are dominated by a N-S and WNW-ESE structural grain. This is expressed by an arch-shaped salt diapir and an E-W orientated salt diapir. Cross-section A-A in Figure 15 shows that the arch-shaped salt structure is cut off by a NE-SW running fault in the west and has a NE-SW orientated graben over its eastern flank. Cross-section B-B in Figure 15 shows a mild pop-up structure above the eastern salt diapir limited to the Chalk and lower North Sea formations. This might be related to inversion in the late Cretaceous.

Seismic line C-C in Figure 15 runs through an area where Zechstein thickness is less than 75 ms. In the northern part of the section faults are restricted to the Triassic deposits. The green and yellow fault dipping north align with sub-Zechstein faults and are most likely soft-linked Figure 26 indicates that in this area a reactivated pre-Saalian fault aligns with the soft-linked overburden fault.

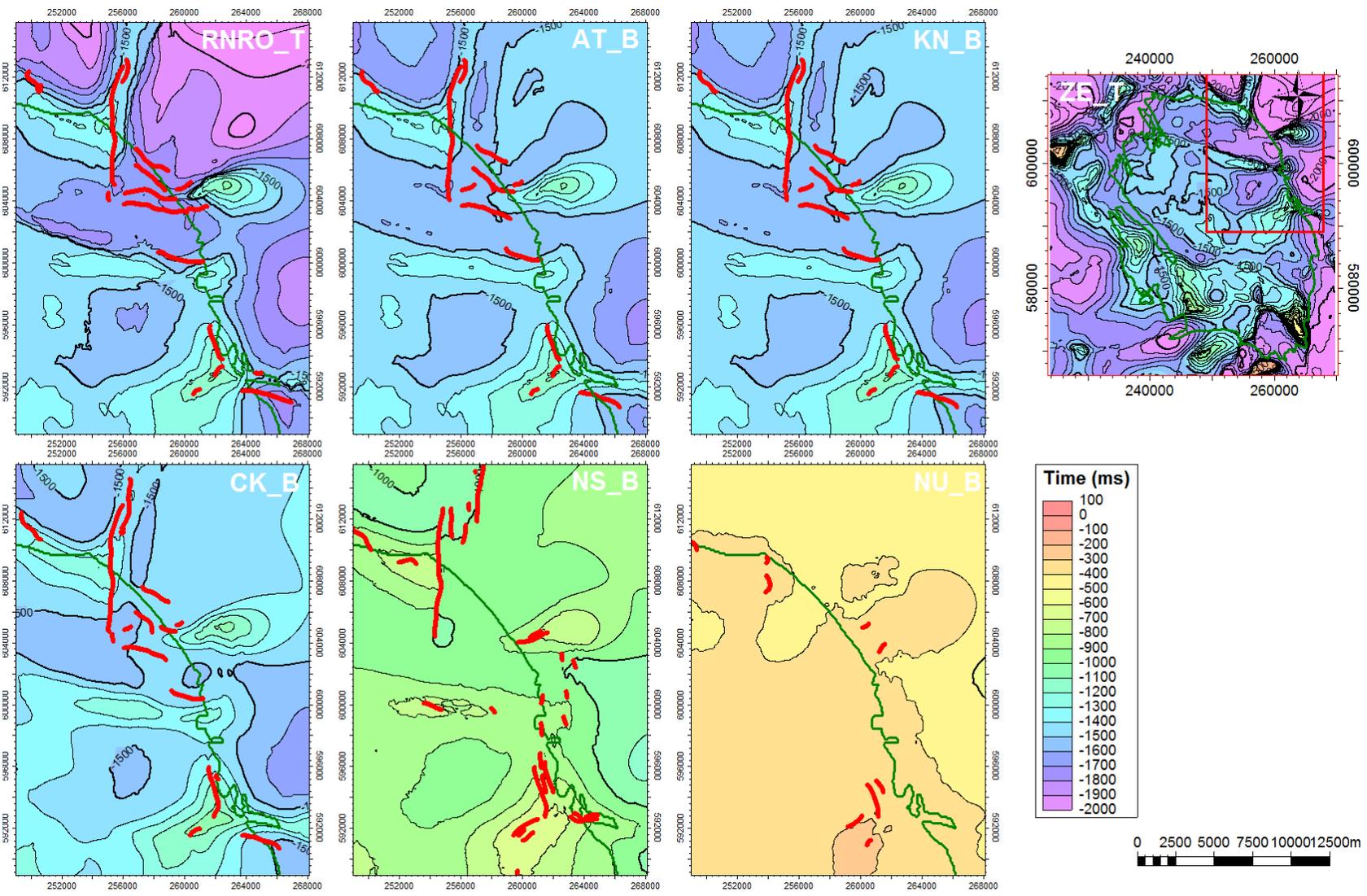


Figure 14: Fault intersection maps of the north-northeastern sub-area.

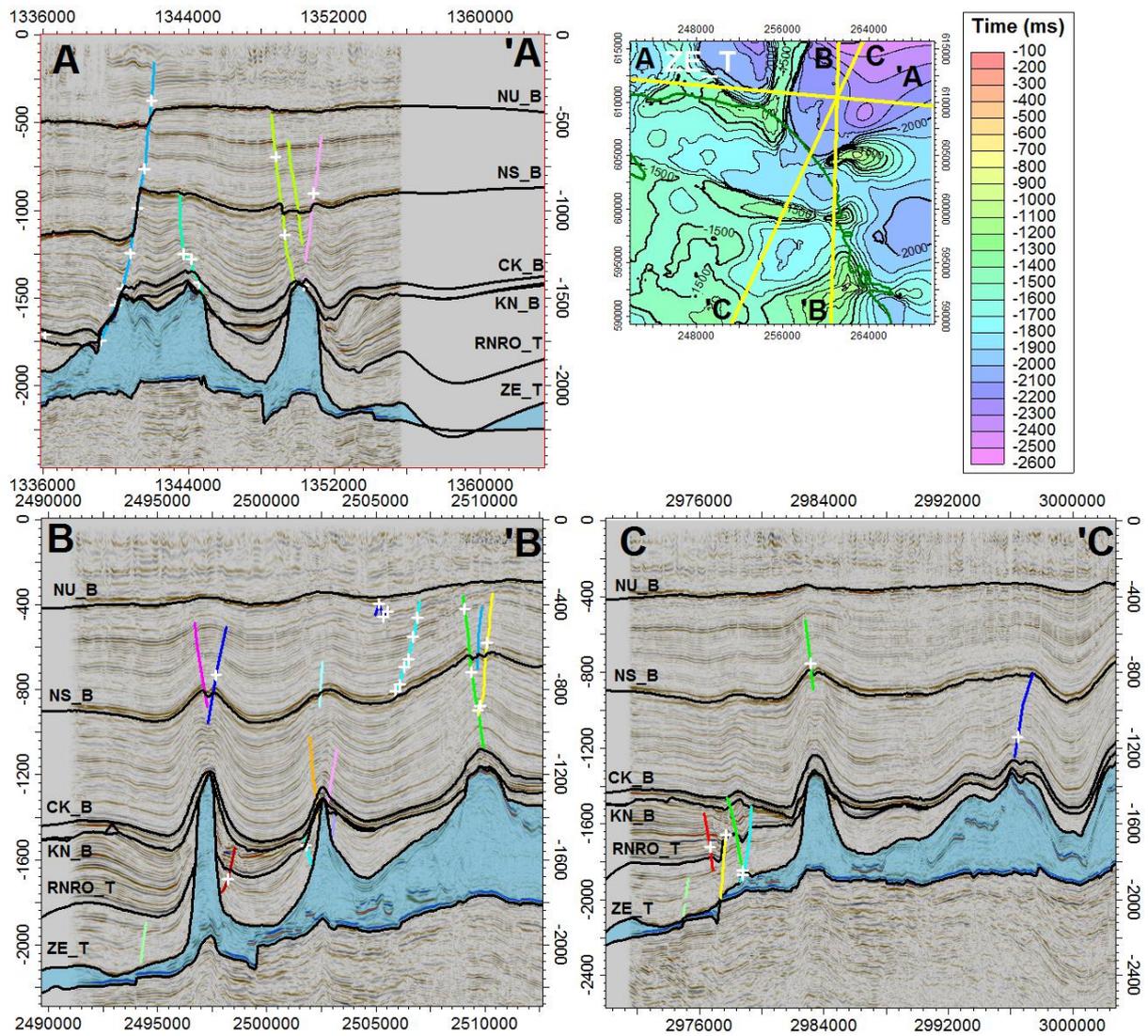


Figure 15: Seismic lines of the north-northeastern sub-area.

