Msc Thesis report

The influence of the Gronau and Boekelo faultzones on the Jurassic and Lower Cretaceous geology of SE Twente

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1 Introduction

1.1 Nouryon

Salt has been mined in Twente since 1918. First in Boekelo later, in the 1930's, salt production was moved to Hengelo (Nouryon, n.d.). On a yearly basis Nouryon produces around 6 million tons of salt. This salt is not produced in Hengelo alone but also in Delfzijl (since the 1950's) and in Mariager, Denmark (since 1963). Through solution mining salt (in the form of brine) is extracted from the subsurface. In Hengelo salt is mined from a Triassic layered salt deposit, the Nouryon plants in Delfzijl and Mariager are supplied with brine from Zechstein diapirs (domal salt deposits). In the coming years a new brine field will be developed near Haaksbergen to supply the Hengelo plant for the coming decades. In Haaksbergen the salt will be mined from a salt pillow also of Zechstein age (Wijermars, 2013).

The majority of the purified salt is used in the production of base chemicals. Other applications of the salt are in the food-processing industry, agriculture, road de-icing and consumer salt. (Wijermars, 2013)

1.2 Geological context

The area of interest for this study is the south-east of Twente. This is located in the east of the Netherlands, against the German border, see Figure 1.

Stratigraphy

Figure 2 shows the stratigraphy of the study area and the tectonic events that took place. There are two large hiatuses in the Mesozoic and Cenozoic stratigraphy. The first one is erosion of the Middle and Lower Jurassic and the upper part of the Upper Triassic, the second of the Upper Cretaceous.

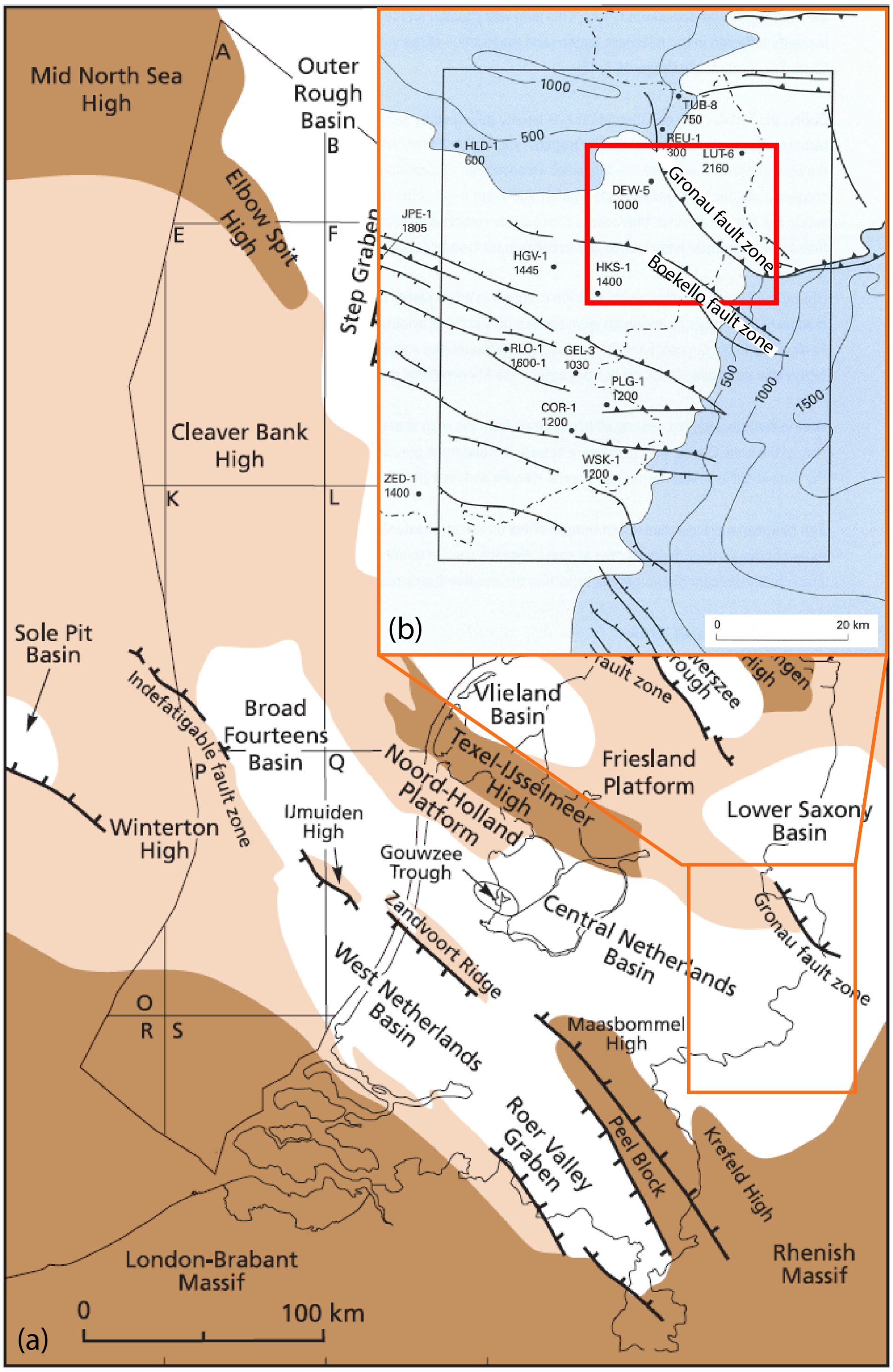


Figure 1: The study area (the red box) and regional context. (a) Map of Late Jurassic to Early Cretaceous structural elements after (van Adrichem-Boogaert & Kouwe, 1993-1997b). (b) Structural elements and amount of erosion during the Sub-Hercynian phase after (NITG-TNO, 1998).

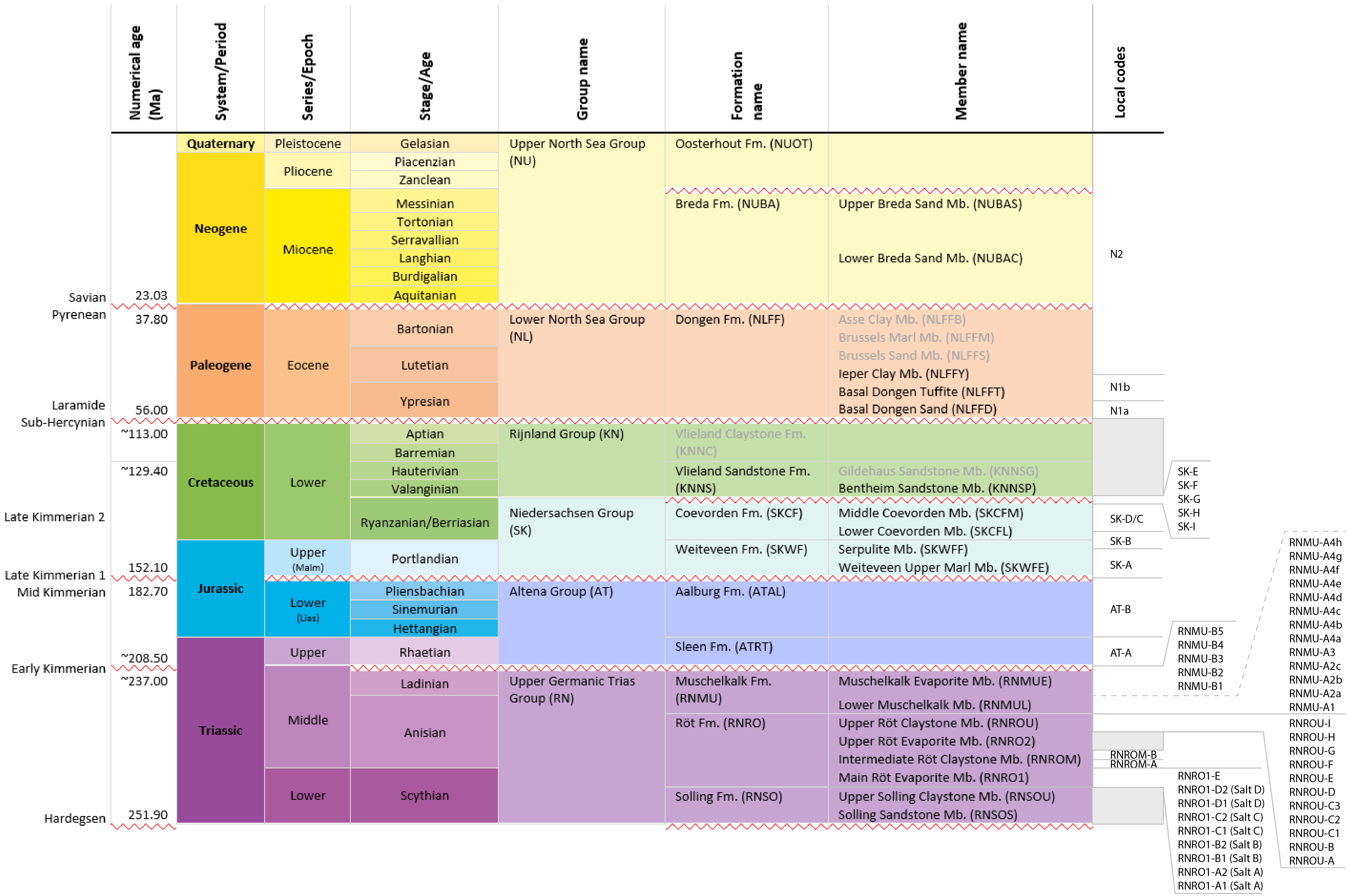

Numerical age (Ma)
System/Period
Series/Epoch
Stage/Age
Group name
Formation name
Member name
Local codes
Quaternary
Pleistocene
Gelasian
Upper North Sea Group (NU)
Oosterhout Fm. (NUOT)
Pliocene
Piacenzian
Zanclean
Neogene
Miocene
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Breda Fm. (NUBA)
Upper Breda Sand Mb. (NUBAS)
Lower Breda Sand Mb. (NUBAC)
N2
Savian
23.03
Pyrenean
37.80
Paleogene
Eocene
Bartonian
Lutetian
Ypresian
Lower North Sea Group (NL)
Dongen Fm. (NLFF)
Asse Clay Mb. (NLFFB)
Brussels Marl Mb. (NLFFM)
Brussels Sand Mb. (NLFFS)
Ieper Clay Mb. (NLFFY)
Basal Dongen Tuffite (NLFFT)
Basal Dongen Sand (NLFFD)
N1b
N1a
Laramide
Sub-Hercynian
56.00
~113.00
~129.40
Cretaceous
Lower
Aptian
Barremian
Hauterivian
Valanginian
Ryazanian/Berriasian
Rijnland Group (KN)
Vlieland Claystone Fm. (KNNC)
Vlieland Sandstone Fm. (KNNS)
Gildehaus Sandstone Mb. (KNNSG)
Bentheim Sandstone Mb. (KNNSP)
SK-E
SK-F
SK-G
SK-H
SK-I
Late Kimmerian 2
Niedersachsen Group (SK)
Coevorden Fm. (SKCF)
Middle Coevorden Mb. (SKCFM)
Lower Coevorden Mb. (SKCFL)
SK-D/C
Weiteveen Fm. (SKWF)
Serpulite Mb. (SKWFF)
Weiteveen Upper Marl Mb. (SKWFE)
SK-B
SK-A
Jurassic
Upper (Malm)
Portlandian
Late Kimmerian 1
152.10
Mid Kimmerian
182.70
Lower (Lias)
Pliensbachian
Sinemurian
Hettangian
Altena Group (AT)
Aalburg Fm. (ATAL)
Sleen Fm. (ATRT)
AT-B
AT-A
Early Kimmerian
~208.50
~237.00
Triassic
Upper
Rhaetian
Middle
Ladinian
Anisian
Lower
Scythian
Upper Germanic Trias Group (RN)
Muschelkalk Fm. (RNMU)
Muschelkalk Evaporite Mb. (RNMUE)
Lower Muschelkalk Mb. (RNMUL)
Röt Fm. (RNRO)
Upper Röt Claystone Mb. (RNROU)
Upper Röt Evaporite Mb. (RNRO2)
Intermediate Röt Claystone Mb. (RNROM)
Main Röt Evaporite Mb. (RNRO1)
Solling Fm. (RNSO)
Upper Solling Claystone Mb. (RNSOU)
Solling Sandstone Mb. (RNSOS)
Hardegsen
251.90
RNROM-B
RNROM-A
RNMU-B5
RNMU-B4
RNMU-B3
RNMU-B2
RNMU-B1
RNMU-A4h
RNMU-A4g
RNMU-A4f
RNMU-A4e
RNMU-A4d
RNMU-A4c
RNMU-A4b
RNMU-A4a
RNMU-A3
RNMU-A2c
RNMU-A2b
RNMU-A2a
RNMU-A1
RNROU-I
RNROU-H
RNROU-G
RNROU-F
RNROU-E
RNROU-D
RNROU-C3
RNROU-C2
RNROU-C1
RNROU-B
RNROU-A
RNRO1-E
RNRO1-D2 (Salt D)
RNRO1-D1 (Salt D)
RNRO1-C2 (Salt C)
RNRO1-C1 (Salt C)
RNRO1-B2 (Salt B)
RNRO1-B1 (Salt B)
RNRO1-A2 (Salt A)
RNRO1-A1 (Salt A)

Figure 2: *(Caption to figure on previous page.)* Stratigraphy of the Twenthe-Rijn concession modified after Kok (2019). sources: GEOWULFLaboratories (2008, 2009a,b, 2011, 2016, 2020); van Adrichem-Boogaert & Kouwe (1993-1997a); Cohen et al. (2018)

Pre-Triassic and Triassic

Throughout the Dutch subsurface a strong NW-SE structural trend is displayed, which was established between 480 and 390 Ma ago, during the Caledonian orogeny (de Jager, 2003). During the Permian and Triassic North-West Europe (and therefore the study area, see Figure 1) was located in a large basin, the Southern Permian Basin. Under the influence of Triassic WNW-ESE extension the Southern Permian basin "broke up" into several depocentres. (NITG-TNO, 1998; Geluk, 2005). One of these sub-basins was the pre-cursor of the Central Netherlands Basin (CNB) (Duin et al., 2006; Doornenbal, 2010). During most of the Permian and Triassic sedimentation took place in arid continental or restricted marine environments. As a result Permian and Triassic strata are dominated by red beds and evaporites (Wolburg, 1969; Doornenbal, 2010). An early Rheatian (Upper Triassic) transgression marked the transition to open marine settings in north-west Europe. The transgression was a result of regional subsidence in combination with sea-level rise. Shallow water, open-marine, fine-grained mudstones, such as the Sleen formation, were deposited (NITG-TNO, 1998; Doornenbal, 2010). The end of the deposition of the Sleen formation is characterised by a brief regression period (NITG-TNO, 1998).

Jurassic

After the short regression at the end of the Triassic, sea-level rise continued into earliest Jurassic times. The shallow marine Aalburg formation was deposited during the this period (Hettangian to Pliensbachian) (NITG-TNO, 1998).
Little is known about the Middle Jurassic, as a result of uplift and subsequent erosion (NITG-TNO, 2000). The Late Jurassic was a tectonically active period. Extensional stresses, related to the break up of the America and Europe (the Late Kimmerian tectonic phase), formed NW-SE trending basins in Northwest Europe (NITG-TNO, 2000; de Jager, 2003). With the reactivation of the Gronau Fault zone the study area is now located on the margin of two basins. In the north-east the Lower Saxony basin has formed, and in the south-west the Central Netherlands Basin formed (Figure 1)(NITG-TNO, 1998, 2000; Wong et al., 2007).
The sediments of the Niedersachsen group were deposited at the time of the reactivation of the Gronau Fault zone, Upper Jurassic (Portlandian) until the lowermost Cretaceous (Ryanzanian) (GEOWULFLaboratories, 2011).

Cretaceous

The Cretaceous is marked by ongoing sea level rise. This sea level rise created a deep marine setting as it came to a highstand in the Late Cretaceous. The deep marine limestones are not preserved in the study area, because as good as all Cretaceous deposits were eroded (NITG-TNO, 1998). Except in a tiny area within the Boekelo Fault zone, where a few meters of the Vlieland Sandstone formation and perhaps Vlieland Claystone formation, have been preserved (GEOWULFLaboratories, 2009b, 2011). Erosion took place due to the inversion during the Upper Cretaceous. During this tectonic event (Sub-

Hercynian phase), which is related to the formation of the Alps, the Gronau Fault zone was reactivated. This caused the inversion of the two basins in the study area (the Central Netherlands Basin and the Lower Saxony Basin) (NITG-TNO, 1998; de Jager, 2003).

Paleogene, Neogene and Quaternary

The Netherlands was located along the southern border of the North Sea basin at Tertiary times. The development of this basin dictates the sedimentation pattern of the Netherlands till this day. During the Paleogene transgression took place, resulting in predominately marine deposits in the Lower North Sea Group. The Upper North Sea group consists of marine to continental sediments as a consequence of rapid shallowing of the North Sea basin in the Neogene (Wong et al., 2007).
A few tectonic events took place during the Tertiary (i.e. the Savian and Pyrenean), leaving some hiatus in the stratigraphy. These events, which once again reactivated the Gronau fault zone, are identified with the uplift of the Alps. The current hilly landscape of Twente was created by glacials and interglacials of the Quaternary period (NITG-TNO, 1998).

1.3 Main objectives

Historically, geological studies (commissioned) by Nouryon were mostly centralised around the characteristics of the Main Röt Evaporite. Later studies were expanded to include research on the geological characteristics of the Triassic Röt and Muschelkalk formations. The characteristics of the cavern field, e.g. cavern diameter or distance between caverns, were also studied. Research on the rest of the overburden remained limited.
In this study an effort was made to not only expand the geological knowledge in the vertical direction (overburden), but also in a lateral direction, to include the surrounding area of South-East Twente. Within the overburden the focus is on the Niedersachsen and Altena groups. Important elements in this study are the influential fault zones in the area, the Gronau Fault zone and the Boekelo Fault zone.
Apart from the academic purpose of furthering knowledge, this study also serves a more practical use. Before drilling a well the dimensions of the to be developed cavern are determined. As part of that the inherently safe height* is calculated. This is done using the following equations:

$$inherently\ safe\ cavern\ height = |depth\ bottom| - |depth\ top|$$

$$depth\ top = \frac{depth\ bottom + (bulking\ factor - 1) \times (base\ Tertiary + 40m)}{bulking\ factor}$$

OR

$$depth\ top = \frac{depth\ bottom + 0.11 \times (base\ Tertiary + 40m)}{1.11}$$

Where "bulking factor" represents the ratio between the volume of loose rock debris and the volume of the same solid rock is.

$$depth\ bottom = \frac{depth\ bottom\ at\ axis + depth\ bottom\ at\ 10m\ from\ axis}{2}$$

*The maximum permissible height of a cavern is chosen in such a way that it is inherently safe, i.e. when the roof of a cavern becomes unstable and collapses despite all precautions (this is called cavern migration), only limited subsidence occurs at the surface, the development of a sinkhole is excluded (Nouryon, 2019)

In any case the following equation needs to be satisfied:

$$|depth\ top\ cavern| \geq |depth\ top\ salt\ C + 5m|$$

(Nouryon, 2019)
The base of the Tertiary is assumed to be the boundary between unconsolidated sediments and consolidated sediments. Because the unit directly below the Tertiary deposits is either a minor amount of Cretaceous sediments or Lower Jurassic / Upper Triassic in age this was never an issue. However, South of the Boekelo Fault zone, the thicknesses of Jurassic and Lower Cretaceous sediments (Niedersachsen and Altena groups) are significantly thicker (GEOWULFLaboratories, 2020).
More knowledge on the characteristics of the overburden could contribute to the determination of the depth and thickness of the inherently safe height of the caverns and is useful for future well abandonments in this area.