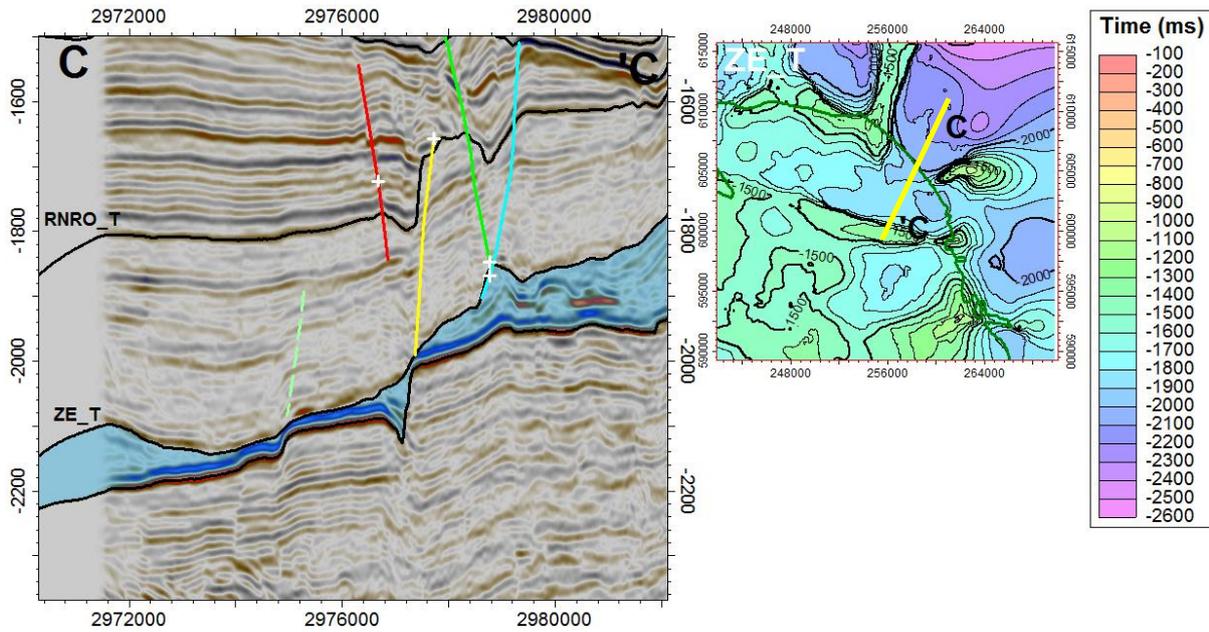


Figure 16: Seismic line zoomed in to soft-linked faults (green and yellow fault).

6.3 The center-east

This part of the study area covers the center of the Groningen gas field and Figure 17 shows that in this area there is a low density of faults. This is in line with the absence of major salt structures in the area. The most pronounced salt structure present is a E-W orientated salt wall diapir that can be extended to the Mesozoic restricted collapse graben that crosses the NE-SW orientated graben in the northwest of the study area. No major overburden faults appear to be associated with the salt wall, but some faults are observed parallel to the salt structure in the Triassic formation and above the salt wall in the Cretaceous- lower North Sea. Cross-section B-B in Figure 18 shows a seismic line perpendicular to the salt wall and the associated faults. The salt wall appears to have been most active in the Triassic-Jurassic period after which these formations were eroded off. A later pulse that might be related to the late Cretaceous inversion is associated with some faults around the top Chalk-base North Sea. A study by van Gent (van Gent, 2010) describes the presence of a large number of minor faults in the Chalk formation that were used for paleostress reconstruction from seismic data, however these were faults restricted to the Chalk formation and picked on extra interpreted reflectors in the Chalk. For this study these minor faults are of no relevance.

The second major fault structure is a N-S orientated graben that is associated with a salt diapir. Seismic line A-A of Figure 18 displays this graben and shows how it extend into the upper part of the lower North Sea formation. The seismic line also shows the relative quiescence in the area crossing the crest of the Groningen high.

North of the eastern part of the salt wall and east of the diapir, areas with a Zechstein thickness less than 75 ms are observed. The seismic lines of Figure 18 show that these areas show no thick skinned faults. Only the northern part of seismic line B-B shows there is a fault marked yellow that might be a thick skinned fault. This fault is associated with salt structures north of the salt wall and these are discussed in chapter 6.2.

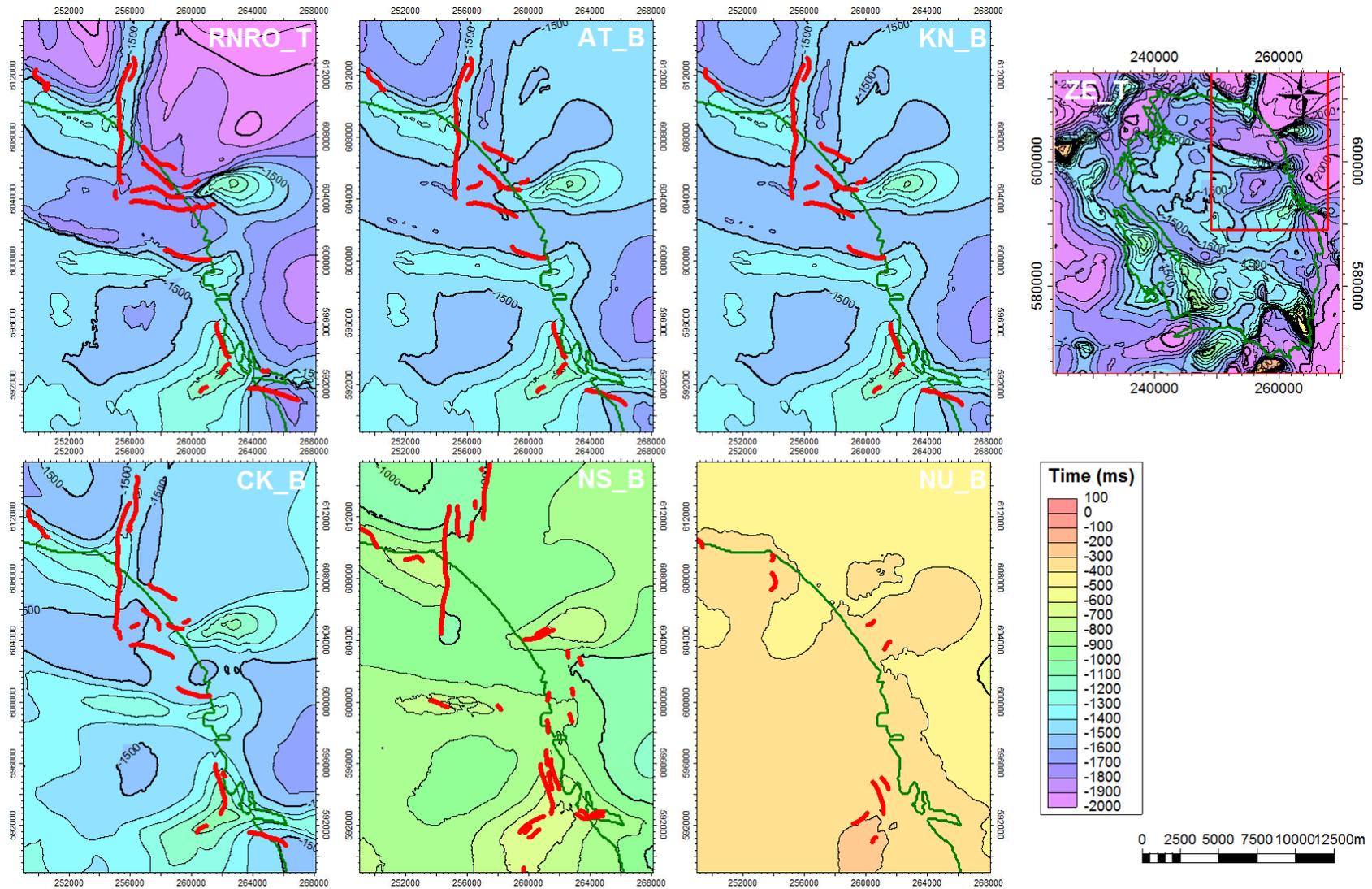


Figure 17: Fault intersection maps of the center-eastern sub-area.