2 Methods & Data

2.1 Methods

Individual analyses were combined following the chart in Figure 3, in order to make a static structural model of the geology of South-East Twente.
Lithological data was collected by means of macroscopic core description. Gamma Ray logs were used for the construction of correlation panels as well as supplementary to the seismic profiles.

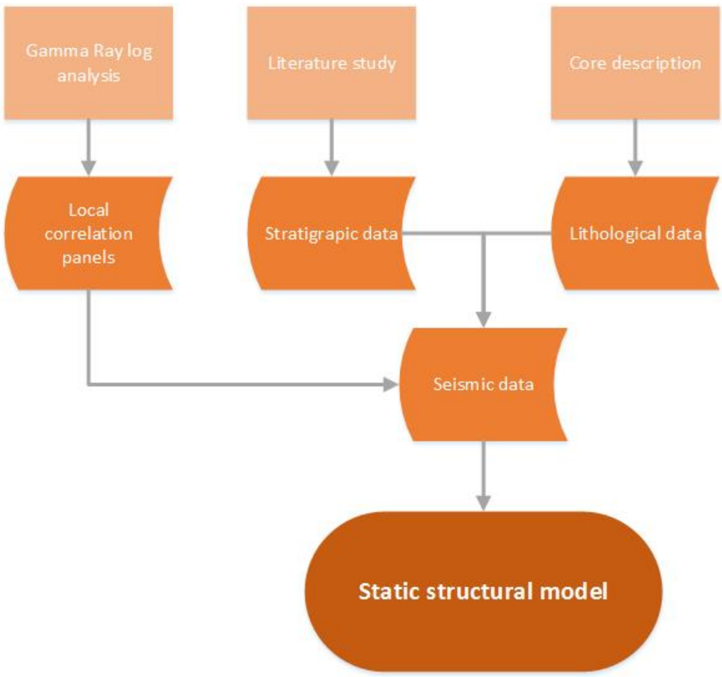


Figure 3: Flow chart with analyses used for this study.

When interpreting seismic profiles a few techniques were used to interpret the section and differentiate reflectors:

- Geology
  Knowledge about the stratigraphy and geological context of the area was used, particularly at interpreting around faultzones and other unconformities.
- Intersection of seismic lines
- Gamma ray logs
  Gamma ray logs of nearby wells were not used in a well tie, as sonic data was not available. They are however used indirectly, as a visual guide.
- Texture
  Texture on seismic sections can give some information about the state or characteristics of an interval or part of the subsurface. The combination of the configuration, continuity and amplitude of reflectors, is called seismic texture. In Figure 4 below a few examples of seismic texture are displayed.

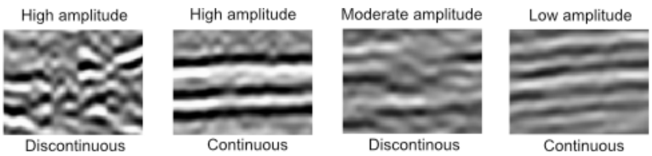


Figure 4: Examples of seismic textures.

- Colour scheme and contrast
  In seismic interpretation software colour schemes of (seismic) data can be changed and contrasts can be adjusted. This was useful in interpreting more indistinct parts of some seismic sections.

Triangulation was used to convert the 2D interpreted reflectors into 3D planes.

2.2 Data

Lithological data

Lithological data on the Niedersachsen and Altena group was acquired by analysing core material from cores; TWR-141, TWR-171, TWR-285 and TWR 558 (see Figure 5 for the locations of the wells). Macroscopic analysis was carried out on approximately 42 meters of core material.

Stratigraphic data

Literature on the geology of the Twenthe-Rijn concession makes use of its own local stratigraphy code. By means of literature study on both local and national (Dutch) stratigraphy a connection between the two could be made.

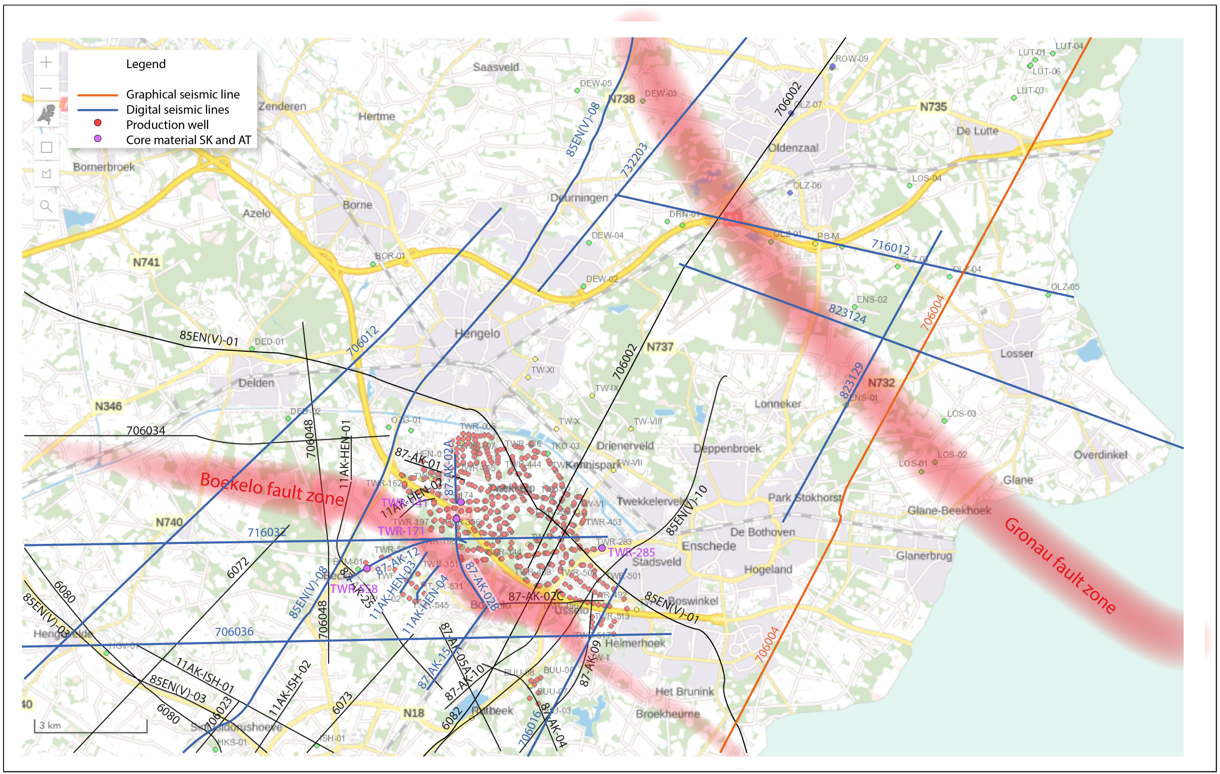


Figure 5: Locations and spatial distribution of subsurface data in relation to the approximate location of the fault zones. Background map from (NLOG, n.d.) location of the faultzones after figure 12.5 from NITG-TNO (1998).

Gamma Ray log

Gamma Ray log analysis of wells within the Twenthe-Rijn concession were used to create correlation panels. These correlation panels visualise the continuation of the stratigraphy on a local (Twenthe-Rijn concession) level. The gamma ray measurements are not in standard API units, but in CPM (counts per minute) or in older logs, CPS (counts per second). The interpretation process remains the same, as both scales are relative. GeoBase was used to analyse the gamma ray logs. The correlation panels were constructed in Adobe Illustrator. The correlation panels are both perpendicular and parallel to the strike of the Boekelo fault zone. That way a (close to) 3D image of the local geology is formed. Not all wells included in the correlation panels are accompanied by a gamma ray log. Because not all wells, especially older wells, have a full length gamma ray logs. The stratigraphy in wells without logs are based on GEOWULF Laboratories studies from *boorboekjes* data.

Seismic data

16 seismic lines were analysed for this study, 15 SGY-files and 1 TIFF-file. The sections are of varying age and quality, overall the quality of the seismic sections is good. A combination of shallow (around 1 sec TWT ≈ 1000m) and deeper (4 sec TWT ≈ 4000m) seismic lines were selected. The shallow seismic lines will be used to identify lithological boundaries and corresponding reflector markers. Shallow lines are often short lines. Deeper seismic lines have been used to gain insight into the lateral continuation of the stratigraphy on a larger (regional) scale, as deeper seismics are often long lines.
Figure 5 shows all seismic data available at Nouryon (including the lines collected from TNO and NAM specifically for this project). Seismic profiles to be included in this study

were selected based on 2 factors. First their proximity to (TWR) wells. Secondly their direction in relation to the structural elements of the area. It should be noted that line 706002 was also selected to be part of this study. Due to issues with plotting, this line was replaced by line 706004.
The 15 SGY-file seismic sections were interpreted using the open source software, OpendTect V6.4.4.
The seismics show a few bold reflectors. These high amplitude reflectors are caused by the high impedance contrast between two layers. The best high amplitude reflectors within this database are;

- **Base North Sea group** The base North Sea group or base N reflector is of lowermost Eocene age. The reflector represents the hiatus created by the erosion that followed the Sub-Hercynian inversion. Due to the density difference between the sandy deposits of the North Sea group and either the clay-rich deposits of the Niedersachsen group, or the limestones of the Muschelkalk formation the high amplitude reflector was created.
- **Top Upper Germanic Trias group (Top Muschelkalk formation)** The top Muschelkalk reflector is roughly between 237 and 242 Ma old, which is the base of the Early Kimmerian hiatus. The reflector is a result of the difference in density between the carbonitic deposits of the Muschelkalk formation and the clayey formations of the Niedersachsen group or the North Sea group.
- **Top Main Röt Evaporite member** In seismic lines salt deposits are always highly reflective, the low density of salt creates a high impedance contrast with the surrounding rock. The Main Röt Evaporite is between 247.2 and 242 Ma old.
- **Top Z1 Anhydrite member** Zechstein salt deposits are significantly older (Late Permian) than the Röt salt deposits, but creates a traceable reflector for the same reasons.

Base Niedersachsen group is not one of the best reflectors, but it is visible on some seismic lines, predominantly the shallower lines. It is uppermost Jurassic in age. The Altena Group is not traced on these seismic lines, due to the limited thickness of the Altena group deposits and the horizontal resolution of seismic lines.

3 Results

3.1 Lithology

During the lithology study several Niedersachsen deposits and several Altena deposits have been studied. Lithological descriptions of the core material for the Niedersachsen and Altena group of wells; TWR-141, TWR-171, TWR-285 and TWR 558 have been published in separate reports. These reports are included in Appendix B.
Niedersachsen deposits have been cored in wells, 141, 171 and 558. Altena deposits have been cored in wells 141, 285 and 558. A comparative summary is presented in Table 1 below.

Table 1: Comparative summary of core description reports. In stratigraphic order.

Well	Depth interval (m-gl)	Stratigraphy	Description
TWR-171	119 - 141.4	Coevorden fm. (SK-C/B)	med grey sub mm lamination varying carbonate content small clasts shell beds decrease with depth halite beds increase with depth
TWR-558	166.18 - 171.78	Weiteveen fm. (SK-A)	med grey sub mm lamination small clast gritty intervals increase with depth (shell beds)
TWR-558	171.78 - 172.64	Aalburg fm. (AT-B)	med grey sub mm lamination pyrite present
TWR-285	92.50 - 96.45	Sleen fm. (AT-A)	dark grey mudstone (no HCl reaction) sub mm lamination pyrite (mineralised) fossils increase with depth
TWR-141	125 - ?	Niedersachsen (SK)*	med grey sub mm laminated to massive no fossils varying carbonate content
TWR-141	? - 141.4	Altena (AT)*	dark grey claystone (no HCl reaction) shale like texture

* Core TWR-141 was too fractured to macroscopically determine further subclassifcations

Strength test have been carried out by Fugro (2020) on core material from well TWR-558. From the two tested samples, one was interpreted as Niedersachsen and one as Altena group. Both tested similar on the uniaxial compressive strength (UCS) test, see Table 2.

Table 2: Uniaxial compressive strength of samples from well TWR-558. Modified after: Fugro (2020)

Well TWR-558	Core 2 box 1 (SK)	Core 2 Box 4 (AT)
UCS [MPa]	15.1194	14.3355

Nouryon

3.2 Stratigraphy

The stratigraphy of south-east Twente, and the connection between the local and national stratigraphy codes are depicted in Figure 6. Depth and thicknesses of these units and the total overburden (within the Twenthe-Rijn concession) can be seen in the table below (Table 3).

Table 3: Thicknesses of the overburden within the Twenthe-Rijn concession (based on GEOWULF Laboratories studies on Gamma ray and *boorboekjes* data.) NOTE: SK, AT and RNMU are not continuously present throughout the Twenthe-Rijn concession subsurface.

	Thickness [m]		
	Average	Minimum	Maximum
Overburden*	384.9	274.6	565.8
North Sea Group (N)	108.4	57.1	150.8
Niedersachsen Group (SK)	11.8	2.9	158.2
Altena Group(AT)	4.5	1.2	210.7
Muschelkalk Fm. (RNMU)	55.9	1.9	257.4
Röt overburden**	141.5	118.6	477.2
	Depth [m]		
	Average	Minimum	Maximum
Overburden*	-	-	-
North Sea Group (N)	0	0	0
Niedersachsen Group (SK)	104.7	57.1	257.8
Altena Group(AT)	137.0	80.6	278.0
Muschelkalk Fm. (RNMU)	129.4	80.9	331.6
Röt overburden**	220.4	101.7	427.6

*From ground level until top Anhydrite. Including Rijnland Group if present.
** Upper Röt Claystone Mb., Upper Röt Evaporite Mb. and Intermediate Röt Claystone Mb.

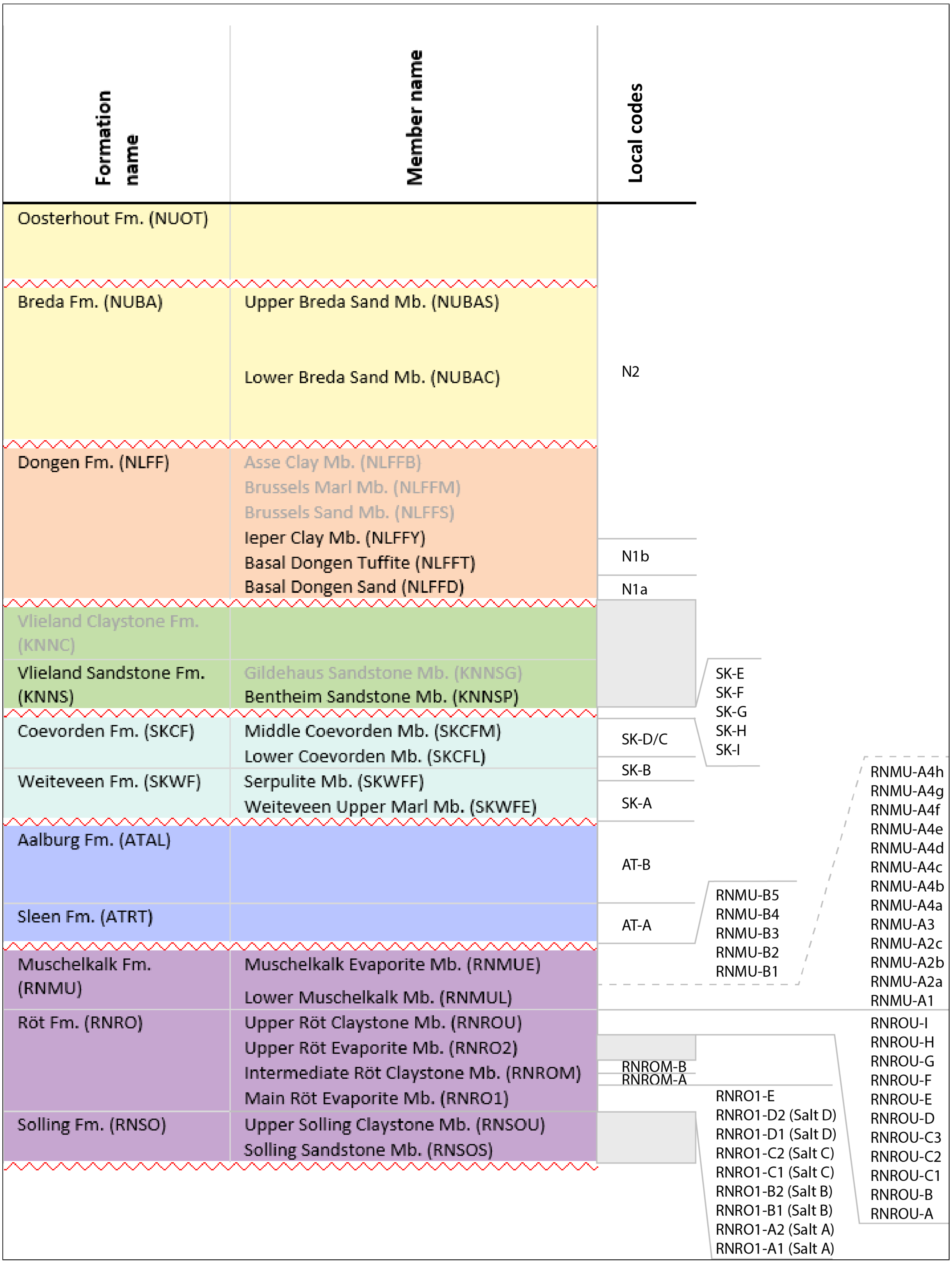


Figure 6: Connection between local and national stratigraphy codes. For the complete figure see Figure 2.

3.3 Correlation panels

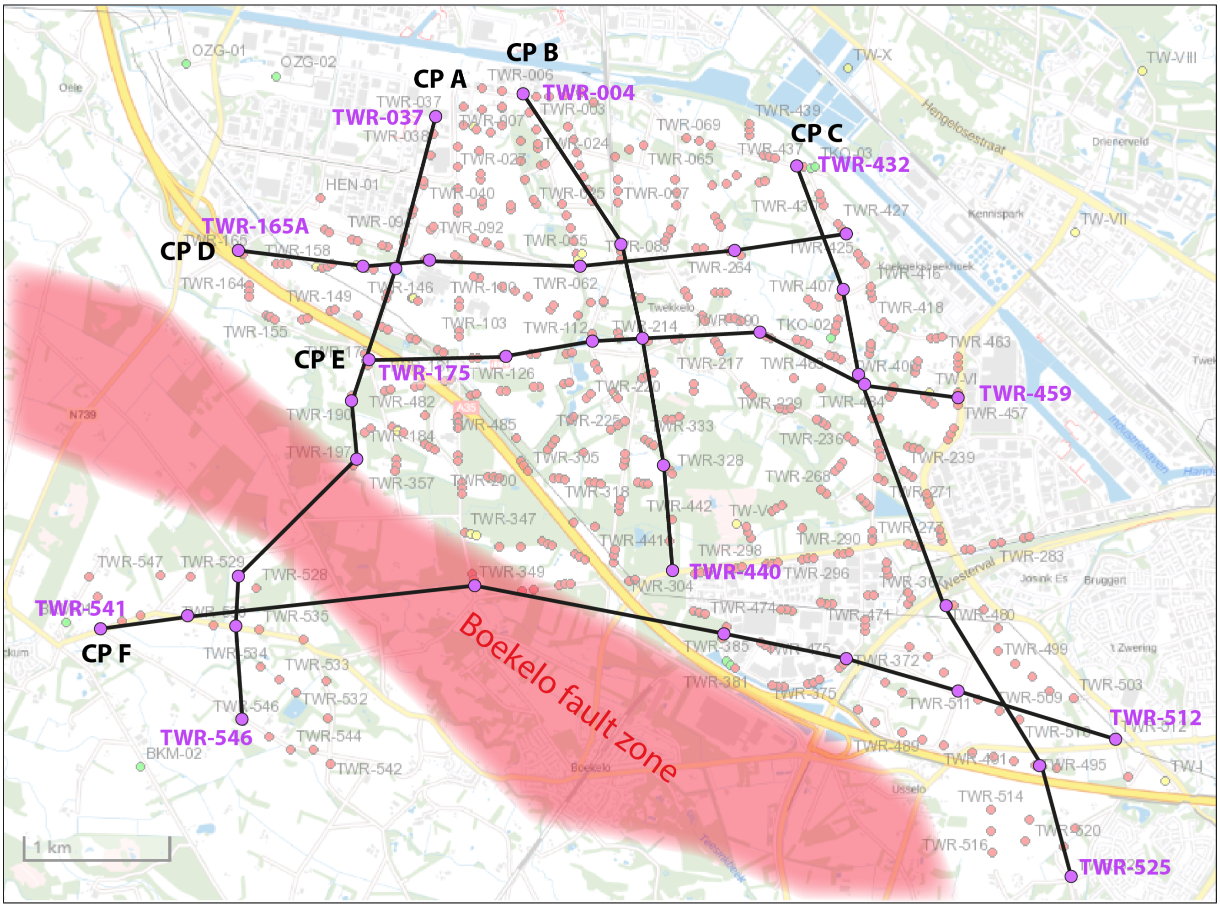


Figure 7: Locations of the correlation panels in the Twenthe-Rijn concession , and approximate location of the Boekelo fault zone.

The correlation panels construct a basic 3D image of the geology of the Twenthe-Rijn concession . From these panels in Figure 8 (and Appendix A) a few trends can be observed. A general shallowing trend towards the east is recognised for the entire succession. This shallowing trend is linked to the thinning of the North Sea Group in a eastern and southern direction. The conservation of the Niedersachsen and Altena group is related to the Boekelo fault zone. In the correlation panels it can be seen that the geological units ”appear” in the Twenthe-Rijn concession parallel to the fault zone, on the north-eastern side. In other words, Niedersachsen and Altena deposits are not present in the northern part of the Twenthe-Rijn concession . Finally the Niedersachsen group deposits seem to increase in thickness in a south-eastern direction.
The 3D image constructed trough correlation panels remains however far too simplified, especially with regards to the faults and fault zones. In order to get a better understanding of the strike and angle of these structures, and their effect on the stratigraphy seimics are needed. The correlation panels therefore form an introduction to the seismic model.

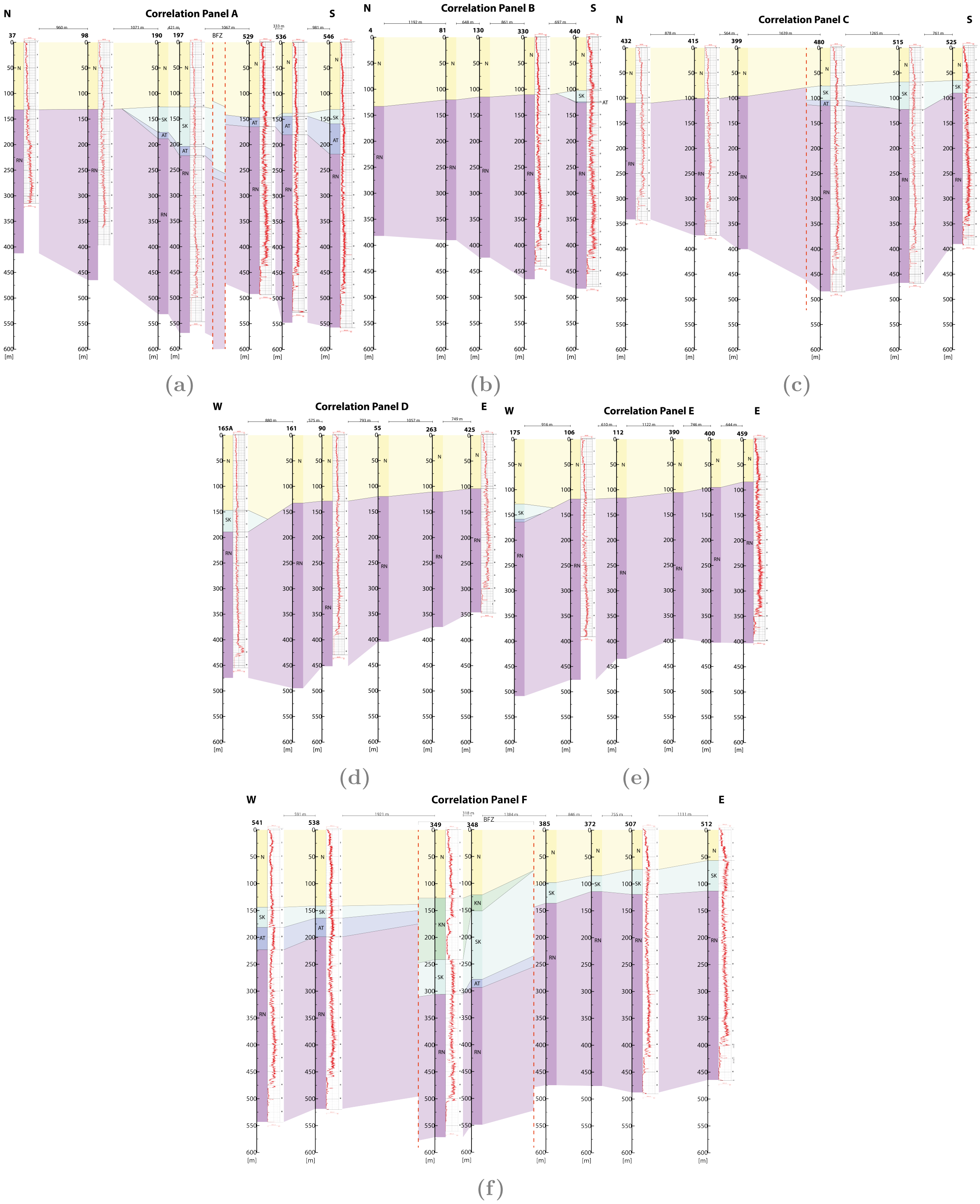
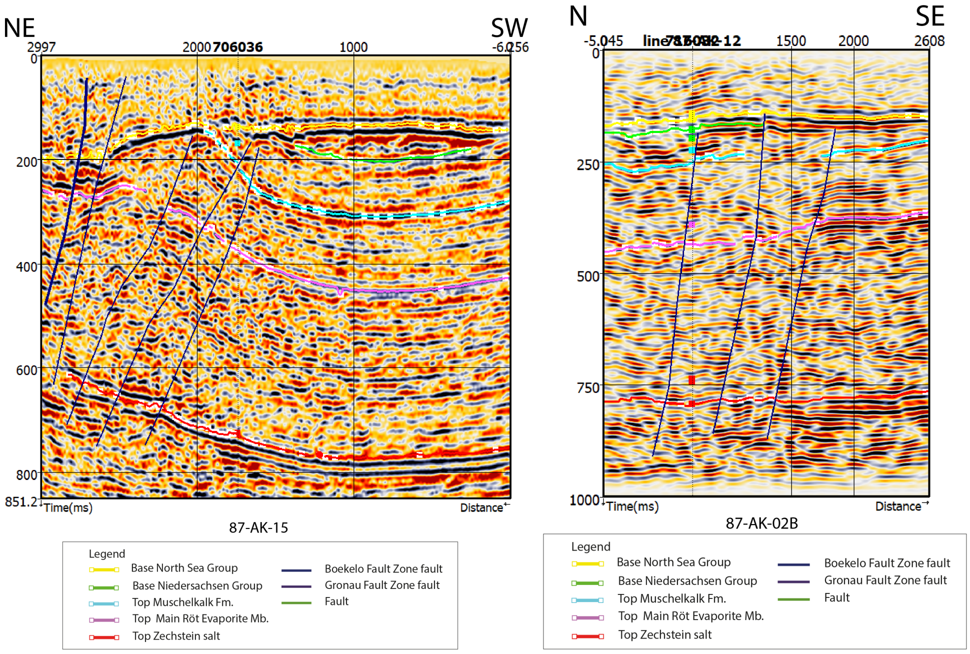


Figure 8: Correlation panels A to F, for location see Figure 7. The fullsize figures are shown in Appendix A. **Note:** All geological groups are separated by hiatus.

3.4 Seismics

Faultzones

The separator between the Lower Saxony basin and the Central Netherlands basin is the Gronau fault zone. The Gronau fault zone has been a major influence in the area throughout geological history. The Gronau Fault Zone and Boekelo Fault Zone have been active at least until well into Quaternary times, and some faults might even still be active today. This is demonstrated in Figure 9. Figure 9a shows that (some of) the faults penetrate the base of the Tertiary (base North Sea group) whereas in Figure 9b the faults stop at the base of the Tertiary. Although Duin et al. (2006) report no activity from the Gronau Fault Zone in the Quaternary, NITG-TNO (1998) and MWH (2010) also conclude that either fault zone might still active.



(a) 87-AK-15 Active faults

(b) 87-AK-02B Inactive faults

Figure 9: Examples of active and inactive faults in the Boekelo Fault Zone . Notice how the faults figure (b) do not pierce through the base of the North Sea group (yellow), while the two left most faults in figure (a) continue above the base of the North Sea group.

The approximate locations (Figure 5) of the Boekelo Fault Zone and the Gronau Fault Zone were unsurprisingly accurate with the findings from the seismic model. The location of the central part of the Boekelo Fault Zone was thoroughly studied by Koopmans et al. (2010). The current study includes more eastern and western parts of the fault zone. The fault zones are partially parallel in strike, NE-SW. In the far west side of the the Boekelo Fault Zone changes to a more E-W strike, while the Gronau Fault Zone continues in a more N-S striking course outside of the study area.
Figure 12 nicely shows the parallel nature of the fault zones (the Boekelo Fault Zone , Gronau Fault Zone and a smaller third fault zone towards the North-east). In this figure the fault zones show a slight dip in the Northern direction. The combination of NE-SW lines and roughly E-W striking lines reveals that the true dip direction is closer to ENE. The dip angle of the Boekelo Fault Zone changes along the strike, toward the east (in between lines 87-AK-15 and 706016) the fault zone gets narrower and more symmetrical. As a result of the steeper dip angles of the faults, see Figure 10.

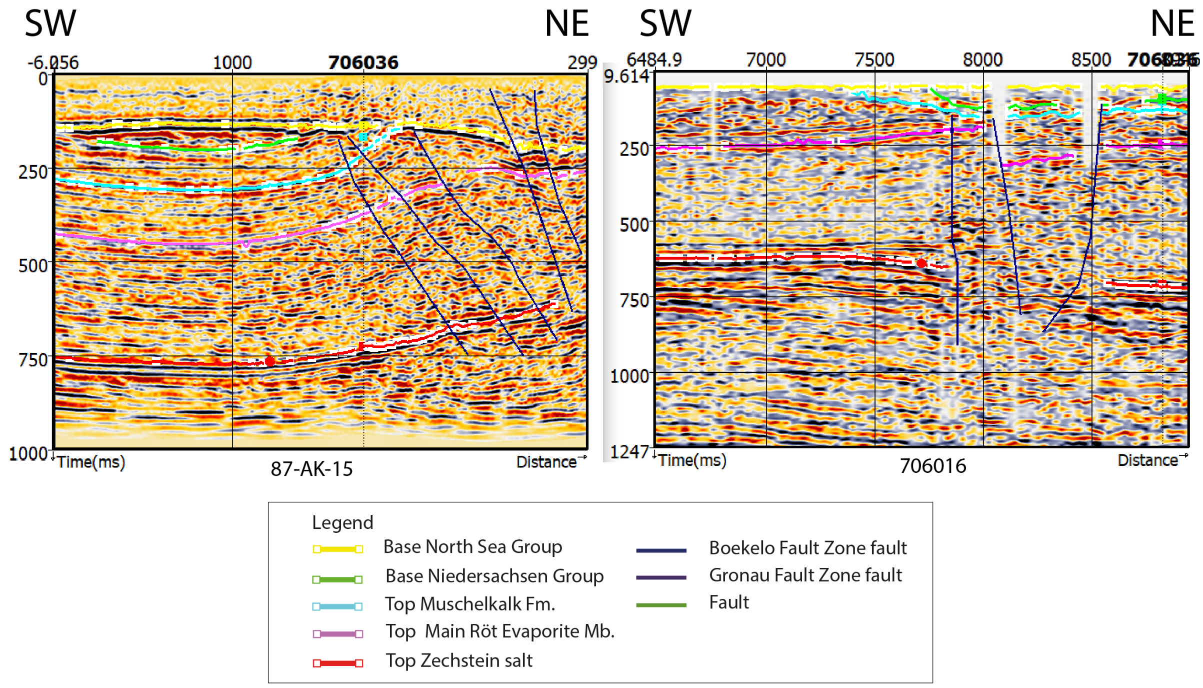


Figure 10: Dip angles Boekelo Fault Zone . Left: 87-AK-15 Right: 706016

Within the Boekelo Fault Zone another fault structure has been observed. Figure 11 shows a negative flower structure, a flower structure suggest a shear component to the fault movement. It is however not an indication for the direction of the shear. From previous studies it is known that the sense of shear is dextral (NITG-TNO, 1998; Koopmans et al., 2010).

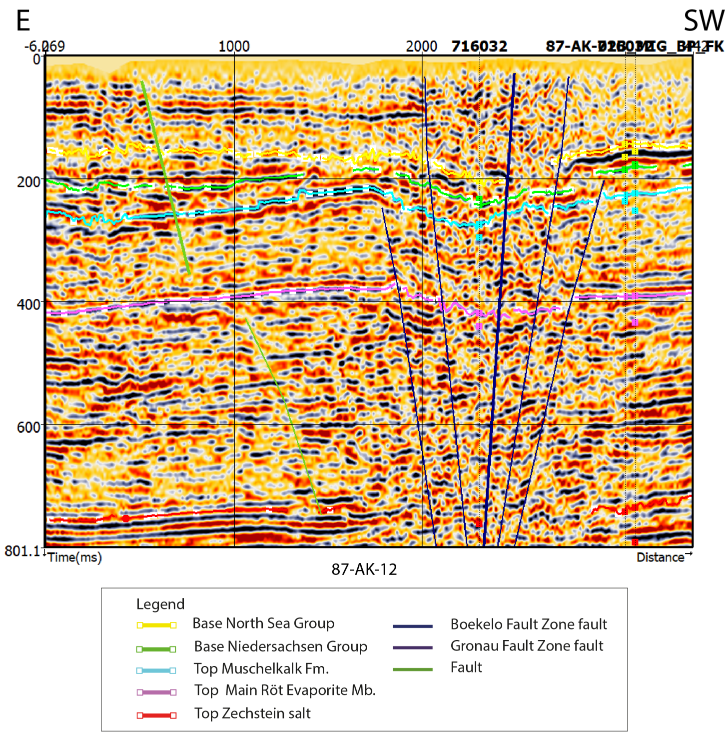
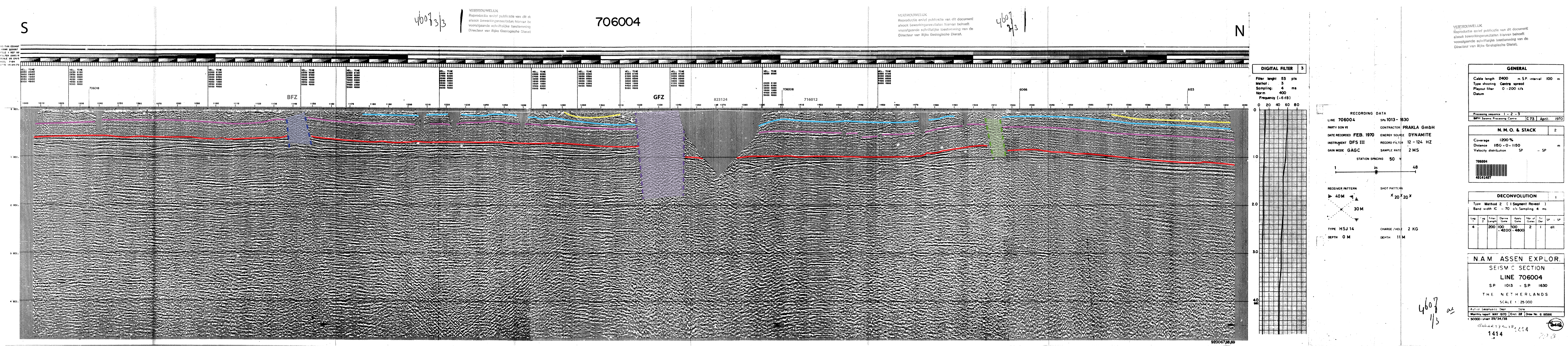


Figure 11: 87-AK-12 (Negative) flower structure is an indicator for strike-slip movement along the fault zone.



Legend

- Base North Sea Group
- Top Muschelkalk fm
- Top Main Röt Evaporite
- Top Zechstein
- Boekelo Fault Zone fault
- Gronau Fault Zone fault
- Fault

Figure 12: *(Caption to figure on previous page.)* Interpretation of seismic line 706004 for location see Figure 5

A notable difference between the two fault zones is the amount of vertical displacement along the faults. In the Boekelo Fault Zone vertical displacement differs greatly along the strike of the fault zone. In the eastern part of the fault zone, the vertical displacement is relatively large at the Röt and Muschelkalk formation levels (see lines 706016 and 706036). The "centre" of the Boekelo Fault Zone displays minimal along the individual faults, as is shown in lines 87-AK-02B, 87-AK-15, 11AK-HEN-04 and 716032 i.a.) Towards the west the amount of vertical displacement along the faults increases again, however not only on Triassic level, but on all Pre-Tertiary strata. The Gronau Fault Zone displays large amounts of vertical displacement, and on the north-eastern side of the fault zone (in the Lower Saxony basin) significantly more deformation has taken place.

Other geology

It is observed that the Niedersachsen group emerges within the stratigraphy north of and parallel to the Boekelo Fault Zone , at a distance of approximately 2 km (very roughly estimated), similarly to the correlation panels. The Niedersachsen group is mostly present in local lows, e.g. the Boekelo Fault Zone within the Twenthe-Rijn concession .
Also similar to the correlation panels a shallowing of the stratigraphy in eastern direction is observed extending outside the Twenthe-Rijn concession (see Figure 13).