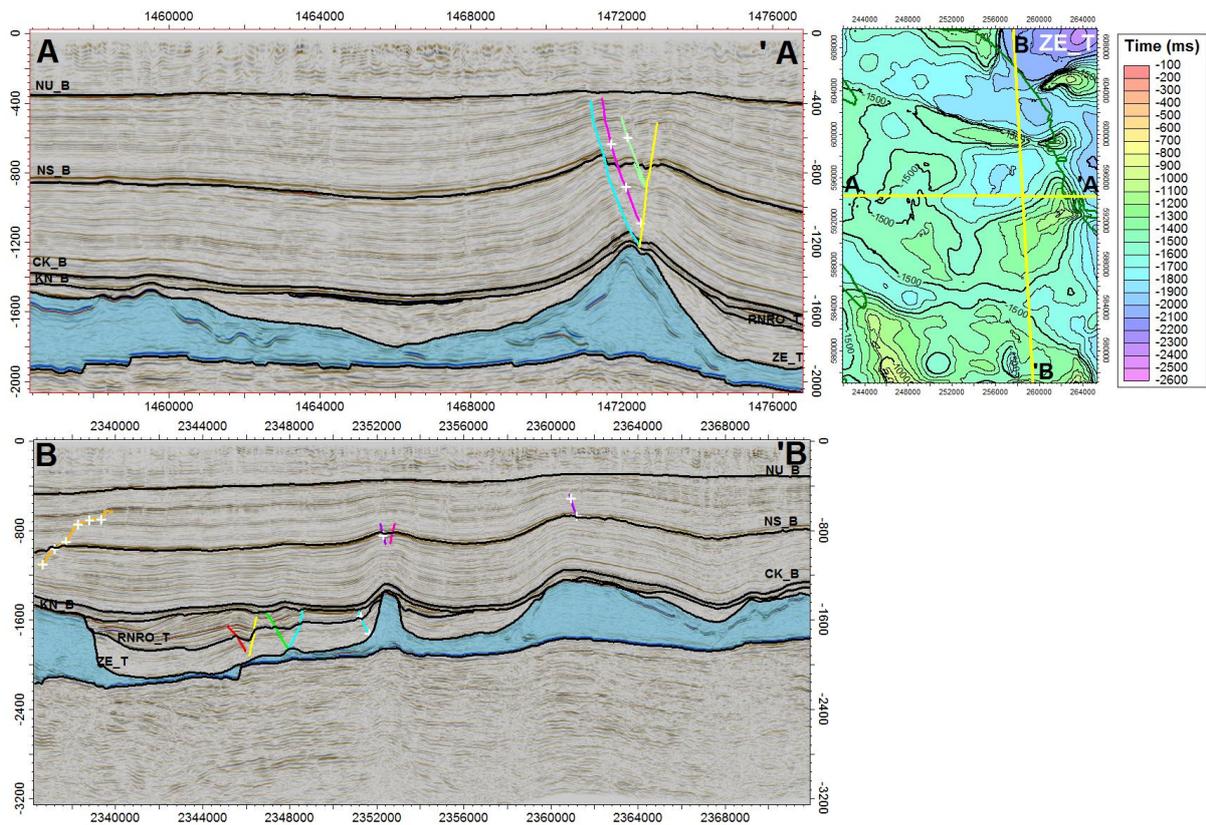


Figure 18: Seismic lines of the center-eastern sub-area.

6.4 The southeast

This part of the study area is dominated by two salt diapirs and a major curved shaped extensional fault that runs perpendicular to the NW-SE orientated en echelon shaped grabens northeast of it. Both seismic line A-A and B-B of Figure 20 display the fault marked in red. This fault cuts off the salt pillow located west of it, runs into the eastern salt diapir and extends into the upper North Sea formation (Figure 19).

A second major fault runs N-S and is related to the eastern salt diapir. Seismic line B-B in Figure 20 shows the fault running atop of the diapir. Seismic line C-C in Figure 20 shows a fault with a similar orientation running into the diapir (Figure 19).

The major diapir is present in the southern part of the area. Seismic line A-A of Figure 20 shows how the diapir pierces through its overlying deposits and almost has expression uptill surface. No major faults are associated with the diapir, but cross-section C-C in Figure 20 shows a high level of minor N-S orientated faults that are limited to the Chalk and lower North Sea formation north of the diapir.

With two major salt diapirs present in the area, depleting the surrounding Zechstein group, in this part of the study area there is also an area with a Zechstein thickness of less than a 75 ms. The two major faults described above and shown on cross-section C-C of Figure 20 appear to have a strong relation with sub Zechstein faults. The most eastern N-S orientated fault marked in light green appears to be correlatable to a fault sub-Zechstein and thus soft-linked. Figure 26 shows it aligns with a sub-Zechstein Pre-Saalian reactivated fault. The major fault marked red on cross-section C-C also appears to be directly linked to a sub-Zechstein fault.

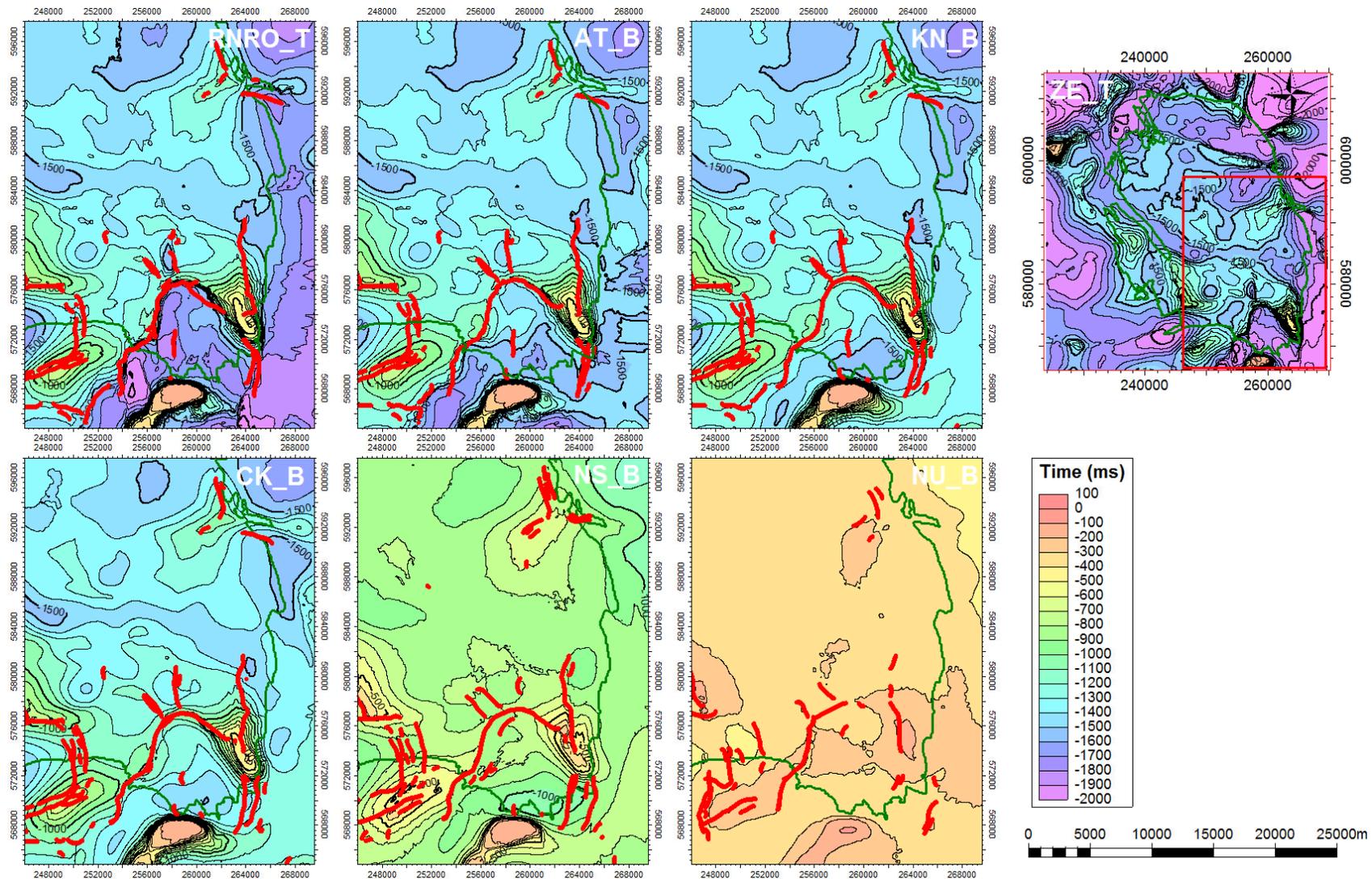


Figure 19: Fault intersection maps of the southeastern sub-area.