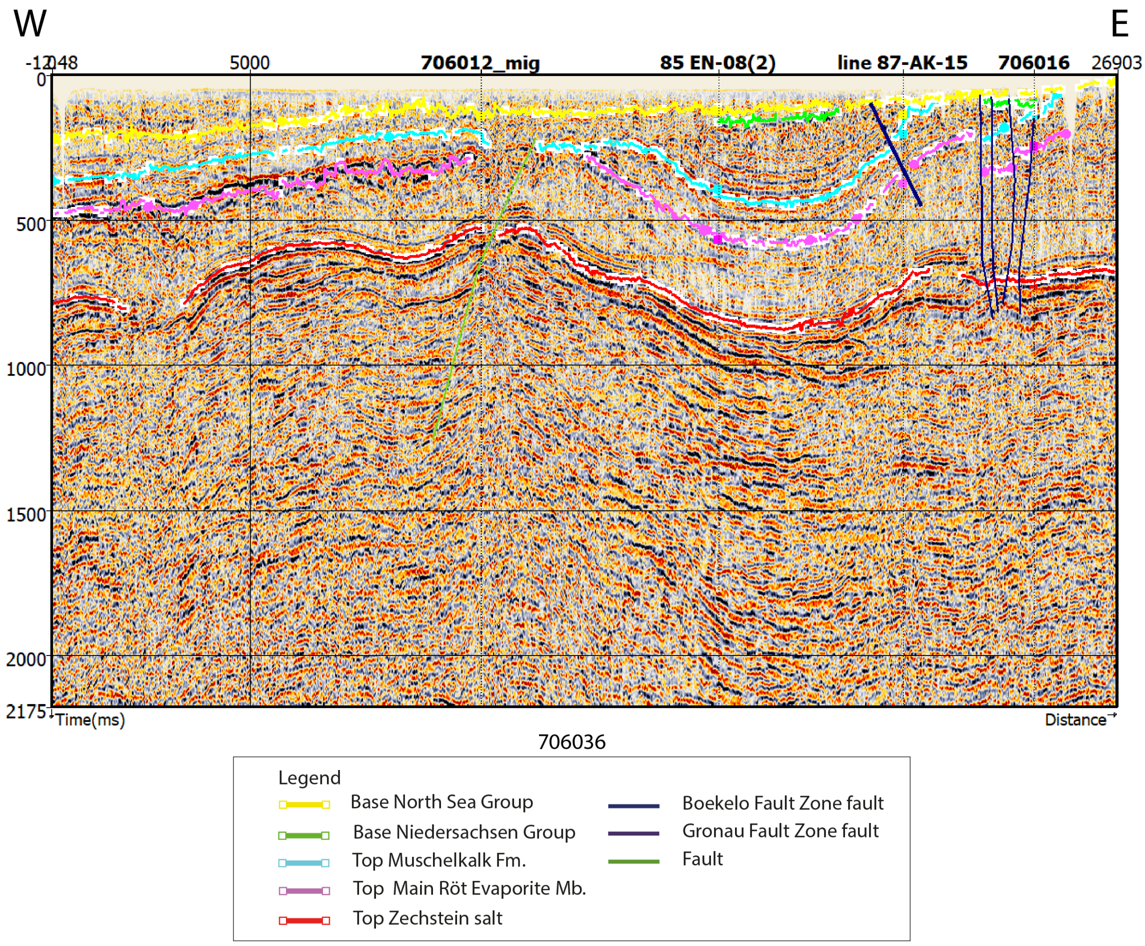


Figure 13: 706036 Shallowing of the stratigraphy towards the east.

Throughout the seismic model the results of the erosion that followed the Cretaceous inversion can be seen, the base Tertiary (North Sea group) lies directly on top of much older strata (most often Triassic strata). Due to this rigorous erosion evidence of the inversion is sparsely preserved. Figure 14 shows the angular unconformity between the tilted pre-Tertiary strata and the post-inversion North Sea deposits.
The syn-rift nature of the Niedersachsen group (Wong et al., 2007; GEOWULFLaboratories, 2007, 2008, 2011) can be seen in the seismic sections. Specifically in the relationship between the fault zone and thickness of the stratigraphic unit. The Niedersachsen group thickens towards the fault zone (see Figure 15).

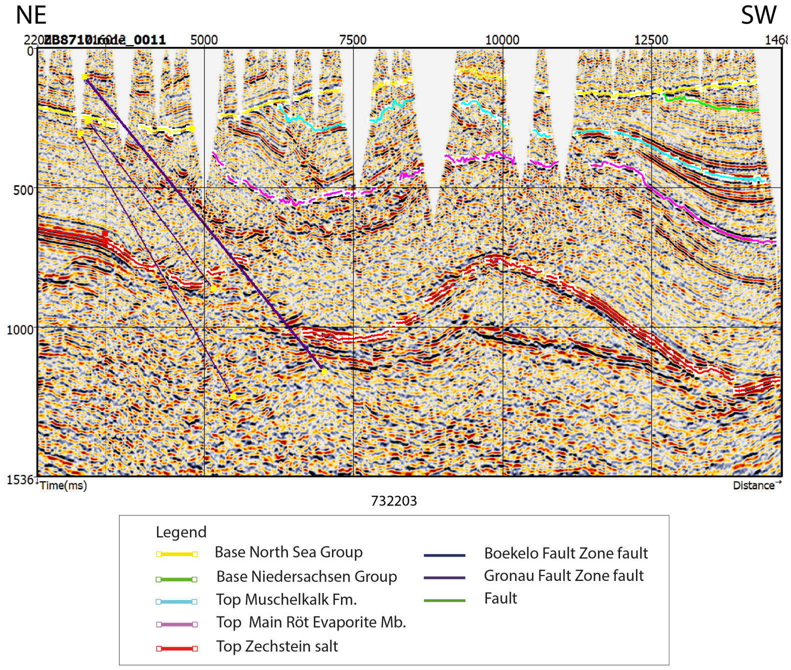


Figure 14: 732203 Tilted and folded pre-Tertiary strata, as a result of the Cretaceous inversion

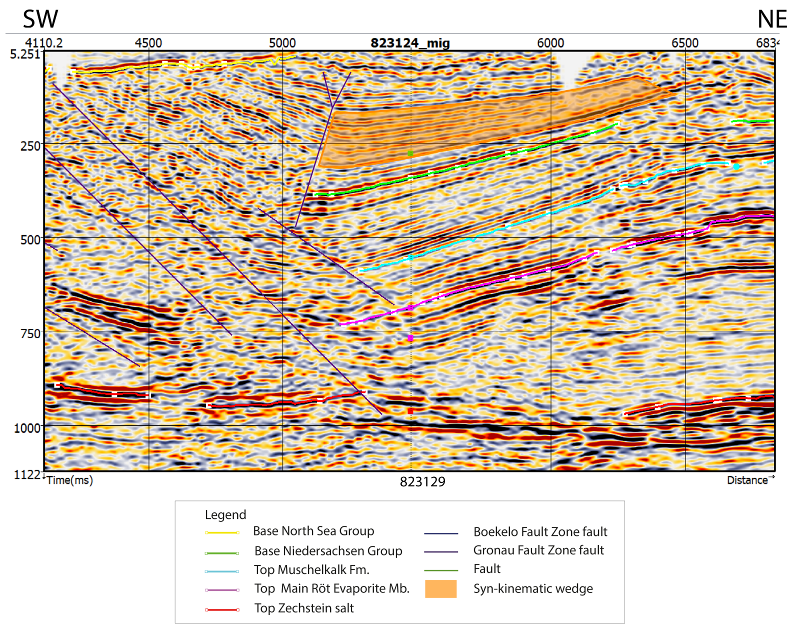


Figure 15: 823129 (SW-NE) Niedersachsen syn-rift wedge

4 Discussion

4.1 Lithology

No direct correlation can be made between the studied core intervals, as all cored intervals belong to a different formation class. Therefore no comments can be made on the lateral continuation of the formations based on this data. However literature shows that the Altena group are very uniform deposits even on the scale of north-west Europe (Wong et al., 2007). The uniform nature of the Altena group is a result of the pre-rift deposition (Wong et al., 2007). The Niedersachsen group consist of syn-rift deposits (Wong et al., 2007; GEOWULFLaboratories, 2007, 2008, 2011). This could be reflected in the cored material of well TWR-171, which can be interpreted as the flooding of a basin. From a high saline environment (halite beds) to a marine environment where mollusks thrive. Note that a correlation between wells has been made on the basis of gamma ray data, Figure 8.
GEOWULFLaboratories (2020) has conducted a microscopic study on cutting samples of well TWR-558, and were able to make a lateral correlation with wells towards the north-west and east. They concurred that the cored section shows very little variation in comparison to wells to the north-west and east, both in the horizontal and vertical direction. The Niedersachsen interval was concluded to be a-typical, and contained more clastic material in comparison (GEOWULFLaboratories, 2020).
The compressive strength of well TWR-558 measured by Fugro (2020) of around 15MPa is very low, in comparison, a limestone has a compressive strength between 30 - 250 MPa, a sandstone between 20 - 170 MPa. The measured strength is in all probability not representative. The actual strength is probably closer to the strength of limestone, which is probably more in the direction of the strength of the Muschelkalk fm., as the Muschelkalk fm. largely consist of limestone and dolomite.
It is speculated that this has originated from the coring troubles surrounding core TWR-558 (related to the core bit and/or composition of the drilling mud, for more detail see Appendix B.4). The rock might also have been weakened due to previously existing micro fractures in the subsurface. It is therefore recommended that more strength testing is done the next time Niedersachsen or Altena group deposits are cored. Or to make use of strength proxies like sonic logging or porosity measurements. Porosity is a measure for amount of compaction but can be used as an estimate of strength (Singer & Müller, 1983). Drilling ease can also be used as a non-quantitative estimate of rock strength. Sonic logging is favoured as it: **I.** a quantitative measure, **II.** is likely to be cheaper, **III.** can be applied retro-actively **IV.** and has multiple applications (e.g. it can be used to tie wells to seismic sections).

4.2 Stratigraphy

Due to the poorly reflective nature of the Altena deposits and the scale of the seismic lines, the presence and absence of the Altena group is not traced in the seimic model. However if the correlation panels are taken as example, most places where ever the stratigraphy includes sediments from the Niedersachsen group it includes Altena group sediments. Based on this information Niedersachsen sediments could be used as a rough indicator for Altena deposits. Yet from Figure 16 from van Adrichem-Boogaert & Kouwe (1993-1997a) it is seen that the Altena deposits are more widespread than the deposits of the Niedersachsen group (within the study area). When taking a closer look at the stratigraphy within the Twenthe-Rijn concession , specifically to the southeast, often wells are interpreted to have no Altena deposits but do contain Niedersachsen deposits. This shows that generally speaking Niedersachsen deposits might be a preliminary indicator for the presence of Altena deposits, local variations may occur.

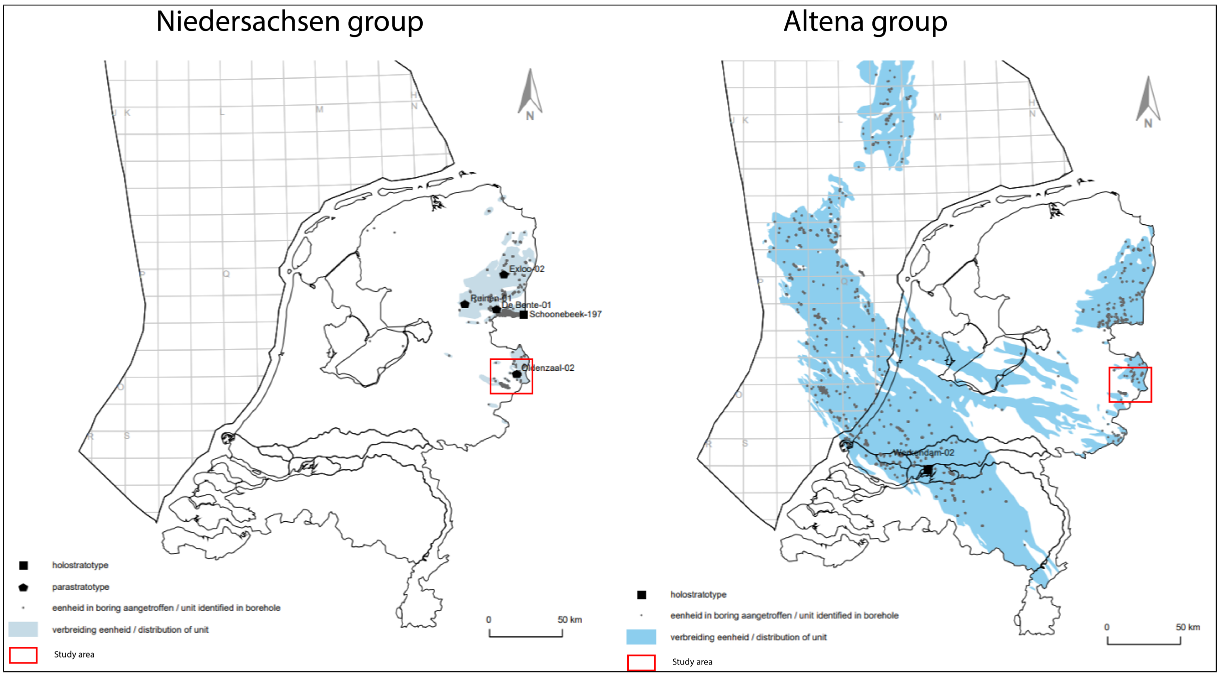


Figure 16: Distribution of Niedersachsen and Altena deposits in the Dutch subsurface. Adapted from van Adrichem-Boogaert & Kouwe (1993-1997a).

4.3 Faults and Fault zones

The Boekelo fault zone is inferred to be branch of the Gronau fault zone (Koopmans et al., 2010). However no evidence for this was was found during this study. The Gronau Fault Zone and Boekelo Fault Zone do not connect at depth. They have in fact more or less the same dip angle, and do not have a decollement. Although the Zechstein salt does prohibit the interpretation of faults and strata at deeper levels. It is far more likely that they originated as two parallel fault systems, affected by the stress regimes throughout time.

Most faults in the study area rather steep to sub-vertical. The sub-vertical nature of faults might suggest a large horizontal component to the movement along the fault. From literature it is known that both the Boekelo Fault Zone and the Gronau Fault Zone have been active during several tectonic phases since the Carboniferous and that the fault zones display a dextral sense of shear (NITG-TNO, 1998; Duin et al., 2006; Wong et al., 2007; GEOWULFLaboratories, 2008; MWH, 2010; Koopmans et al., 2010). However there is no way of estimating the amount of horizontal displacement (throughout geologic history) without clear markers.

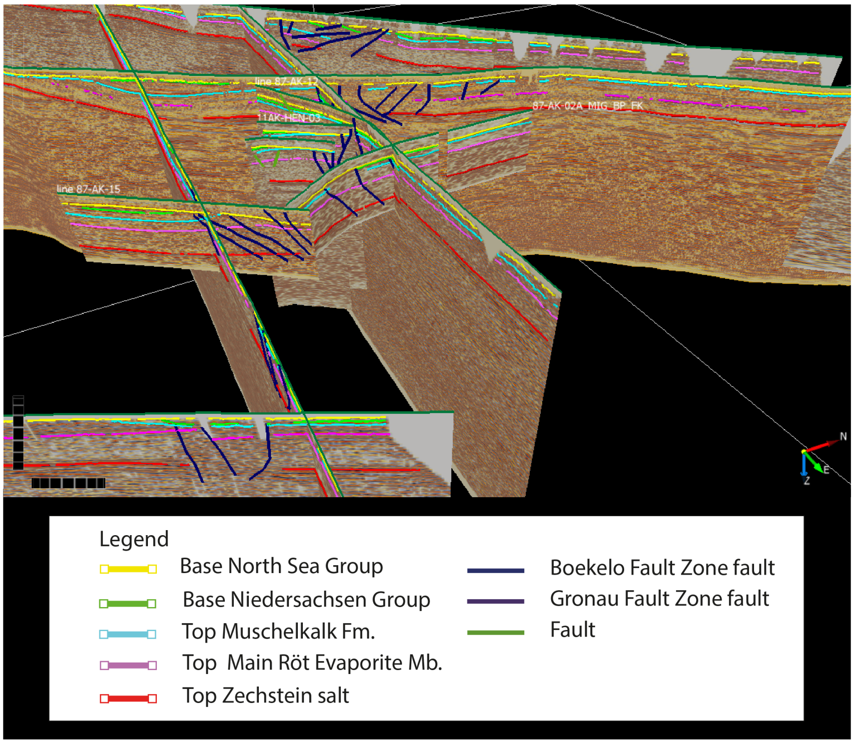


Figure 17: The faults of the Boekelo Fault Zone . Most faults in the Boekelo Fault Zone dip towards the North-east, in line 706012 (last line, in the background) prominent southwest dipping faults have been observed.

Notably is the change in general dip of the faults from the Boekelo Fault Zone in seismic line 706012. As is visible in Figure 17 the majority of the faults in lines 706012 dip towards the south-west. Coincidentally is this the same location where the Boekelo Fault Zone changes in strike, from NW-SE to more E-W. The change in dip might be a result of (change in) local stress regime. To properly draw conclusions more than 1 seismic line in the western part of the Boekelo Fault Zone should be analysed. Line 706048 (located between 85-EN(V)-08 and 706012) was interpreted by MWH (2010). A rather symmetrical fault zone was interpreted at that location. Line 7056, located west of Delden, might give some more useful insights. Unfortunately line 7056 is not available in this study. MWH (2010) proposed that an underlying reason for the volatility or local differences of the Boekelo Fault Zone might be the thickness difference in the Zechstein salt below, as a result of halokinesis. The differential displacement along the Boekelo Fault Zone could also be explained as an effect of its surroundings. When looking at structural units map from GEOWULFLaboratories (2017), it can be seen that the "centre" of the Boekelo Fault Zone is roughly surrounded by structural highs, while the Eastern and Western parts are enclosed by structural lows Figure 18.

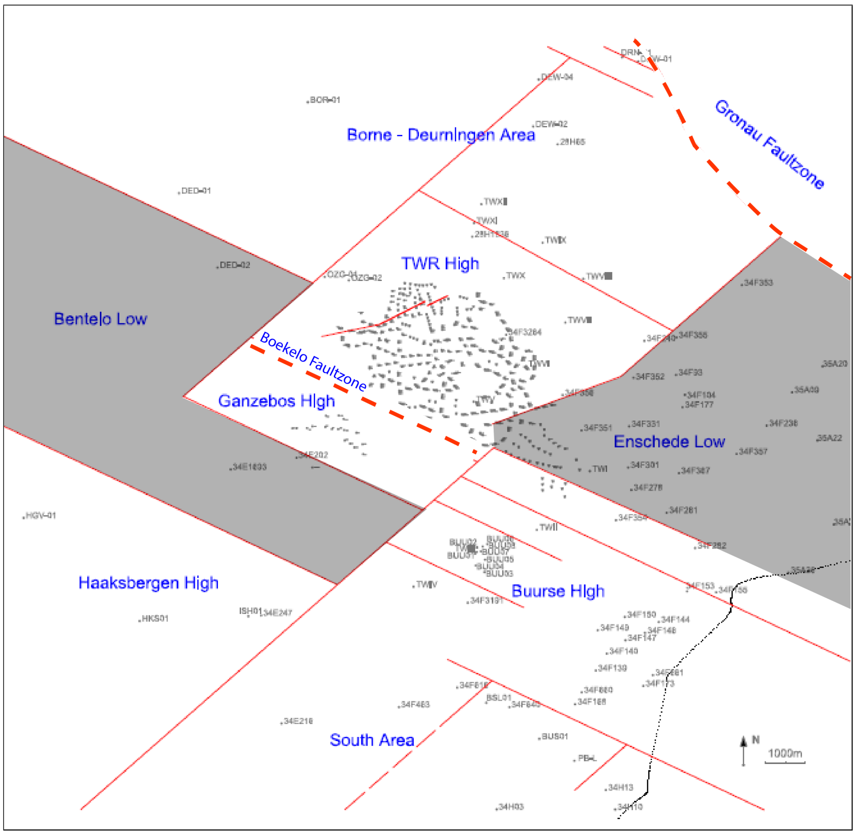


Figure 18: Map of structural elements in the Twenthe-Rijn concession , modified after GEOWULFLaboratories (2017). Note that the location of the Boekelo Fault Zone in this map was based on well data alone.

5 Conclusion

In this study the correlation between different scales is important. Data has been acquired on a very local scale (vertical well data), on a local level (correlation panels across the Twenthe-Rijn concession) and a regional level (seismic data of SE Twente).These three levels of study have provided some insight in the characteristics of the Niedersachsen and Altena group deposits throughout the South-East of Twente.

The characteristics of the overburden are important in the determination of the inherently safe height of the salt caverns, as well as important for method of abandonment. Thickness and strength of the different geological units are the two most important characteristics. The shallowing of the stratigraphy towards the east, and local lows directly affect the thickness of the overburden. The current strength measurement of 15 MPa is very unlikely representative for the Jurassic and Lower Cretaceous sediments. Therefore strength proxy measurements are recommended such as sonic logging or porosity (log) measurements. The strength of the Niedersachsen and Altena groups are probably closer to the strength of limestone. In that case the determined safe height for the caverns is reliable.

The lithology of a geological unit plays a large role in it's strength. The Niedersachsen group consist of grey calcareous claystones. The carbonate content varies greatly with depth, limestone and more marly beds alternate. Shell beds and more clastic intervals are present as well but are more localised features. It can be difficult to distinguish the Altena and Niedersachsen deposits in the study area sometimes. Altena deposits can be medium to dark grey. The claystones of the Altena group are generally less calcareous in comparison to the Niedersachsen deposits. Altena sediments can also contain fossils but are often mineralised and/or more isolated, a singular fossil or shell bed as opposed to an interval of shell beds. Pyrite is frequently present. The Altena group is laterally very homogeneous across North-West Europe. The Niedersachsen group is not, not even on the scale of the Twenthe-Rijn concession .

Within the study area Niedersachsen and Altena deposit are only present in local lows. Both groups are abundantly present in the Lower Saxony basin (on the NE of the Gronau Fault Zone). The minimum depth of the Lower Cretaceous deposits within the Twenthe-Rijn concession is 57.1 m below the surface. The thickness of the deposits are between 2.9 - 158.2 m (SK) and 1.2 - 210.7 m (AT). Small local faults can have a large impact on the preserved thickness of these sediments.

The characteristics mentioned above are a result of the depositional environment and tectonics. Both the Boekelo Fault Zone and the Gronau Fault Zone have been a major influence on the regional stratigraphy including the Jurassic and Cretaceous geology (Niedersachsen and Altena Group). During the deposition of the Niedersachsen sediments Europe and America started breaking apart to create the Atlantic ocean, giving the Niedersachsen deposits their syn-rift nature. This is also likely to be the reason for its heterogeneic character, as the extension created local depocentres. The Altena group was deposited pre-rift in the large Permo-Triassic basin. The limited appearance (both in area and thickness) of these deposits are a result of the erosion that followed the Cretaceous (Sub-Hercynian) inversion.

Acknowledgements

First and foremost I would like to thank everyone directly and indirectly involved in this project for their patience. Patience from supervisors during my struggles of getting familiar with the software involved. Patience and support from family while working from home during the quarantine. I wish to express my gratitude towards my supervisor at Nouryon, Els Wijermars and to Marinus den Hartogh, Tjeerd Koopmans and to Liviu Matenco (from Utrecht University) for their remarks and constructive criticism on this report. As well as to Jeroen Smit, my supervisor at Utrecht University, for the guidance, encouragement and advice he has provided throughout this project. I would like to thank Andrzej Slupik for his help and hospitality at the TNO core storage, and Alice Post from NAM for providing part of the seismic data.

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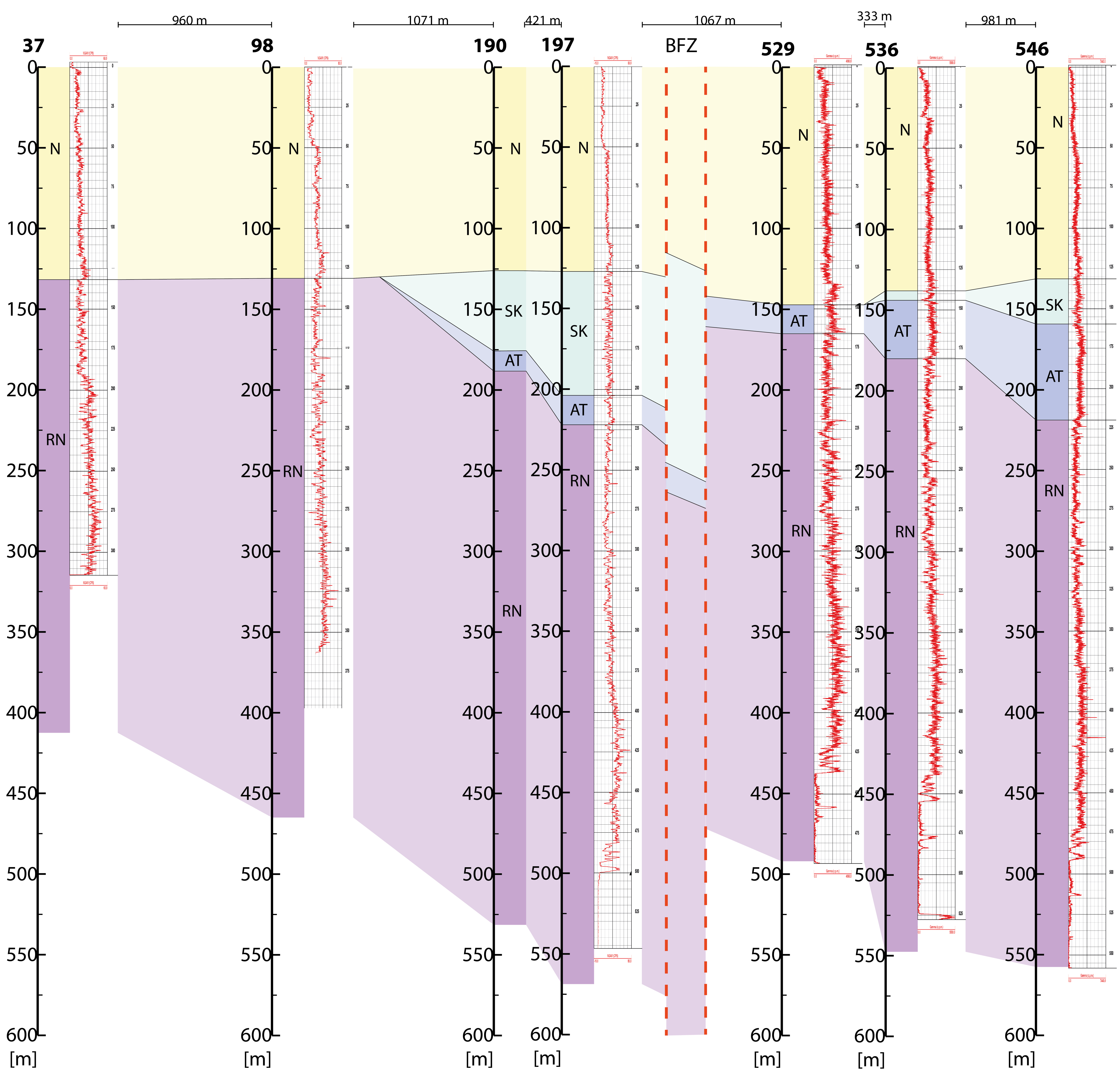
Appendices

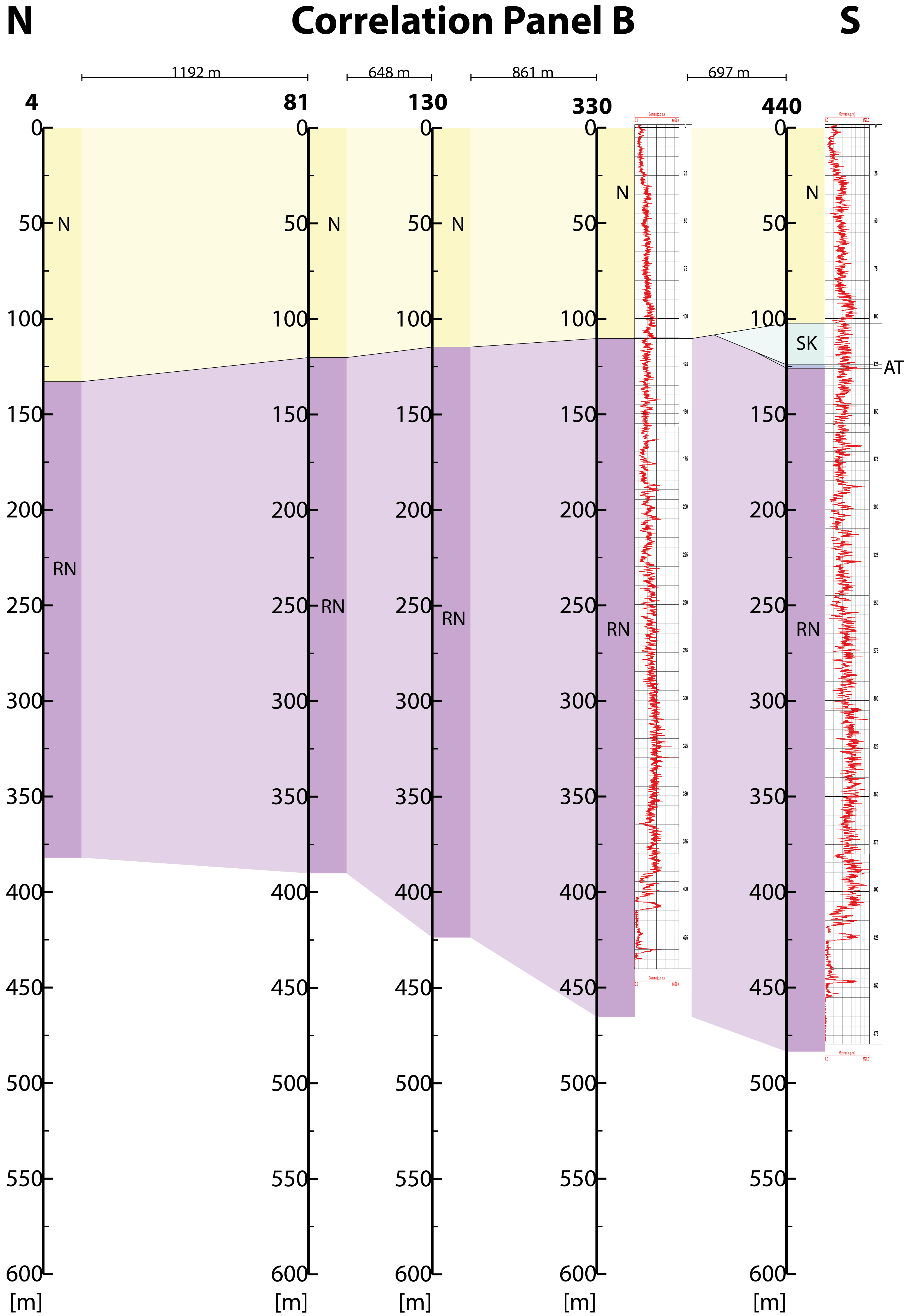
A Correlation Panels

Correlation panels A to F, for location see Figure 7. **Note:** All geological groups are separated by hiatus.