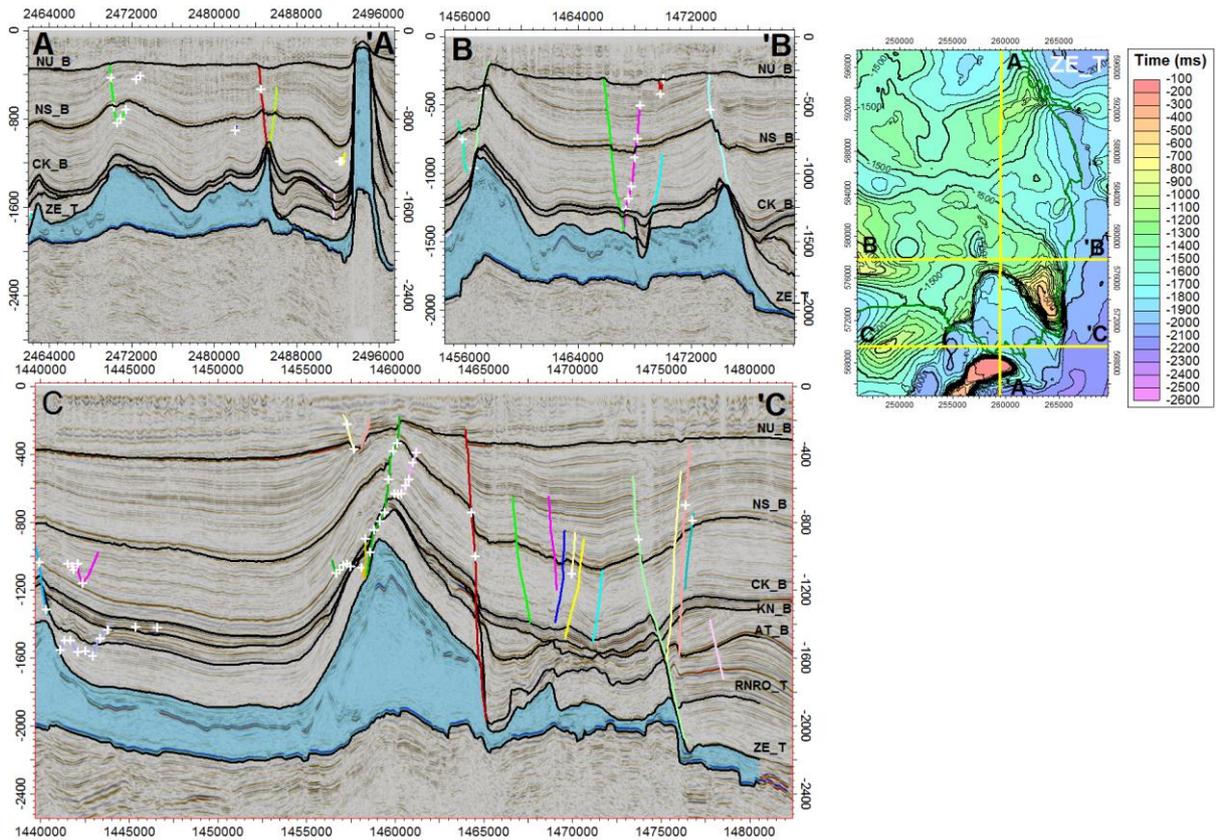


Figure 20: Seismic lines of the southeastern sub-area.

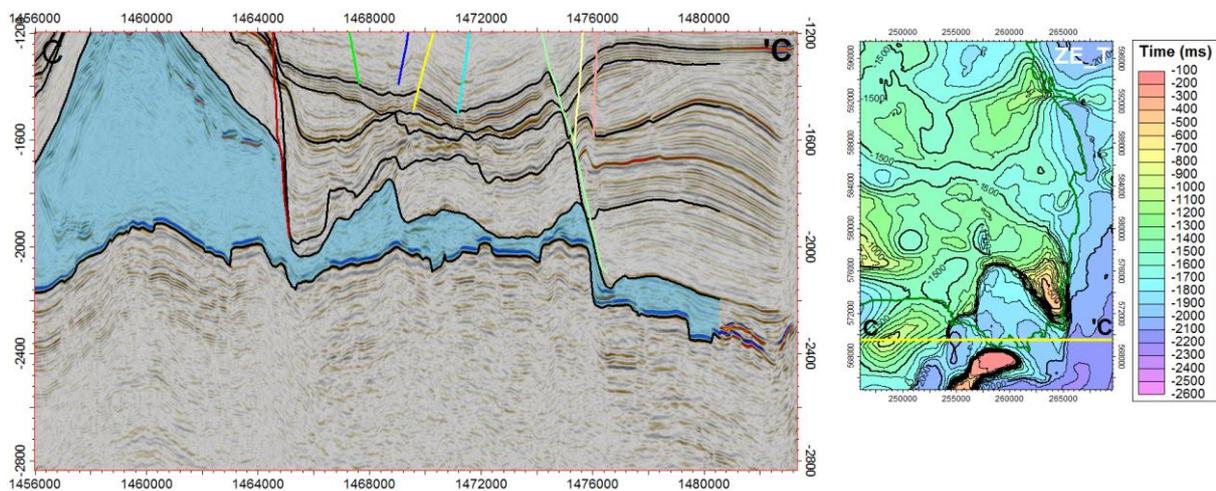


Figure 21: Seismic line zoomed in to soft-linked faults (red and green fault).

6.5 The west-southwest

In the western-southwestern part of the study area we find a NW-SE orientated arch of four salt pillows. These are associated with extensional en echelon shaped grabens. This is an indication of reactivation of major sub-Zechstein faults affecting the overburden. In Figure 26 a sub-Zechstein Pre-Saalian fault aligns with the salt structures. Figure 22 shows how this fault system extends into the upper North Sea formation. Seismic lines A-A', B-B' and C-C' of Figure 23 show the faults at top of the salt pillows.

A second structural component of the this part of the study area is a group of SW-NE orientated collapse grabens cutting off and running into the NW-SE orientated grabens. These die out in the upper Cretaceous and are dominantly present in the Triassic formation (Figure 22). The orientation of these faults coincides with the orientation of post-Rotliegend faults in the Rotliegend formation (Figure 26). Seismic line D-D of Figure 23 crosses the three minor grabens perpendicular and shows their absence in post Jurassic deposits.

Figure 9 indicates that thick-skinned faulting is only likely to be present between the the two most southern salt pillows as this is the only area where Zechstein thickness is less than a 75ms. Seismic line E-E in Figure 23 shows a synclinal structure above the thin Zechstein area, but no thick-skinned faulting related to it.

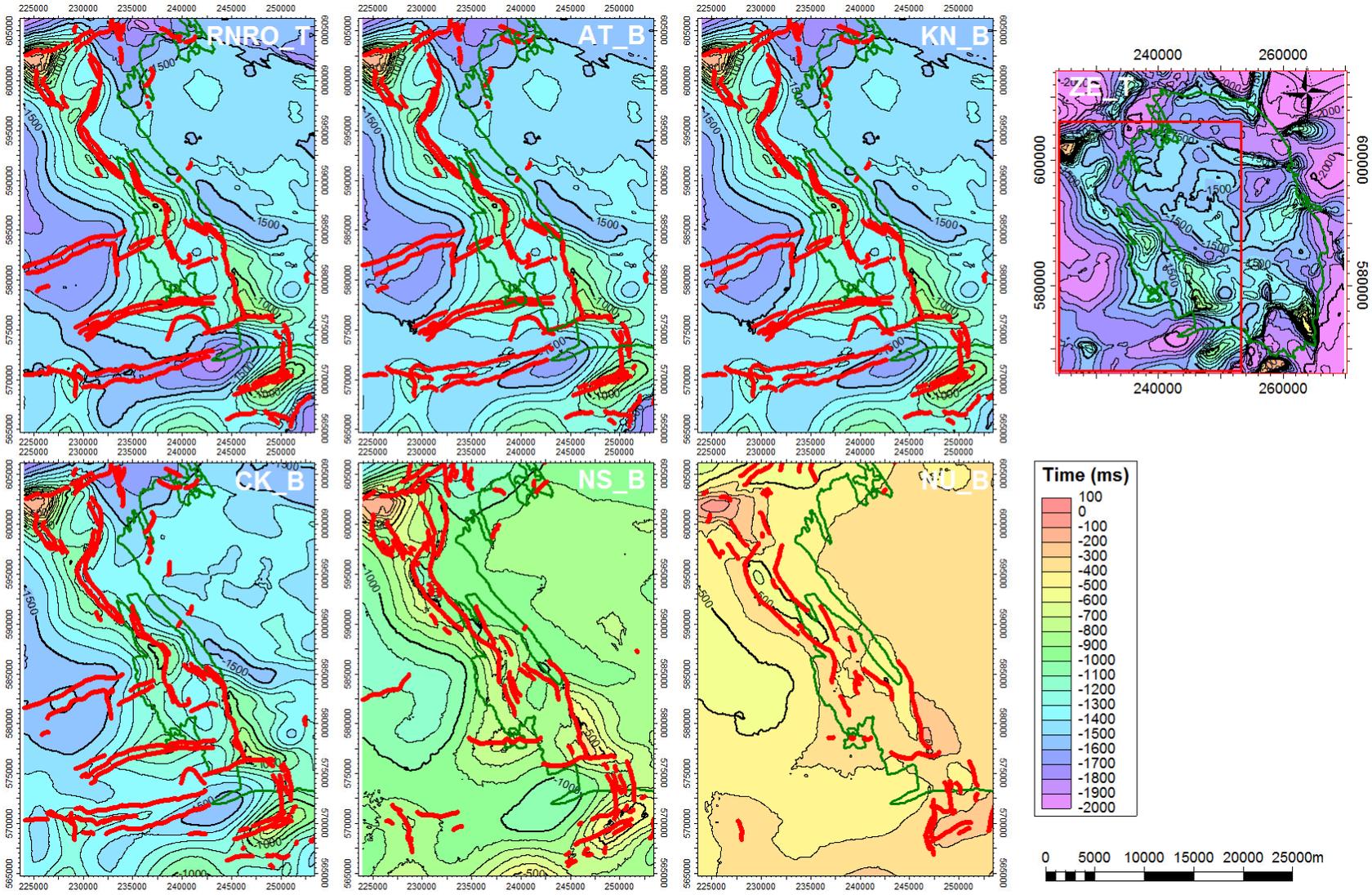


Figure 22: Fault intersection maps of the west-southwest part of the study area.