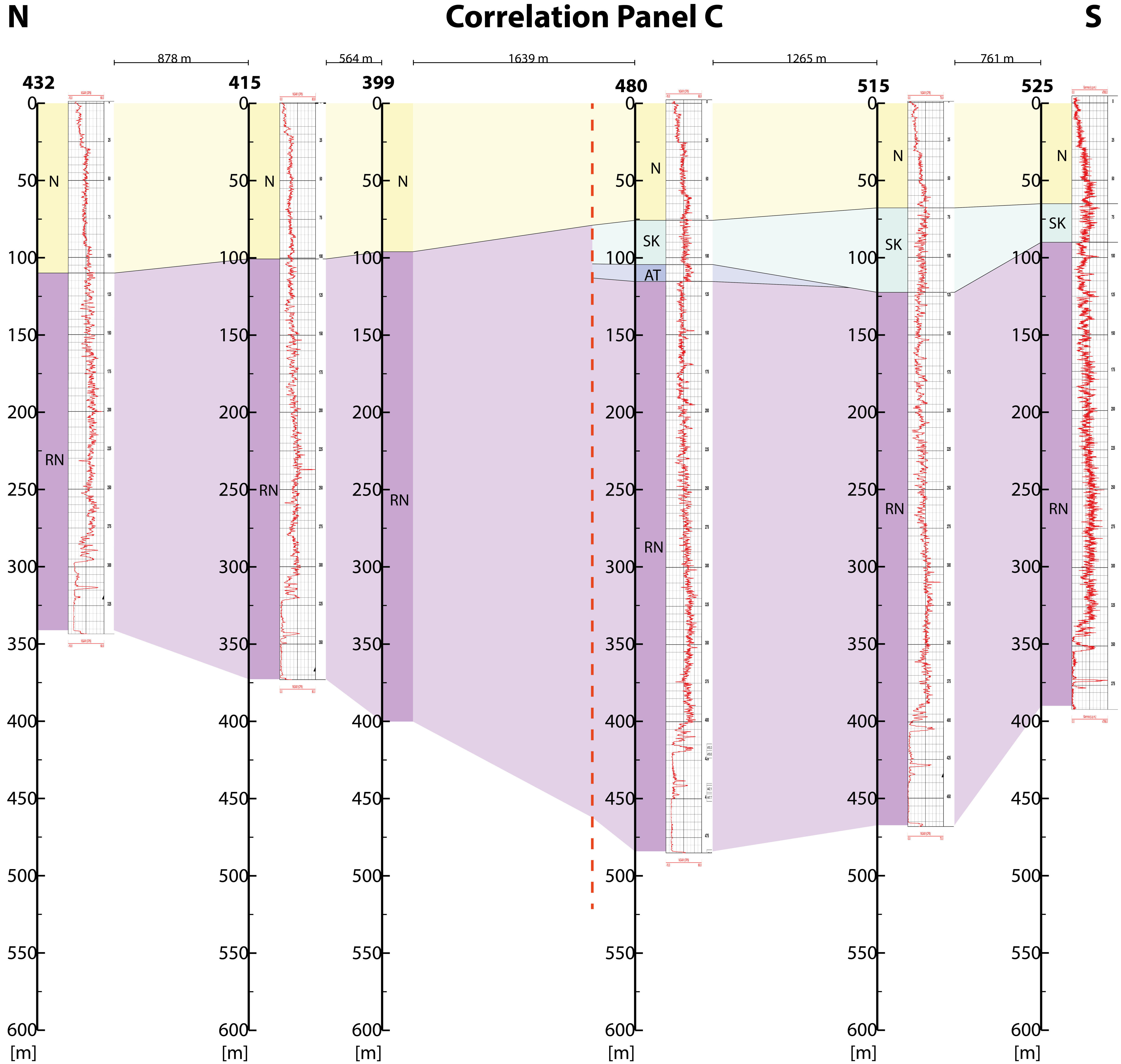
Correlation Panel A



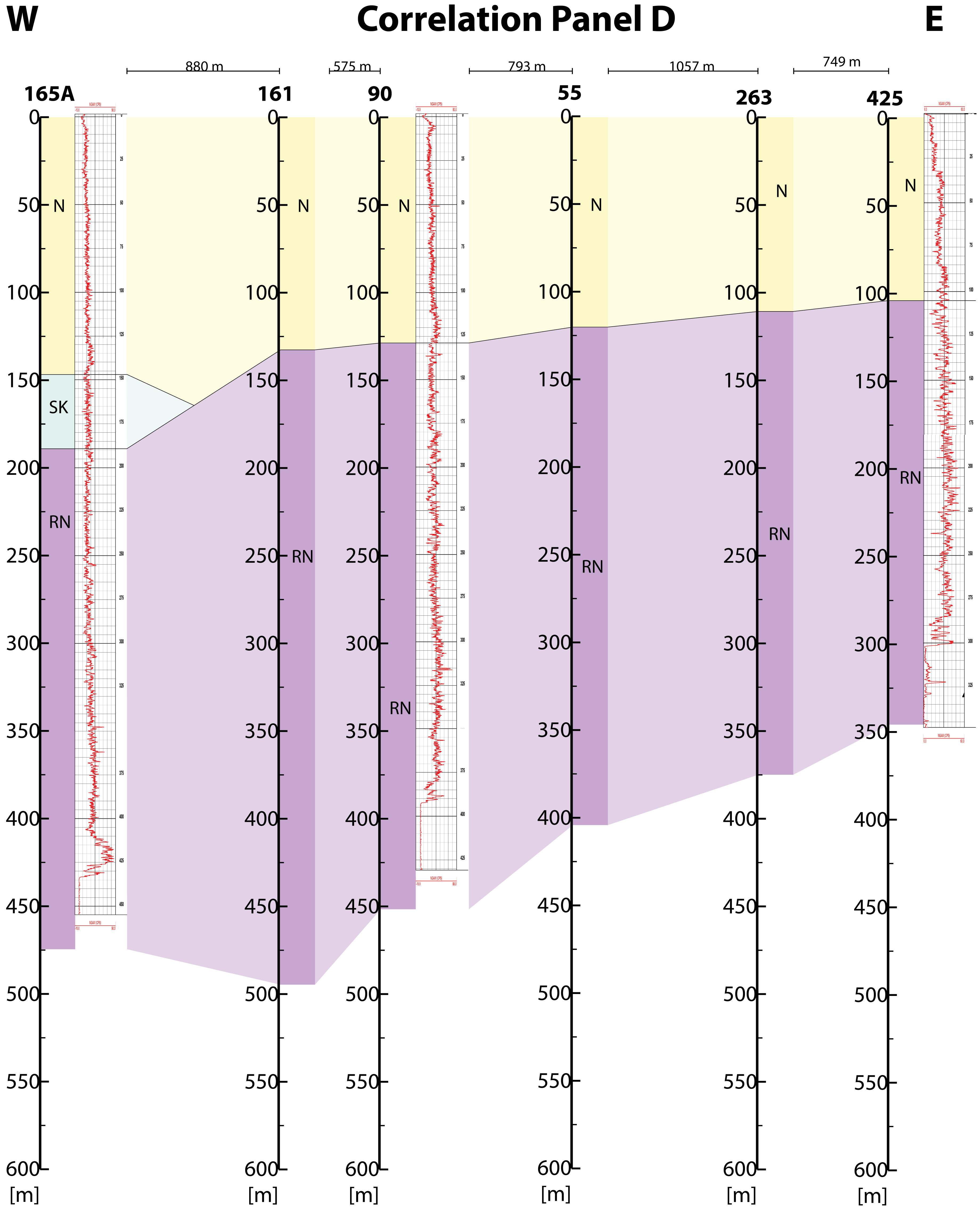
Correlation Panel B



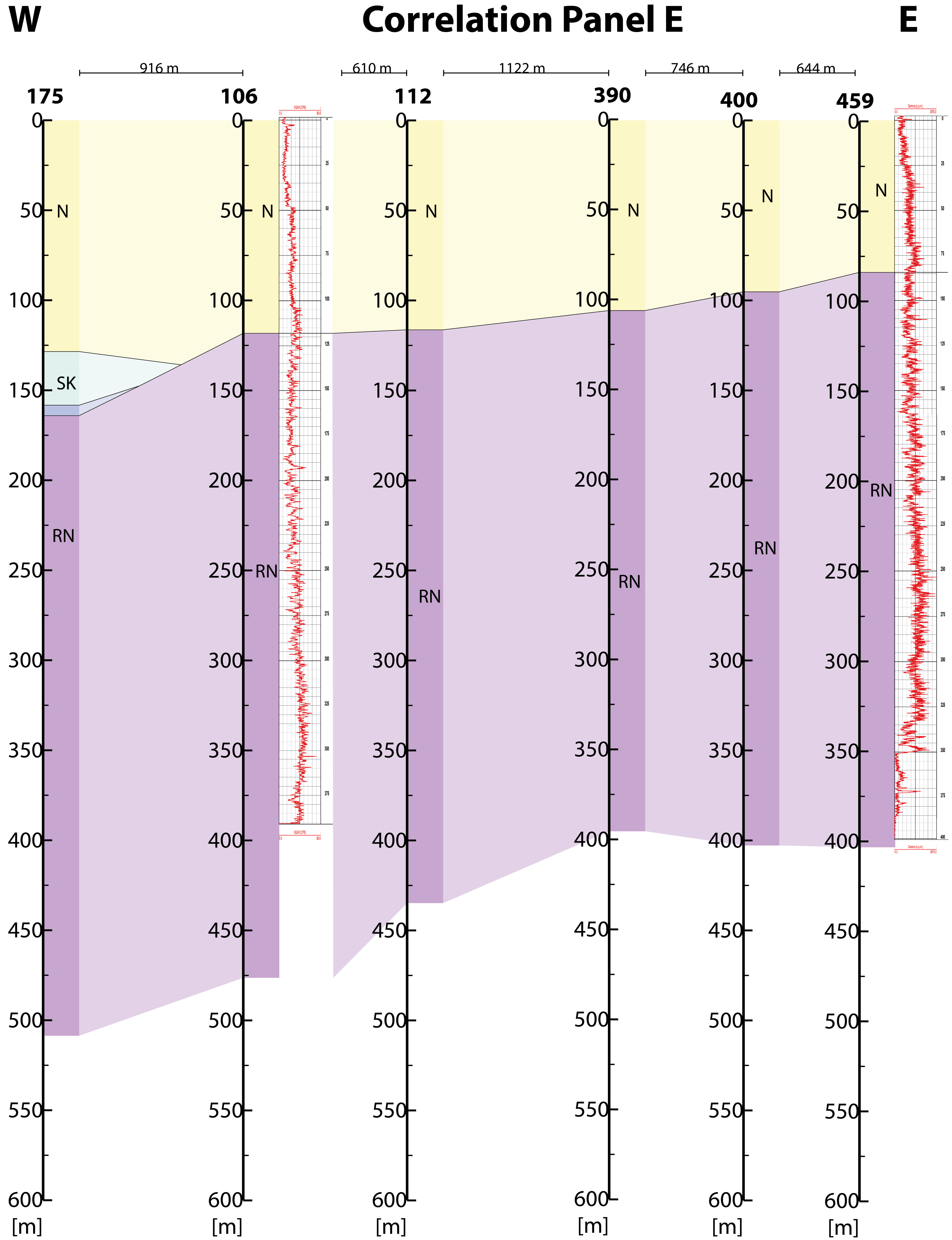
Correlation Panel C



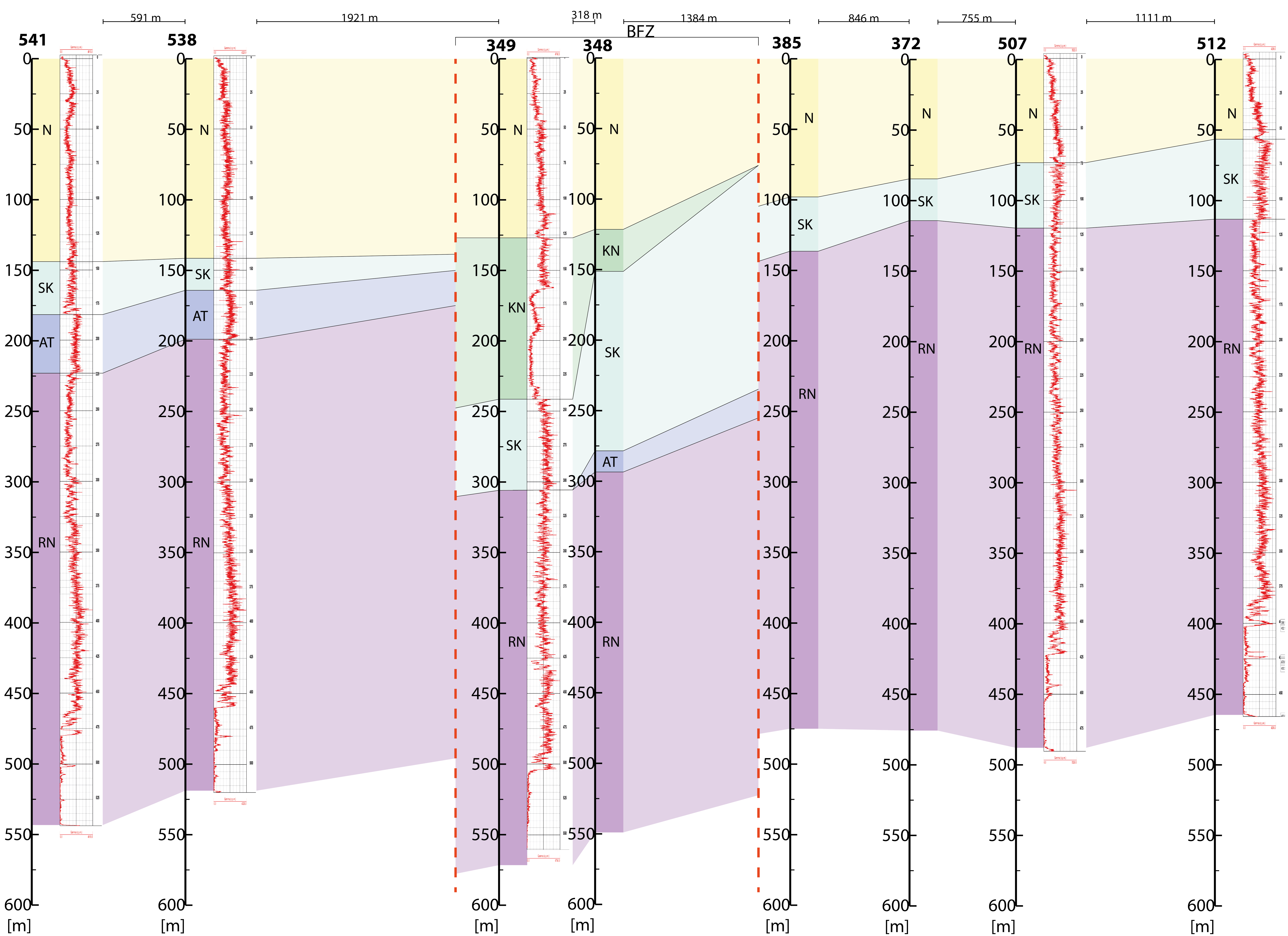
Correlation Panel D



Correlation Panel E



Correlation Panel F



B Core description reports

B.1 TWR-141

Mining Development & Compliance

Nouryon

Core description of well TWR-141

Macroscopic description of core material

November 5, 2019
Tineke Kok

Contents

1. Introduction

The core material of well TWR-141 was cored on 17th of February 1968. The cored interval ranges from 125 m below ground level (bgl) until 141.4 m below ground level. Ground level is 21.48m above NAP at the location of well TWR-141. The core material of this well is (for the most part) severely fractured. There is no documentation on the interval per box.

2. Summary

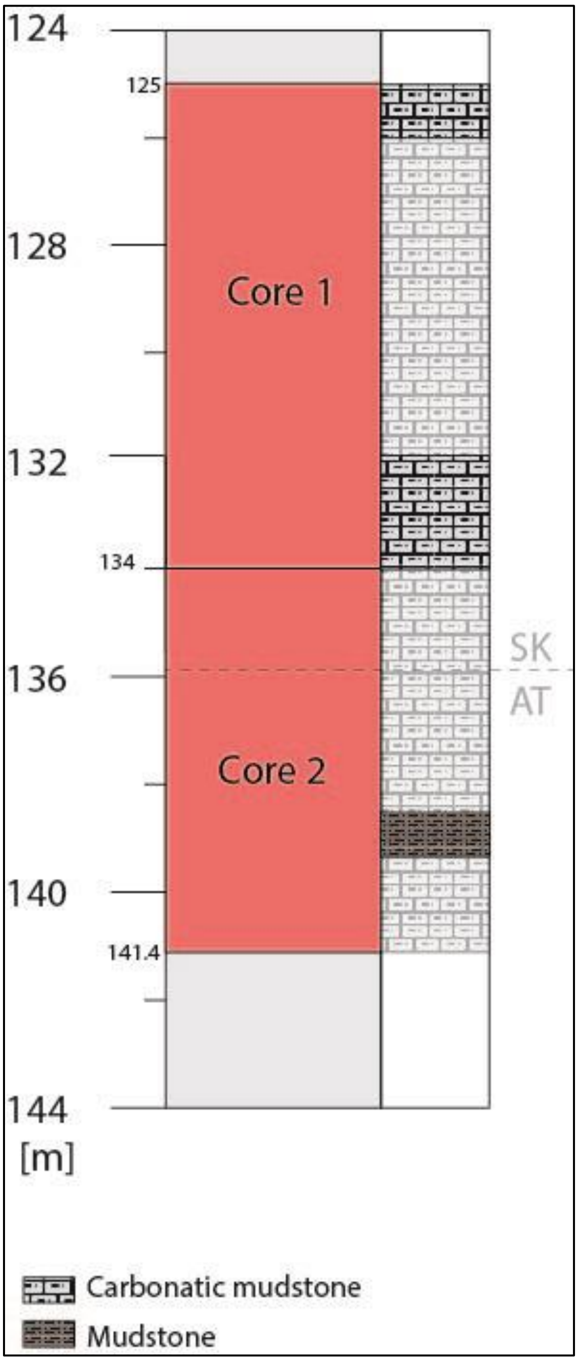


Figure: Visual summary of the cored material. Note that the lithological boundaries depicted are estimates since the exact depths per box are undocumented. Therefore, the lithological boundaries are not labeled. Indicated in grey is the boundary between Niedersachsen (SK) and Altena (AT) group in neighboring well TWR-140.

The majority of the observed core material of TWR-141 is a faintly laminated to massive medium grey claystone with varying carbonate content. In box 4 of core 2 an interval of dark grey claystone without carbonates is recognised.

3. Core 1

Date: 17-02-1968 **Core interval** **Top [bgl]: 125.00m** **Bottom [bgl]: 134.00m**

Table 1: Core data on core 1. Boxes indicated in black have been studied. The exact intervals of core material in the boxes is undocumented.

Box	Barcode core storage	Top [bgl]	Bottom [bgl]
1	0.050.311	125.00 m	*undocumented*
2	0.050.307	*undocumented*	*undocumented*
3	0.050.310	*undocumented*	*undocumented*
4	0.050.308	*undocumented*	*undocumented*
5	0.050.309	*undocumented*	*undocumented*
6	0.050.318	*undocumented*	*undocumented*
7	0.050.319	*undocumented*	*undocumented*
8	0.050.317	*undocumented*	*undocumented*
9	0.050.315	*undocumented*	*undocumented*
10	0.050.313	*undocumented*	134.00 m

3.1. Core description

Box	Top [bgl]	Bottom [bgl]	
1	125.00 m	*undocumented*	Faintly laminated to massive light to medium grey calcareous claystone. no fossils observed.
9	*undocumented*	*undocumented*	Medium grey massive soft claystone. no fossils observed.
10	*undocumented*	134.00 m	Medium grey massive claystone.

The three boxes with the least fractured material from the cored interval were selected. The investigated cores are rather homogenous with depth, however the carbonate content will vary.

3.2. Core photos

Figure 1 Core 1 box 1

Figure 2 Core 1 box 9

Figure 3 Core 1 box 10

4. Core 2

Date: 17-02-1968 **Core interval** **Top [bgl]: 134.00m** **Bottom [bgl]: 141.40m**

Table 2: Core data on core 2 Boxes indicated in black have been studied. The exact intervals of core material in the boxes is undocumented.

Box	Barcode core storage	Top [bgl]	Bottom [bgl]
1	0.050.314	134.00 m	*undocumented*
2	0.050.316	*undocumented*	*undocumented*
3	0.050.325	*undocumented*	*undocumented*
4	0.050.326	*undocumented*	*undocumented*
5	0.050.321	*undocumented*	*141.40 m*

4.1. Core description

Box	Top [bgl]	Bottom [bgl]	
4	*undocumented*	*undocumented*	Very fractured material. Top: Soft grey laminated calcareous claystone. Medium grey and light grey laminae, see figure 5. Bottom: Dark hard claystone with shale like texture (figure 6)

The box with the least fractured content was selected.

4.2. Core photos

Figure 4 Core 2 box 4

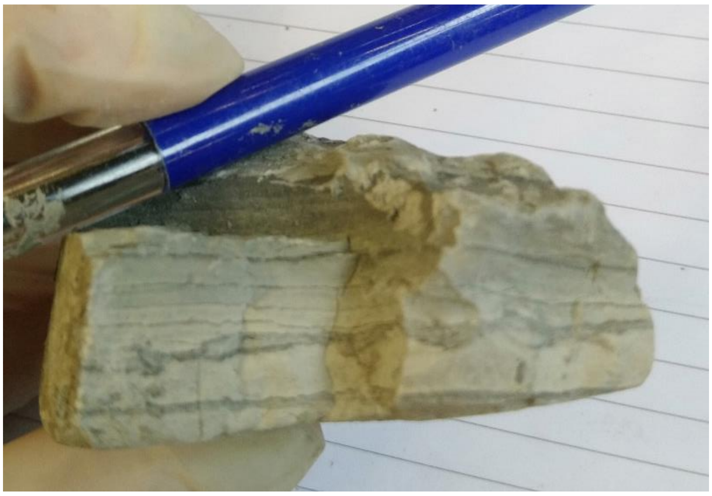


Figure 5 Core 2 box 4 light and medium grey laminae.

Figure 6 Core 2 box 4 dark claystone.

Nouryon

B.2 TWR-171

Mining Development & Compliance

Nouryon

Core description of well TWR-171

Macroscopic description of core material

November 8, 2019
Tineke Kok

Contents

1. Introduction

The core material of well TWR-171 was cored on 22nd of August 1969. The cored interval ranges from 119 m below ground level (bgl) until 141.4 m below ground level. Ground level is 22.48m above NAP at the location of well TWR-171. There is no documentation on the interval per box.

2. Summary

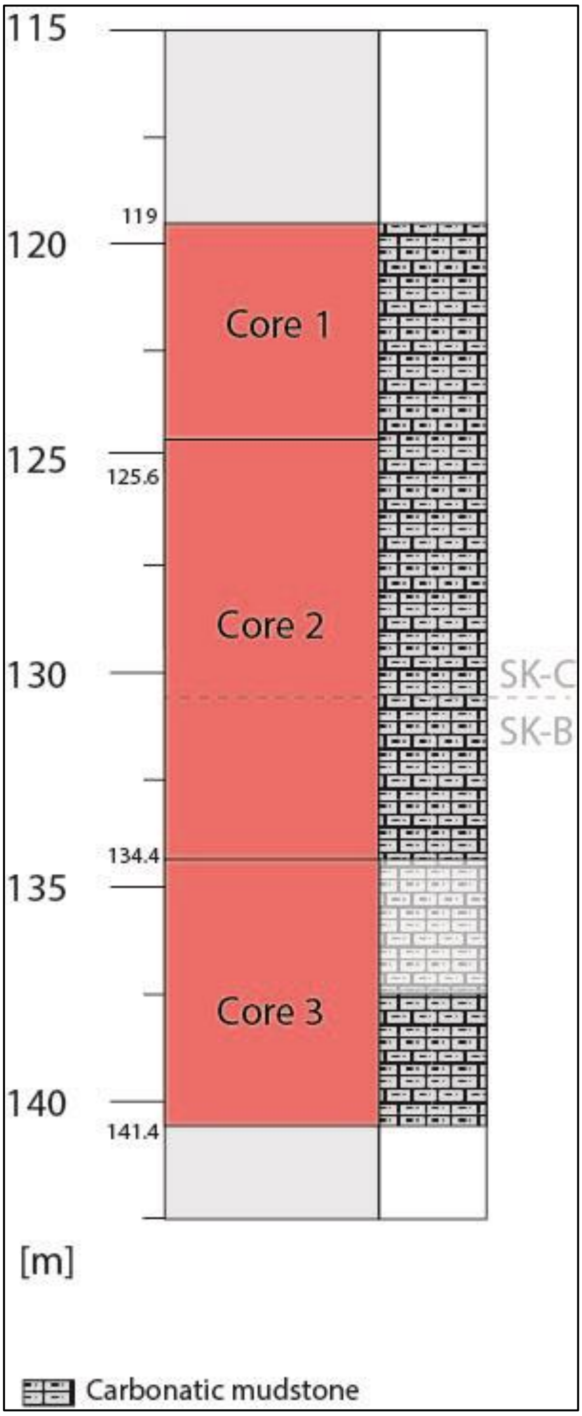


Figure: Visual summary of the cored material. Note that the lithological boundaries depicted are estimates since the exact depths per box are undocumented. Therefore, the lithological boundaries are not labeled. Indicated in grey is the boundary between SK-C and SK-B as interpreted by Geowulf.

Medium grey faintly laminated claystone with varying amounts of calcareous content. Decreasing amounts of fossils and mineralogical deposits with depth. Starting halfway core 2 halite beds start to appear. Therefore, the cored interval is interpreted as the lower part of the Coevorden fm. (note that at the core storage this interval is labelled Weiteveen fm.).