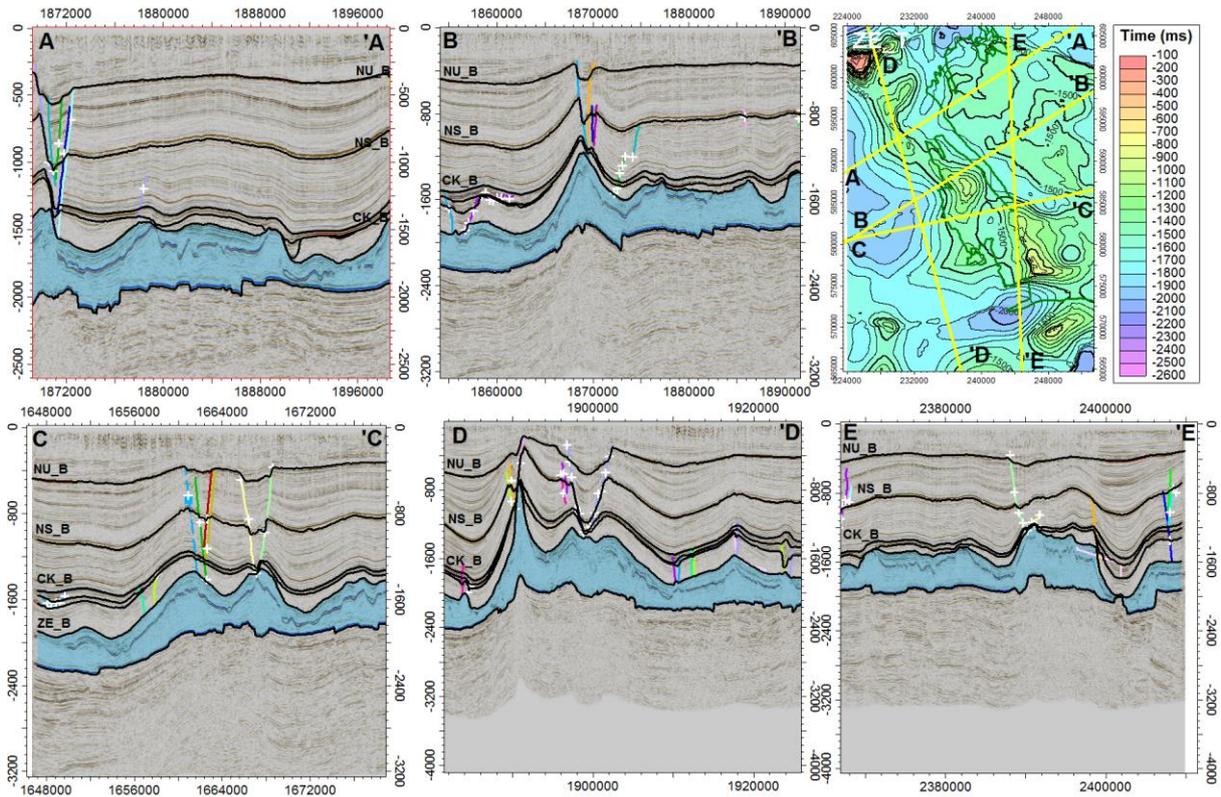


Figure 23: Seismic lines of the west-southwestern sub-area.

7 Structural evolution of the supra-Zechstein overburden

7.1 Isochore maps

To better understand how the study area developed structurally, thickness maps are integrated with the fault interpretation. Figure 24 displays the isochore maps with the Zechstein group in the left corner and the upper North Sea formation the bottom right corner. These are later displayed with the faults intersecting the base of the formation in yellow and the faults intersecting the top of the formation in red. The Groningen gas field is projected onto the maps in green.

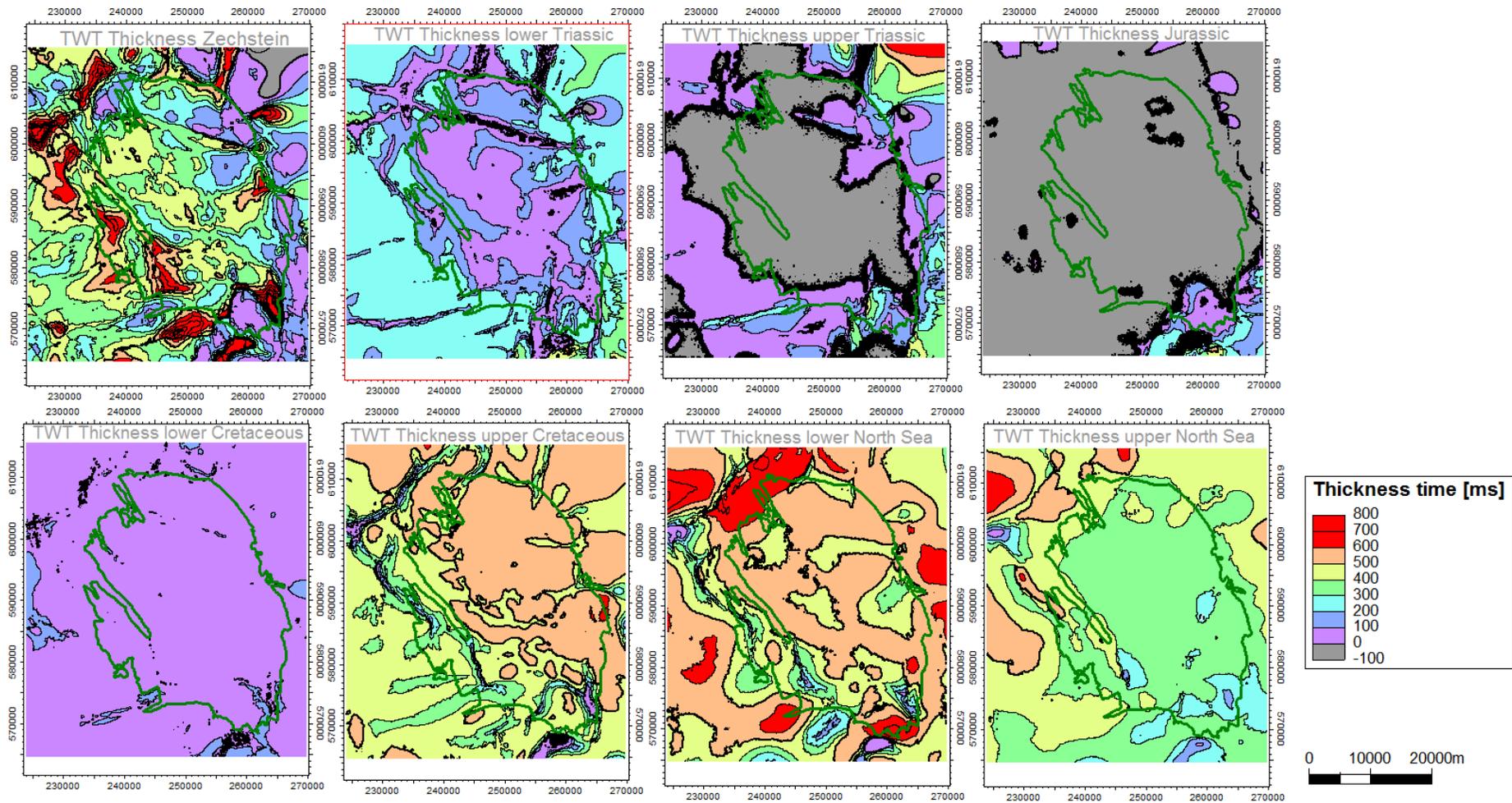


Figure 24: Isochore maps of the overburden formations and the Zechstein group displayed chronologically from top left to bottom right.

7.1.1 Lower Triassic

Integrating the lower Triassic thickness map with the faults intersecting its top horizon (top Röt, RNRO_T) in Figure 25 show that thickness trends are already coinciding with the fault structures at this stage of the tectonic history. It should be made clear that it is not suggested that all faults shown at this level are Triassic in age. Faults that correspond to thickness changes are likely to have initiated at this stage, but faults that are in the middle of thin parts are probably younger in age and only formed when the salt structures really took off causing larger overburden strains.