3. Core 1

Date: 22-08-1969 **Core interval** **Top [bgl]: 119m** **Bottom [bgl]: 125.60m**

Table 1: Core data on core 1. Boxes indicated in black have been studied. The exact intervals of core material in the boxes is undocumented.

Box	Barcode core storage	Top [bgl]	Bottom [bgl]
1	0.050.388	119 m	*undocumented*
2	0.050.389	*undocumented*	*undocumented*
3	0.050.389	*undocumented*	*undocumented*
4	0.050.390	*undocumented*	*undocumented*
5	0.050.390	*undocumented*	*undocumented*
6	0.050.391	*undocumented*	*undocumented*
7	0.050.391	*undocumented*	125.60 m

3.1. Core description

Box	Top [bgl]	Bottom [bgl]	
1	119 m	*undocumented*	Planar laminated medium grey rock containing calcareous matter. Top half contains shell beds (as can be seen in figures 8 and 9). Most shells are broken, some shellbeds contain only shell fragments. The shells are thin. Small inclusions have been observed of a few mm's big (figure 10).
2	*undocumented*	*undocumented*	Bottom half of de core interval is blueish grey with a lot of bioclastic material see figure 11. Top half (laminated) medium grey claystone alternated with more calcareous layers. Some molluscs present.
3	*undocumented*	*undocumented*	Medium grey faintly laminated rock. Thin layers of claystone alternating with limestone. Shell beds are present mostly intact mollusc. Figures 12 and 13 give examples of different types of shell beds.
4	*undocumented*	*undocumented*	Top of the box: Medium grey laminated mudstone with shell beds, similar to those in figures 9 and 12. Bottom of the box: Light grey unsupported bioclastic mudstone. Sparse plant fragments, for an example see figure 14. Oil stain observed at ~ 34 cm.
5	*undocumented*	*undocumented*	Laminated light grey to brownish grey claystone (figure 15)
6	*undocumented*	*undocumented*	Light grey laminated clay stone with an oil spot at around 30 cm. From ~44 cm until 60 cm vuggy limestone. Light grey massive claystone with a few bio clasts, mostly molluscs, above that.

7	*undocumented*	125.60 m	Light grey to brownish grey laminated claystone. Bioclastic layer about halfway in the box.

3.2. Core photos

Figure 1 Core 1 box 1

Figure 2 Core 1 box 2

Figure 3 Core 1 box 3

Figure 4 Core 1 box 4

Figure 5 Core 1 box 5

Figure 6 Core 1 box 6

Figure 7 Core 1 box 7

Figure 8 Core 1 box 1 shell beds

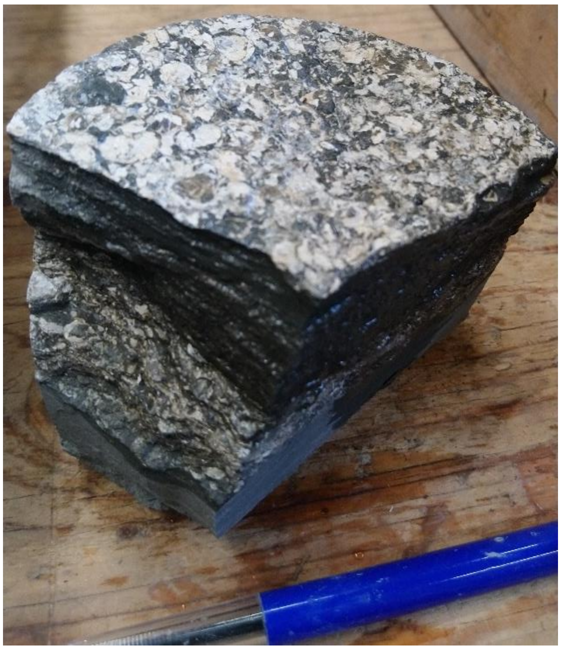


Figure 9 Core 1 box 1 shell beds

Figure 10 Core 1 box 1 inclusions

Figure 11 Core 1 box 2 bioclastic limestone?

Figure 12 Core 1 box 3 an example of a shell bed.

Figure 13 Figure 12 Core 1 box 3 an example of a shell bed.

Figure 14 Core 1 box 4 example of a plant fragment.

Figure 15 Core 1 box 5 light grey and brownish grey laminae.

4. Core 2

Date: 22-08-1969 **Core interval** **Top [bgl]: 125.60m** **Bottom [bgl]: 134.40m**

Table 2: Core data on core 2. Boxes indicated in black have been studied. The exact intervals of core material in the boxes is undocumented.

Box	Barcode core storage	Top [bgl]	Bottom [bgl]
1	0.050.387	125.60 m	*undocumented*
2	0.050.395	*undocumented*	*undocumented*
3	0.050.395	*undocumented*	*undocumented*
4	0.050.398	*undocumented*	*undocumented*
5	0.050.398	*undocumented*	*undocumented*
6	0.050.397	*undocumented*	*undocumented*
7	0.050.397	*undocumented*	*undocumented*
8	0.050.403	*undocumented*	*undocumented*
9	0.050.403	*undocumented*	134.40 m

4.1. Core description

Box	Top [bgl]	Bottom [bgl]	
1	125.60 m	*undocumented*	Light to medium grey laminated calcareous claystone. Some (rusted) shell beds present similar to those depicted in figure 29. Figure 25 shows plant fragments and a compressional deformation structure.
2	*undocumented*	*undocumented*	More brittle interval. Medium grey faintly laminated claystone. Very few shell beds compared to other boxes.
3	*undocumented*	*undocumented*	Medium grey faintly laminated claystone. Very few shell beds compared to other boxes.
4	*undocumented*	*undocumented*	Medium grey faintly laminated claystone. Very few shell beds compared to other boxes.
5	*undocumented*	*undocumented*	Medium grey laminated calcareous claystone with sporadic fossils mainly shells. At the top of the box small interval ~ 5cm with shale like texture with no reaction to HCl. Bioclastic bed at around 15 cm, ~10 cm thick.
6	*undocumented*	*undocumented*	About 20 cm thick: Medium grey laminated calcareous rock. Layered with halite beds of a few mm to 1,5 cm thick (see figure 26). Massive claystone containing biotite. Around halfway in the box a shell bed with intact shells observed. 40 cm thick interval with halite and calcareous rock layered, similar to described above.

7	*undocumented*	*undocumented*	Med grey (faintly) laminated calcareous claystone. some shell beds present (65 cm and 75 cm) the one at 65 cm is severely rusted. A halite layer has been observed.
8	*undocumented*	*undocumented*	Faintly laminated medium grey calcareous rock with biotite (figure 27) and halite. In figure 28 a thick halite bed (2.5 cm) can be seen with mud clasts.
9	*undocumented*	134.40 m	Medium grey laminated calcareous claystone layered with (oxidized) shell beds and halite beds (figure 29).

4.2. Core photos

Figure 16 Core 2 box 1

Figure 17 Core 2 box 2

Figure 18 Core 2 box 3

Figure 19 Core 2 box 4

Figure 20 Core 2 box 5

Figure 21 Core 2 box 6

Figure 22 Core 2 box 7

Figure 23 Core 2 box 8

Figure 24 Core 2 box 9

Figure 25 Core 2 box 1 On top some sort of deformation (compression) structure. Circled in red a plant fragment.

Figure 26 Core 2 box 6 Halite

Figure 27 Core 2 box 8 Biotite

Figure 28 Core 2 box 8 Thick halite bed with mud clasts (indicated in white).

Figure 29 Core 2 box 9 Oxidized shells

5. Core 3

Date: 22-08-1969 **Core interval** **Top [bgl]: 134.40m** **Bottom [bgl]: 141.40m**

Table 3: Core data on core 3. Boxes indicated in black have been studied. The exact intervals of core material in the boxes is undocumented. It is known that the top of the core was retrieved from 134.40m depth.

Box	Barcode core storage	Top [bgl]	Bottom [bgl]
1	0.050.396	*undocumented*	*undocumented*
2	0.050.396	*undocumented*	*undocumented*
1	0.050.400	*undocumented*	*undocumented*
2	0.050.400	*undocumented*	*undocumented*
5	0.050.401	*undocumented*	*undocumented*
6	0.050.401	*undocumented*	*undocumented*
7	0.050.399	*undocumented*	*undocumented*
8	0.050.399	*undocumented*	*undocumented*
9	0.050.402	*undocumented*	*undocumented*
10	0.050.402	*undocumented*	141.40 m

Note that there are two boxes indicated as “box 1” and two boxes indicated as “box 2” the order of these boxes is unknown.

5.1. Core description

Box	Top [bgl]	Bottom [bgl]	
7	*undocumented*	*undocumented*	Medium grey laminated calcareous claystone with halite. No fossils no biotite.
8	*undocumented*	*undocumented*	Medium grey laminated to massive claystone with biotite, layered with halite. No fossils observed.
9	*undocumented*	*undocumented*	Top half: Massive medium grey claystone with some halite. Bottom half: laminated medium grey claystone.
10	*undocumented*	141.40 m	Medium grey calcareous claystone with halite and traces of biotite.

5.2. Core photos

Figure 30 Core 3 box 7

Figure 31 Core 3 box 8

Figure 32 Core 3 box 9

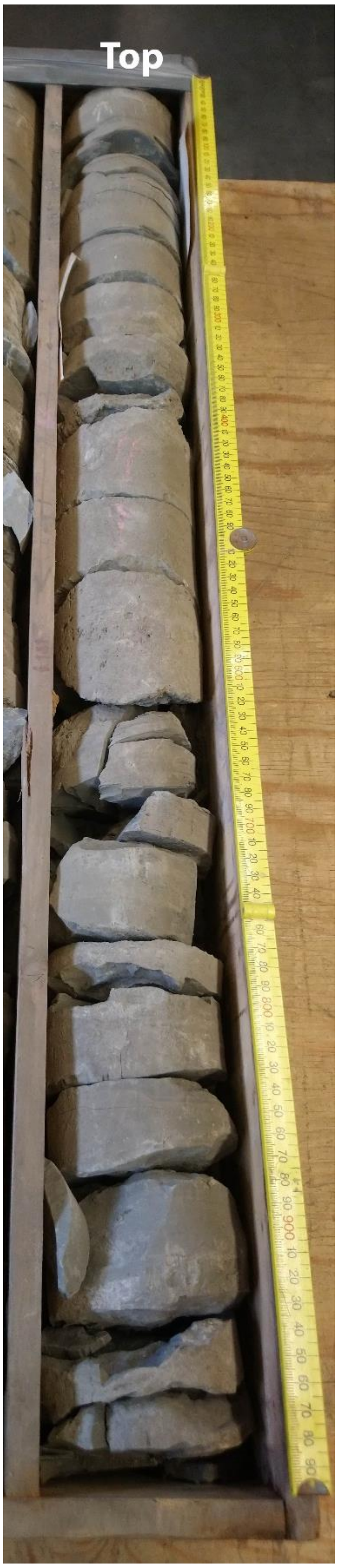


Figure 33 Core 3 box 10

B.3 TWR-285

Mining Development & Compliance

Nouryon

Core description of well TWR-285

Macroscopic description of core material

October 25, 2019
Tineke Kok

Contents

1. Introduction

The core material of well TWR-285 was cored on 15th of December 1977. The cored interval ranges from 92.5 m below ground level (bgl) until 104 m below ground level. Ground level is 28.82m above NAP at the location of well TWR-285.

2. Summary

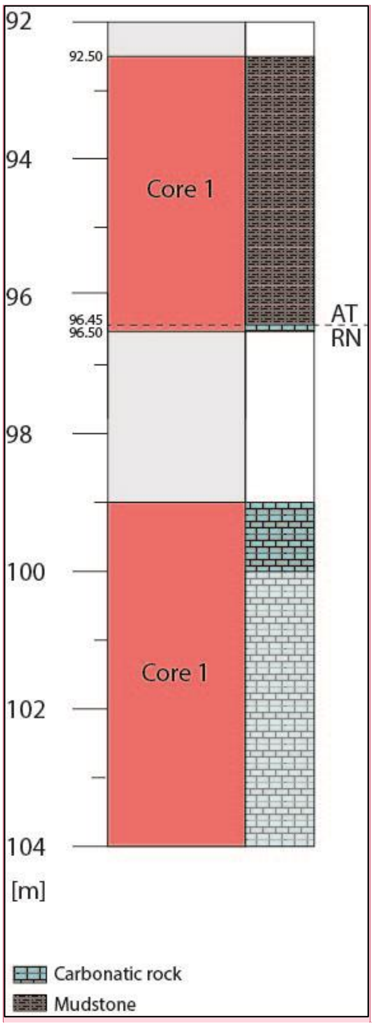


Figure: Visual summary of the cored material.

Commented [KT(1]: Boundary AT/RN in box at 98,95 according to Geowulf (pers. Comm.) however there's no box containing material from that depth.

From 92.50 m until 96.45 m is interpreted as Sleen formation from the Altena group. The Sleen formation consists of a dark grey faintly laminated mudstone with pyrite. Very few molluscs and bivalves present in the formation. In the bottom some biotite was observed.

From 96.45 m until 100.00 (and presumably the 4 remaining boxes, until 104.00 m, as well) are thought to belong to the Upper Muschelkalk member. And according to GeoWulf Laboratories the above-mentioned interval is part of the local stratigraphic unit RNMU-B4. The unit is made up of limestone, it is much lighter in colour and the laminations are more pronounced and irregular (wavy).

3. Core 1

Date: 15-12-1977 **Core interval** **Top [bgl]:** 92.50m **Bottom [bgl]:** 104m

Table 1: Core data on core 1. Boxes indicated in black have been studied.

Box	Barcode core storage	Top [bgl]	Bottom [bgl]
1	0.050.404	92.50 m	93.50 m
2	0.050.405	93.50 m	94.50 m
3	0.050.406	94.50 m	95.50 m
4	0.050.408	95.50 m	96.50 m
5	0.050.409	99.00 m	100.00 m
6	0.050.410	100.00 m	101.00 m
7	0.050.407	101.00 m	102.00 m
8	0.050.412	102.00 m	103.00 m
9	0.050.411	103.00 m	104.00 m

3.1. Core description

Box	Top [bgl]	Bottom [bgl]	
1	92.50 m	93.50 m	Dark grey laminated mudstone. Top 15 cm change in colour to more blueish dark grey. Some pyrite observed. Mud clasts? (see figure 6). Square black mineral present at ~93.28 m. Rhaetian age was determined by palynological analysis (RGD, 12 Jan. 1978, report nr. 2139).
2	93.50 m	94.50 m	Dark grey faintly laminated claystone. Almost massive looking. Pyrite present.
3	94.50 m	95.50 m	Dark grey faintly laminated to massive claystone, containing pyrite. Pyrite fossil observed, some type of mollusc (figure 7). Inclusions (figure 8) at ~95.10 m, green yellowish in colour, oval to triangular shaped, flaky texture and metallic lustre. It is therefore most likely to be minerals or mineralised fossils.
4	95.50 m	96.50 m	Dark grey faintly laminated claystone. With biotite in interval between 96.00 m and 96.45 m. Small bivalve (~0.5 cm wide) at 95.55 m. Bottom 5 cm light grey rock, with wavy lamination. No grains visible. No reaction to HCl on intact rock. Dolomite. Core in box 5 more fractured compared to other boxes.
6	99.00 m	100.00 m	Light grey wavy laminated rock. Reacts with HCl. Limestone.

From 92.50 m until 96.45 m is interpreted as Sleen formation from the Altena group.
From 96.45 m until 100.00 (and presumably the 4 remaining boxes, until 104.00 m, as well) are thought to belong to the Upper Muschelkalk member. And according to GeoWulf Laboratories the above-mentioned interval is part of the local stratigraphic unit RNMU-B4.

3.2. Core photos

Figure 1 Core 1 box 1. Note the ruler is upside down

Figure 2 Core 1 box 2

Figure 3 Core 1 box 3

Figure 4 Core 1 box 5

Figure 5 Core 1 box 6

Figure 6 Core 1 box 1 Mud clasts? At ~92.88 m depth. Pen for scale.

Figure 7 Core 1 box 3. Pyrite fossil at 95,31 m.

Figure 8 Core 1 box 3 at 95,10 m depth. Inclusions, possibly mineralized fossils.

Core description of well TWR-285

B.4 TWR-558

Mining Development & Compliance

Nouryon

Core description of well TWR-558

Macroscopic description of
Niedersachsen and Altena group cores

October 9, 2019
Tineke Kok

Contents

1. Introduction

The preserved thickness of the Niedersachsen group (SK) and the Altena group (AT) increases south of the Boekelo fault zone (BFZ), in the Ganzebos area (Geowulf Laboratories, 2016). In relation to the determination of the inherently safe cavern height, and future abandonments, more information is desired about the geomechanical properties of these groups. Geomechanical properties could include, strength, density and permeability of the formations. Material of the Niedersachsen and Altena groups is therefore cored, with the drilling of a new well (TWR-558).

The expected depths and thicknesses of the Niedersachsen group and the Altena group are based on Geowulf Laboratories (2018). The possibility of deviations in the expected depths and thicknesses, must be considered.

Table 1: Expected depth and thickness at the location of well TWR-558

Top SK	148m
Bottom SK	186m
Thickness SK	38m
Top AT	186m
Bottom AT	206m
Thickness AT	20m

This report is based on macroscopic observations of freshly unearthed and uncut cores. The depths indicated in the descriptions are in meters below ground level (bgl). Ground level at the location of well TWR-558 is 21.18 m above NAP.

2. Summary

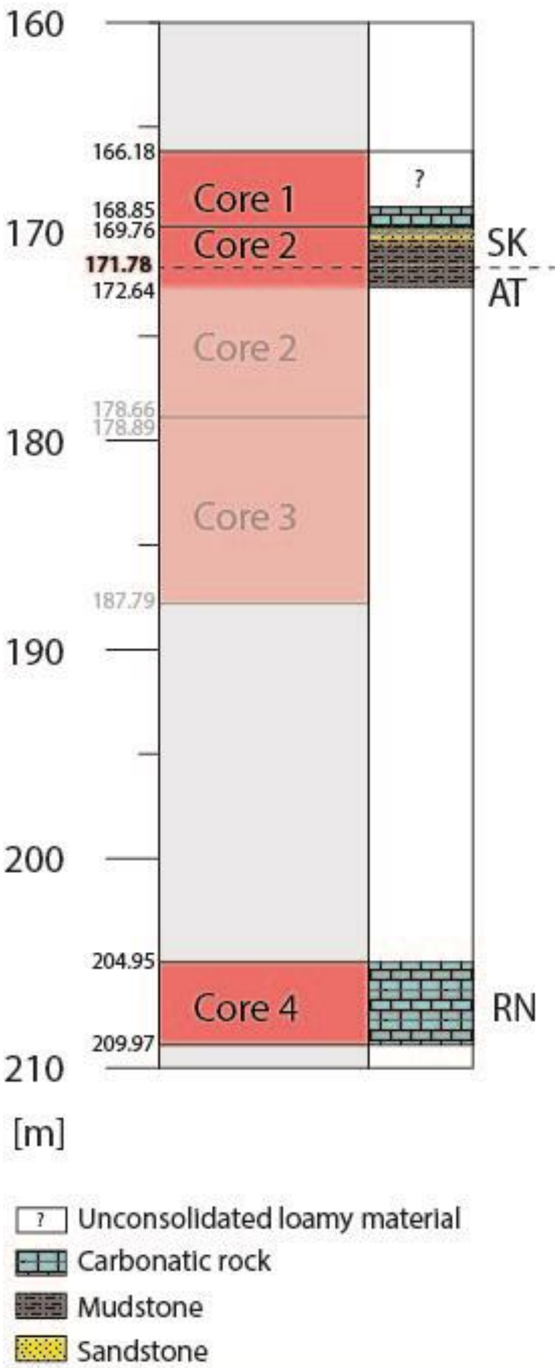


Figure 1: Overview of the cored trajectory and lithological boundaries in meters relative to ground level. Core material of core 3 was lost while retrieving the core from the subsurface. The depth of the Niedersachsen-Altena group boundary is indicated. The boundary between Altena and Muschelkalk (AT-RN boundary) lies somewhere between core 3 and 4.