The NW-SE oriented en echelon faults in the western part of the study area coincide with thinner lower Triassic deposits, as for the SW-NE orientated grabens in the southwest, the N-S orientated faults in the east and WNW-ESE orientated structures in the center-east of the study area. As these faults are associated with salt tectonics, this indicates that Zechstein salt movement occurred at this stage. With thickness trends corresponding to sub-Zechstein fault orientations and already displaying all the major structural features of the interpreted faults, it can be assumed that reactivation of sub-Zechstein faults controlled the location of the major salt structures and the associated overburden faults. Their presence in the lower Triassic isochore map shows that already at this stage all major structural features were 'imprinted' in the Zechstein and in the overburden. This is in line with the general consensus that Rotliegend fault patterns are in part derived from rejuvenation of older deeper-seated faults (de Keijzer, M., 2008). The resemblance between the overburden fault interpretation and the Rotliegend fault map (Figure 26) is also striking. The reactivation of some faults may be linked to the Hardegsen phase in which uplift was followed by mild rifting in the early Triassic (de Keijzer, M., 2008). This event is assumed to have initiated halokinesis in the area (van der Es, J.S., 1995).

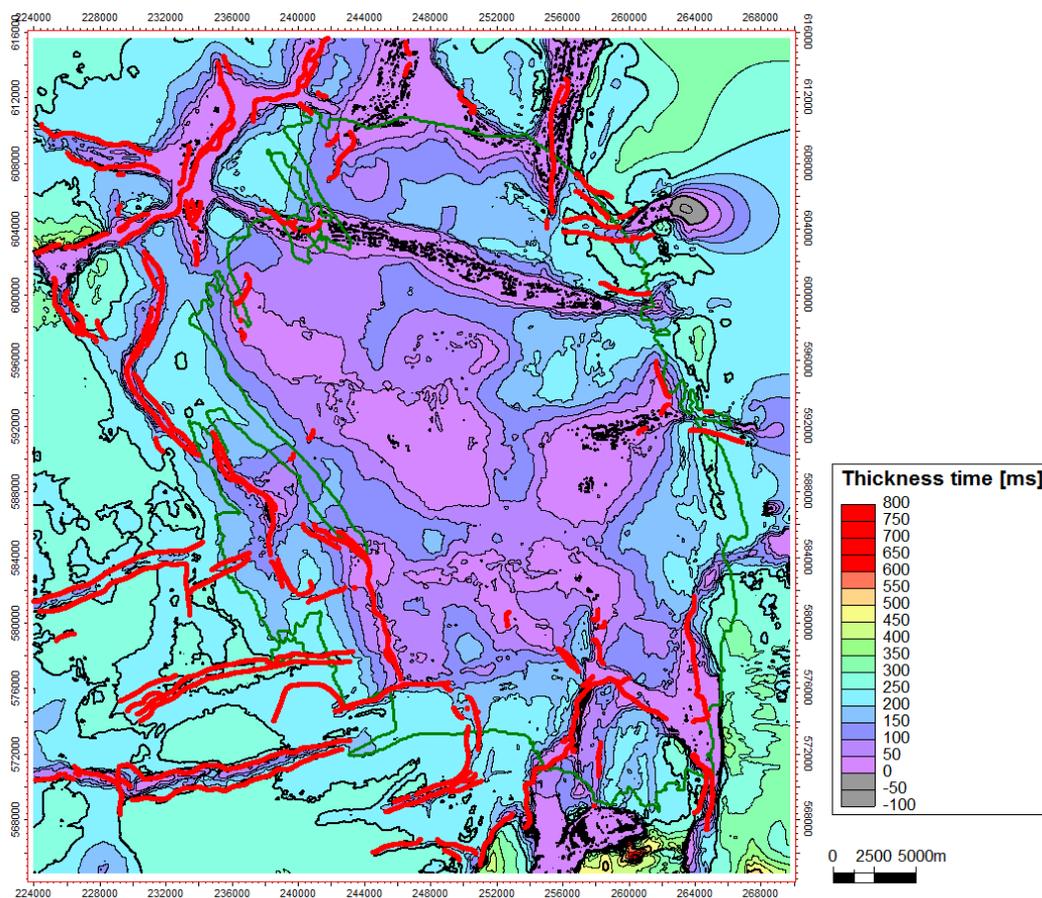


Figure 25: Thickness map of the lower Triassic, with the ZE_T (top Zechstein) used as base and the T_RNRO (top Röt) as top of the section.

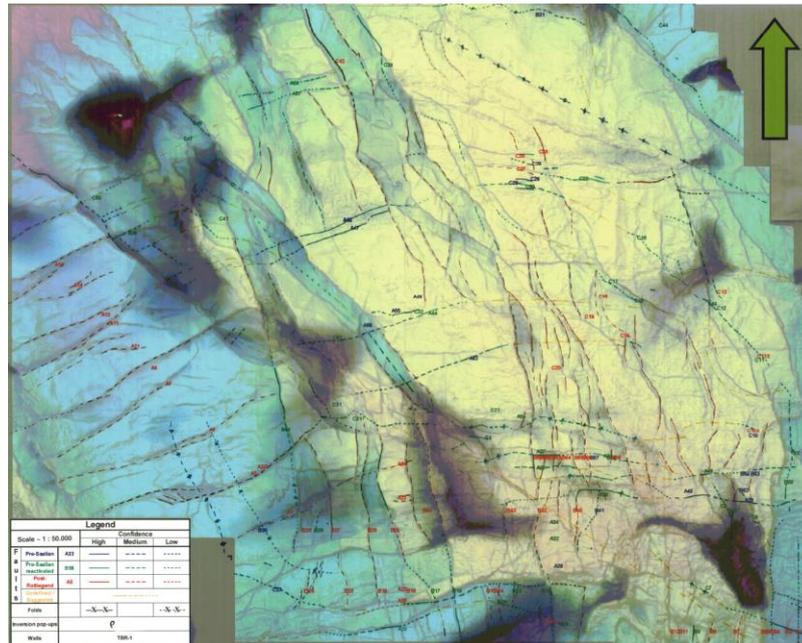


Figure 26: Rotliedend fault map by de (de Keijzer, M., 2008) made with the objective of delineating the different fault families. Map also shows the Zechstein isochores in bluish purple where >1000m thick.

7.1.2 Upper Triassic & Jurassic

The isochore maps displayed in Figure 27 show that the upper Triassic and the Jurassic deposits are strongly affected by an erosional event. This is related to the uplift of the Groningen high, starting in middle Jurassic times and with further uplift as a rift shoulder in later Jurassic times (de Keijzer, M., 2008). As a result, Jurassic deposits are only preserved in the southeast of the study area, associated with the major thick-skinned fault system orientated SW-NE, and upper Triassic deposits are absent in the center of the Groningen high.

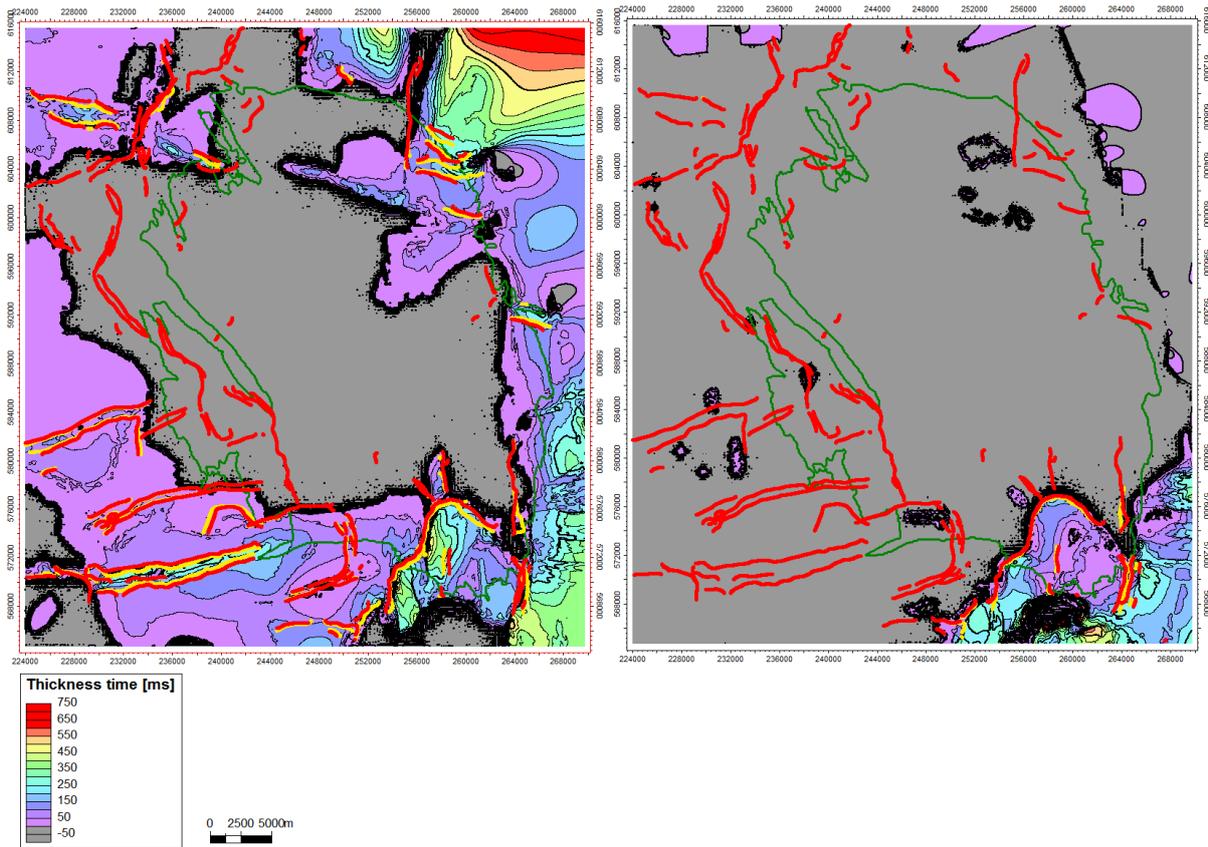


Figure 27: Left: Isochore map of the upper Triassic, with the T_RNRO (top Röt) used as base and the AT_B (base Altena) as top of the section. Right: Isochore map of the Jurassic with the AT_B (base Altena) as base and KN_B (base Rijland) as top of the section.

7.1.3 Lower & Upper Cretaceous

The lower Cretaceous thickness map in Figure 28 shows less deposition in the center of the study area. Thicker deposits are found in the southeast surrounding the major salt diapirs. This indicates salt removal around the salt structures, creating depositional space.

Late Cretaceous tectonic events were related to regional tectonic inversion associated with multiple key pulses (de Keijzer, M., 2008). The intensity of the inversion varies per basin and the inversion in the Lauwerszee through and the Groningen high was mild (de Keijzer, M., 2008) compared to for example the Broad Fourteens Basin. The overburden deposits mainly exhibit extensional deformation during the upper Cretaceous (van Gent, 2010). However in the center-eastern part some faults in the upper Cretaceous - lower North Sea sections are pop-up structures overhead salt structures presumably related to inversion.

A progressing subsidence associated with post-rift cooling and sea level rise resulted in the deposition of the late Cretaceous chalk (van der Es, J.S., 1995). This is also shown in the upper Cretaceous thickness map of Figure 28, with depositional thicknesses more than 300ms (~1200m, assuming an average velocity of 4000m/s). The southwest does have a thinner upper Cretaceous deposit, associated with the NW-SE orientated salt pillows. This is an indication of a salt tectonic pulse at this stage. In the upper Cretaceous deposits, the SW-NE oriented faults die out vertically.

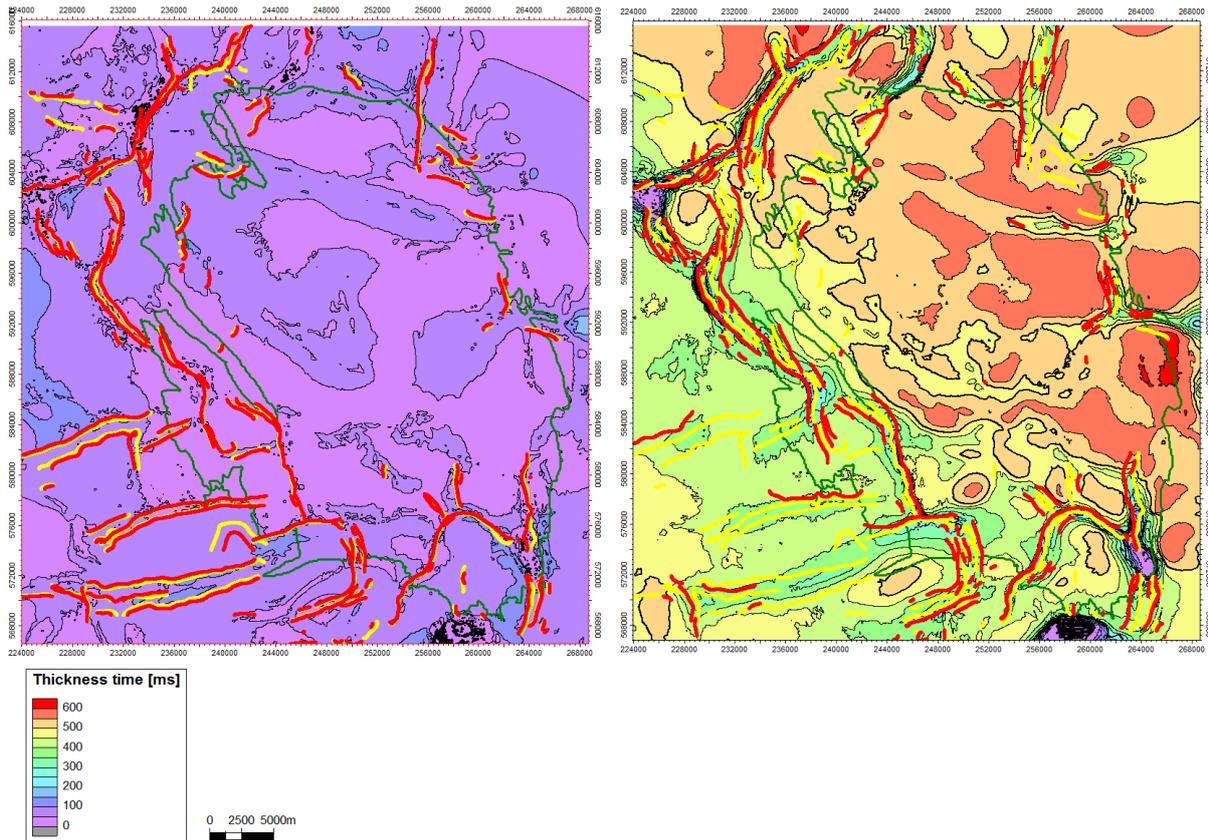


Figure 28: Isochore map of the lower Cretaceous, with the KN_B (base Rijnland) used as base and the CK_B (base Chalk) as top of the section, displayed left. Isochore map of the upper Cretaceous with the CK_B (base Chalk) as base and NS_B (base North Sea) as top of the section.

7.1.4 Paleogene (lower North Sea) and Neogene (upper North Sea)

Subsidence resumed in the Paleogene and Neogene resulting in the deposition of a thick sequence of marine and fluvial sediments (van der Es, J.S., 1995). The thickness map of the lower North Sea of Figure 29 shows how deposits are thick, but still follow the topography of the major salt structures, indicating continued halokinesis.

The isochore map of the upper North Sea formation shows how deposits are distributed relatively uniform at this stage, but the collapse grabens related to the NW-SE orientated salt pillows in the east and grabens related to the salt structures in the northeast of the study area have thicker deposits.

Due to the poor seismic quality of the upper 300ms of the seismic dataset caused by acquisition artifacts it is not possible to give a decisive answer to whether faults extend to surface. Figure 30 shows the fault intersections with the base upper North Sea horizon projected on the present-day elevation map. No obvious correlation is observed, but the Drentse heuvelrug in the southwest does align with the NW-SE orientated collapse grabens north of it.

Fault interpretation of the Groningen area supra-Zechstein Overburden

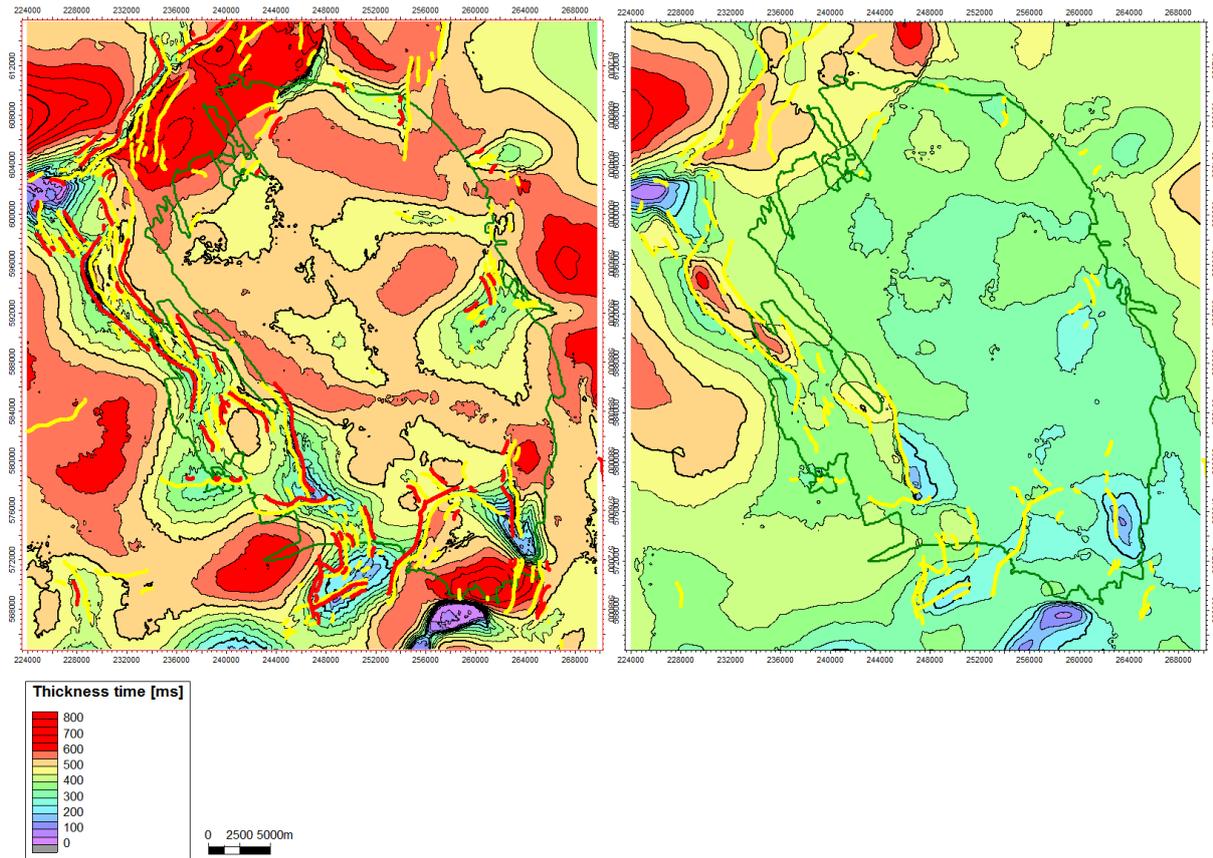


Figure 29: Isochore map of the lower North Sea, with the NS_B (base North Sea) used as base and the NU_B (base upper North Sea) as top of the section, displayed left. Isochore map of the upper North sea with the NU_B (base Chalk) as base and 0 (with the absence of surface height coordinates 0 was used) as top of the section

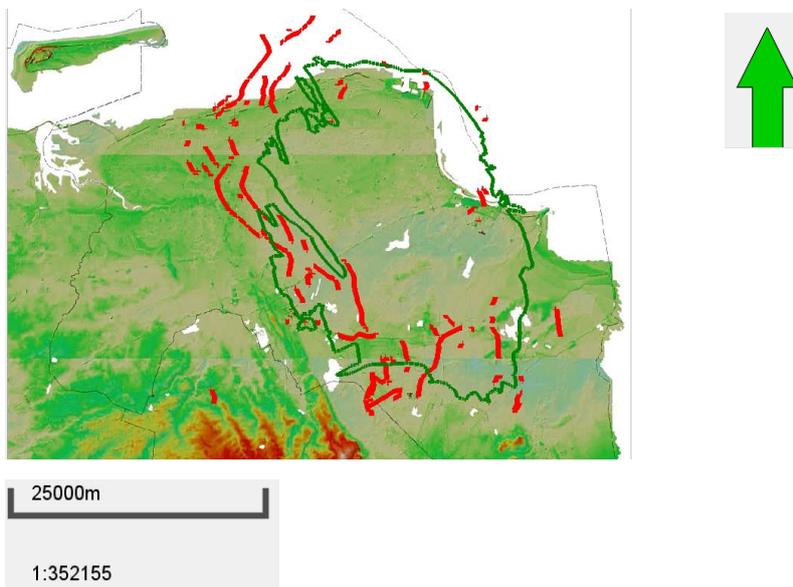


Figure 30: Topographical/elevation map (generated by the Actueel Hoogtebestand Nederland) of the Groningen province with the fault intersections of the NU_B horizon projected onto the map in red and the outline of the gas-water contact projected in green. E-W lines are caused by the merging of maps.

8 Summary and conclusions

The new supra-Zechstein overburden fault interpretation shows that most of the larger fault structures are related to halokinesis of the Zechstein evaporites. Projecting the outline of the gas-water contact of the Groningen field onto the top Zechstein horizon shows that the largest salt structures are positioned at the periphery of the Groningen gas field. Consequently, this is also the area where a high density of faults is found. Northwest of the field, a NE-SW orientated collapse graben is associated with two salt diapirs. Moving south along the western boundary of the field, a series of grabens are linked to the presence of four salt pillows with a NW-SE orientation. The main fault shaping the southern graben extends into the Groningen field. In the southeast a major 'arch-shaped' normal fault crosses the southeastern part of the field area. Southeast of this fault a N-S orientated fault is developed. Along the eastern boundary of the Groningen field area, some N-S and E-W oriented faults are associated with salt structures. The northeastern part of the study area shows a salt wall diapir and an arch-shaped diapir. These have caused overburden faulting. In addition, E-W orientated faults are found that are not linked to the salt structures. In the crestal region of the field, no salt structures of significance are observed and therefore also no associated overburden faults.

To assess a possible relation between sub-and supra-Zechstein faults, areas with a Zechstein time thickness of less than a 75ms have been closely examined from seismic cross-sections. Such a limited thickness mainly occurs in the eastern part. Soft-linked faulting is observed in the southeast and northeast. In the southeast two overburden faults are closely associated with sub-Zechstein faults. The eastern 'curved shaped' fault aligns with a mapped sub-Zechstein Pre-Saalian reactivated fault. The eastern N-S orientated fault aligns with a mapped sub-Zechstein post-Rotliegend fault. Both faults can be traced up into the North Sea formation, but the area where soft-linked faulting is observed is outside the Groningen gas field. In the northeast two north dipping faults are associated with thick-skinned faulting, of which the most northern fault shows soft-linked faulting corresponding to a sub-Zechstein pre-Saalian reactivated fault. These faults extend into upper Triassic - Jurassic deposits.

By integrating the fault interpretation with isochore maps it becomes clear that the dominant structural features of the study area were present as of mid-to late Triassic times, and continued to evolve since. The supra-Zechstein fault orientations align with the main sub-Zechstein fault trends. This is an indication that reactivation of sub-Zechstein faults controlled the shaping of the Zechstein salt structures and thereby indirectly also the overburden fault structures. Upper Triassic and Jurassic thickness maps show the expression of an erosional event in middle-late Jurassic times, in most places eroding down into lower Triassic deposits. Deposits in the lower Cretaceous are followed by thick deposits in the upper Cretaceous honouring a NW-SE trend, in which the NW-SE orientated 'salt-pillow' grabens show thinner deposits than the rest of the study area. This is an indication of a salt pulse at this stage. Halokinesis locally continued into the Paleogene and Neogene, primarily in the eastern part of the study area.

The seismic quality of the upper 300ms make it impossible to give a decisive answer to whether faults extend to surface. Projecting the fault - upper North Sea horizon intersections onto the present-day elevation map indicates that these faults have no discernible expression at surface.

Based on the study the following conclusions are made:

1. Faulting in the overburden above the Groningen field is primarily associated with halokinesis of Zechstein evaporites.
2. Areas of highest fault density coincide with areas of strongest halokinesis, which are located outside, or in the peripheral parts of, the Groningen field.
3. Sub-Zechstein and supra-Zechstein faults are generally decoupled, soft-linkage is only observed to the east of the Groningen field.
4. Some supra-Zechstein faults continue into the Lower North Sea Group, but seem to die out at shallower depths. However, the seismic quality in the topmost 300 ms of the overburden is not sufficient to do a proper assessment of the presence of faults. There is no expression of subsurface faults in the present-day topography in the study area.

109 Recommendations for further work

- Integrate the overburden fault interpretation with recorded seismic events and focal mechanisms.
- Convert fault model to depth domain and use RDR tools to further QC the interpretation and calculate max throw/displacement of the faults. This can help determine the magnitude of the seismic events the faults could potentially have caused.
- Further investigate the relation between specific sub-Zechstein faults and salt structures/overburden faults and make a proper reconstruction of salt tectonics in the area. In order to get a better view on which unlinked faults could potentially become soft-linked or which soft-linked faults could become hard-linked.
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110 Fault interpretation project

Software

Petrel 2014 was used for the 3D seismic interpretation and was used to generate horizon, fault-horizon intersection and isochore maps.

Location

The fault interpretation project is stored in the following location:

\\europe.shell.com\tcs\ams\ui.nam\data\petrel03\epe_land\ groningen\nl groningen\petrel_final\2016_GFR_Thomas_Logeman_Structural_OverburdenFaultInterpretation_EP201703226971

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