Figure 1 summarizes the cored trajectories and the observed lithologies.

When drilling the cores (in the shallow subsurface) unexpected complications have occurred. As a result, limited core material was retrieved. However, both material from the Niedersachsen group as from the Altena group was acquired, as well as material from the Upper Germanic Triassic group.

The cored trajectory can be subdivided into the following lithological intervals:

- **166.18m – ~168.85m**
  Unconsolidated grey loamy material with a few powdery gypsum clasts.
- **~168.85m – 169.76m**
  Grey colored carbonatic rock, presumably (muddy) limestone. White powdery gypsum clasts are observed.
- **169.76m – 172.64m**
  Grey mudstone/claystone with some sandy layers of a few centimeters thick. It most likely contains some varying amounts of carbonatic material however no HCl tests were performed to confirm this. Biotite crystals have been observed in the top of the interval, pyrite at the lowermost bottom.
- **204.95m – 209.97m**
  The lowermost cored interval is made up of mm scale laminated argillaceous limestone, the laminae are wavy and get thicker with depth. Small (maximum 1 cm) escape structures observed, as well as bioturbation channels.

2.1. General interpretations

Core 1 and core 2
The interval between 166.18 m and 171.78 m is hypothesized to be SK-B, due to the muddy nature of the lime- (and clay-) stones as well as lack of macroscopic bioclasts in the rock. Local unit SK-B consists of the Lower Coevorden member and the Serpulite member.

The lowermost part of core 2 is classified as Altena group by Geowulf Laboratories.

Core 4
The interval of core 4 is interpreted as RNMU, specifically the Lower Muschelkalk member. The laminae represent a slight change in environment, like a change in sediment source or fluctuating sea-level. These small-scale features might encapsulate large amounts of time.

3. Core 1

Date: 12-09-2019 **Core interval** **Top [bgl]:** 166.00m **Bottom [bgl]:** 169.67m **Recovered:** 3.58m

Table 2: Core data on core 1

Box	Top [bgl]	Bottom [bgl]
4	166.18 m	167.15 m
3	167.15 m	168.17 m
2	168.17 m	169.10 m
1	169.10 m	169.76 m

Note: the numbering of the boxes is bottom to top!

No progress was made with the fine core bit "*kernkroon*", after 3.8m.
Including the muddy material at the top of the core, over 3.8 meters has been cored. It is hypothesized that this extra material is cavings "*naval*" mixed with drilling mud "*boorspoeling*". The cored material is stuck to the coring tube, the coring tube was therefore cut into 0.5 m sections. The bottom 3.8 m of the core has been logged. Any extra material above this has been disposed.

3.1. Core description

Box	Top [bgl]	Bottom [bgl]	
4	166.18 m	167.15 m	Grey material with some cohesion. Loam consistency. Very few powdery gypsum clasts present. The light (white) colored specks are plastic grindings from cutting the core tube (see figures 2 and 3).
3	167.15 m	168.17 m	Grey material with some cohesion. Loam consistency (as seen in figure 4). Clasts present about 0.5 cm.
2	168.17 m	169.10 m	Starting around 168.85m: Grey carbonitic rock? presumably limestone. Some clay stones present. Gypsum vein about 0.5 cm thick. Clast of white powdery material most likely gypsum. Box 2 contains a cut coring tube, in which the core material is stuck. Above that: Grey material with some cohesion. Loam consistency. Very few powdery gypsum clasts present. In the soft material a clear distinction can be observed between the smooth outer-rim/ sides of the core, versus the more chaotic (broken?) center of the core. As is visible in figure 5.
1	169.10 m	169.76 m	Grey carbonitic rock? presumably limestone. Some clay stones present (figure 6). Black mineral present might be biotite at approximately 169.70m (see figure 7). Gypsum veins and inclusions (figure 8) about 1 cm thick.

It should be noted that no HCl tests were done to determine the presence of carbonates.

3.2. Core photos

Figure 2: Core 1 box 4. Overview.

Figure 3: Core 1 box 4. Small white specks from cutting the coring tube. Also, in the picture, a white powdery gypsum clast.

Figure 4: Core 1 box 3. Overview

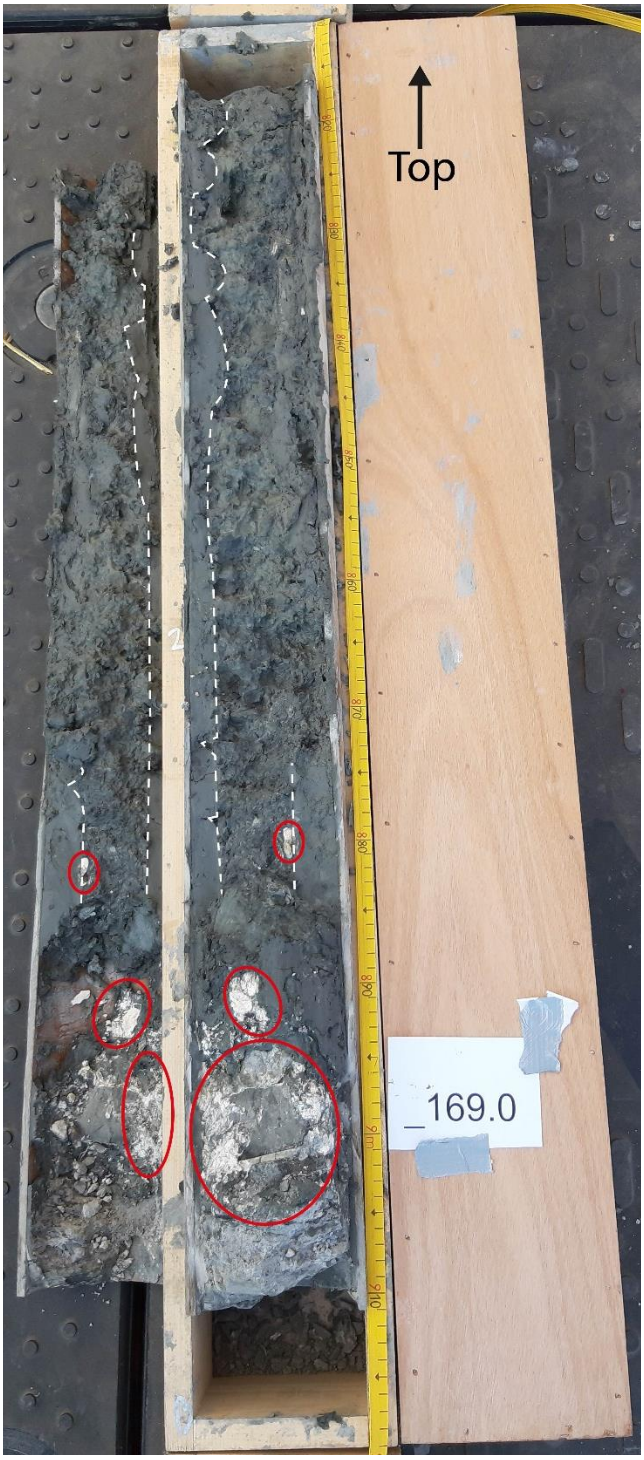


Figure 5: Core 1 box 2. The bottom of the interval is clearly more consolidated compared to the rest of the interval. White dotted lines indicate the boundary between the smooth outer-rim/ sides of the core, versus the more chaotic center of the core. The white powdery gypsum inclusions are marked by a red circle.

Figure 6: Core 1 box 1. Overview.

Figure 7: Core 1 box 1. Black mineral. Pen for scale.

Figure 8: Core 1 box 1: (Gypsum?) inclusions.

4. Core 2

Date: 13-09-2019 **Core interval** **Top [bgl]:** 169.76m **Bottom [bgl]:** 178.66m **Recovered:** 2.88m

Table 3: Core data on core 2

Box	Top [bgl]	Bottom [bgl]
1	169.76m	170.56m
2	170.56m	171.43m
3	171.43m	171.92m
4	171.92m	172.64m

The entire coring tube was filled with material, using the coarse core bit "*kernkroon"*, however only 2.88m was retrieved. It is inferred that this material is the top most ~3m of the cored interval. The bottom ~6m was most likely made up of softer material, which slipped through the smeared catch mechanism "*vange*r". This is in agreement with a remark from the drillers (on Monday 16 September) who noticed that the bottom few meters of the borehole where very soft. Samples were taken from claylike material on the outside of the outer coring tube. The depth (starting from the bottom) on the coring tube has been noted, however this depth is not necessarily the same as the depth of origin in the subsurface.

4.1. Core description

Box	Top [bgl]	Bottom [bgl]	
1	169.76m	170.56m	When dry the rock is light grey. When wet the color changes to dark grey. Sub-mm scale planar laminated mud stone. Some gritty/more coarse intervals of about 10 cm thick. Very few small clasts present maximum 0.5 cm. Sand layer observed at 107.55 m depth about 2 cm thick (see figure 9). Gypsum vein at 107.08 m. Black mineral observed most likely biotite.
2	170.56m	171.43m	Mudstone, when dry the rock is light grey. When wet the color changes to dark grey. The rock has planar lamination on sub-mm scale. Sandy layers at 170.68m 170.80m and 171.18m varying between 1 to 3 cm thick. As can be seen in figure 10.
3	171.43m	171.92m	Grey sub-mm scale planar laminated mudstone. Crack filled with dark muddy material at 171.46m. Sandy interval between 171.50m until 171.69m very fine sand (figure 12). Next sandy interval from 171.75m until 171.79m of poorly sorted fine sand, see figure 11.
4	171.92m	172.64m	Grey sub-mm scale planar laminated mudstone. Pyrite present (figures 13 and 14).

In general, the cored interval gets more clastic with depth. It should be noted however that no HCl tests were done to determine the presence of carbonates.
Core material dried fast and fractured easily perpendicular to the core length.

4.2. Core photos

Figure 9: Core 2 box 1. Overview.

Figure 10: Core 2 box 2. Overview.

Figure 11: Core 2 box 3. Overview.

Figure 12: Core 2 box 3. Example of one of the sandy intervals.

Figure 13: Core 2 box 4. Overview.

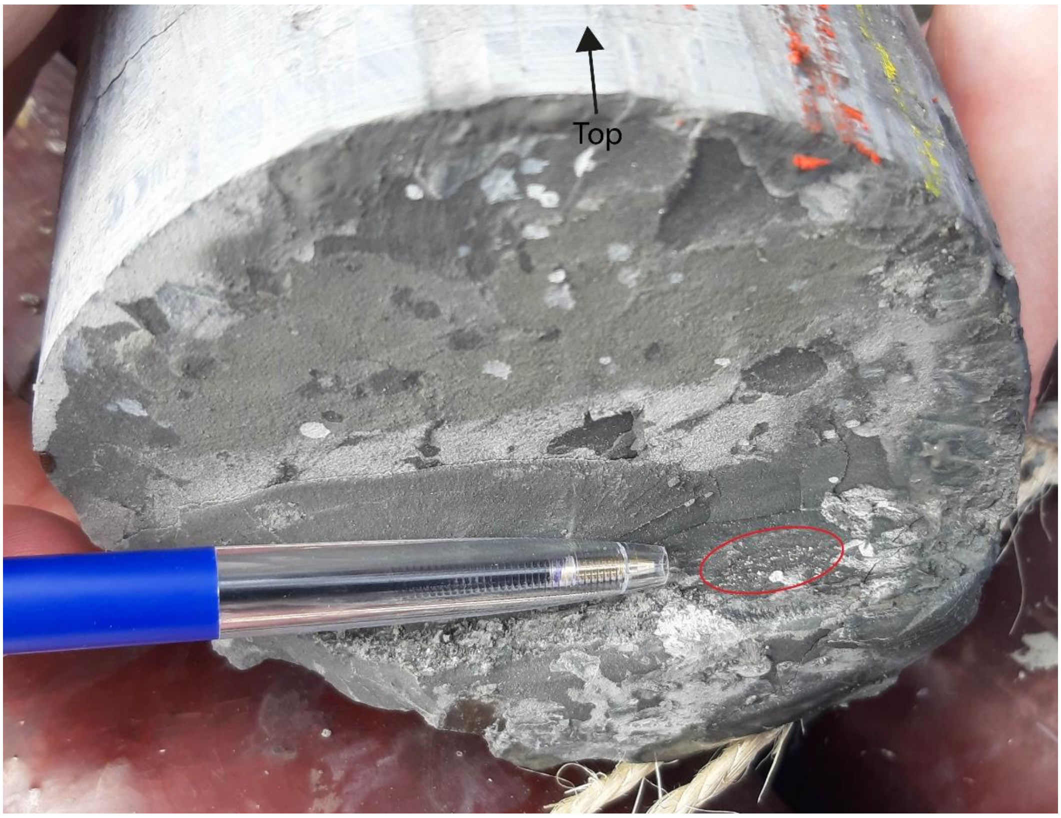


Figure 14: Core 2 box 4. Pyrite crystals on de bottom of core 4. Pen for scale.

5. Core 3

Date: 17-09-2019 **Core interval** **Top [bgl]:** 178.89m **Bottom [bgl]:** 187.79m **Recovered:** 0m

Table 4: Core data on core 3

Box	Top [bgl]	Bottom [bgl]
-	-	-

The coring of core number 3 started at a depth of 178.89m and ended at 187.79m, however the coring tube was completely empty.

For this interval a coarse core bit "*kernkroon"* was used.
There are two theories formulated as to why the tube was empty. Theory 1: the entire interval of the third core consists of soft material, which (just as the bottom of core 2) has slipped through the catch mechanism "*vanger*". The pump pressure during coring was low and the flow averaged around 800 L/min, where 1020 L/min was measured at the previous core. The drillers reported no resistance when pulling up the tubing. Theory 2: the coarse core bit "*kernkroon"* fractured the core material as a result the core wouldn't have been solid and cylindrical, which is why the catch mechanism "*vanger*" couldn't hold the core. During the nightshift it was noted that a lot of material went over the sieve. Fractured material could have traveled up with the drilling mud "*spoeling"*. Samples were again taken from claylike material on the outside of the outer coring tube. The depth (starting from the bottom) on the coring tube has been noted, however this depth is not necessarily the same as the depth of origin in the subsurface.

5.1. Core description

Box	Top [bgl]	Bottom [bgl]	
-	-	-	-

5.2. Core photos

6. Core 4

Date: 18-09-2019 **Core interval** **Top [bgl]: 204.95m** **Bottom [bgl]:209.97m** **Recovered: 3.95m**

Table 5: Core data on core 4

Box	Top [bgl]	Bottom [bgl]
1	204.95m	205.85m
2	205.85m	206.68m
3	206.68m	207.25m
4	207.25m	208.14m
5	208.14m	208.90m

In order to prevent a similar situation as with core 3 (an empty coring tube) a plan was made for coring the next interval. To drill down until harder material was reached and from there start coring again or drill down to 210m and start coring from that depth as that is expected to be the last 11m of the Altena group. The entire interval starting from 187.79m until 208.90m was sampled every 0.5 meters.

Coring started at 204.95m with a fine core bit "*kernkroon*". The first 5 meters of coring where normal flow (1100 L/min) and normal pressure (23 bar). After 5 meter there was a sudden pressure peak of 50 bar. After the peak pressure coring continued with a very low flow of 500 L/min to keep the pressure at 24 bar. But not much progress was made, and it was determined to stop the coring. It was discovered, during the extraction of the coring tube, that the coring pipe was broken at 4m below the top and again further down (see figure 15). It is believed that the coring tube broke as a result of age/weak spot.

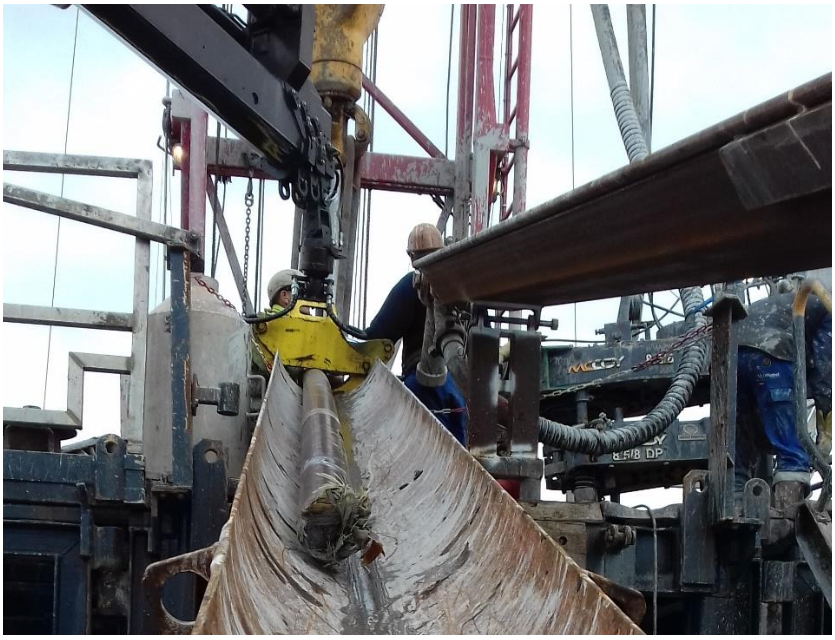


Figure 15: Broken coring tube.

6.1. Core description

Box	Top [bgl]	Bottom [bgl]	
1	204.95m	205.85m	Laminated (mm scale) grey rock. Wavy laminations. No fossils visible with the naked eye (figure 16).
2	205.85m	206.68m	Laminated (mm scale) grey rock. Wavy laminations. No fossils visible with the naked eye. laminations are a little bit thicker in comparison to interval box 1. see figure 17.
3	206.68m	207.25m	Laminated (mm scale) grey rock. Wavy laminations. No fossils visible with the naked eye. (figure 18)
4	207.25m	208.14m	Laminated (mm scale) grey rock. Wavy laminations. No fossils visible with the naked eye. Top of the interval (207.35m – 207.45m) feels slightly coarser (figure 19). Escape structures[1] observed as can be seen in figure 20.
5	208.14m	208.90m	Laminated (tens of mm) grey rock. Wavy laminations. No fossils visible with the naked eye. At 208.35m depth a thick lamina of approx. 1.5 cm thick. Either bioturbation channels or half eroded escape structure[1] observed at 208.83m (see figures 21 and 22).

It should be noted that no HCl tests were done to determine the presence of carbonates. But the grey rock is interpreted as argillaceous limestone or even a marl.
The laminae get thicker with depth starting at a few millimeters thick at the top to about 1 to 1.5 cm at the bottom.
Top part of core deformed during coring. Difficult to determine depth of top and bottom (see figure 16).

[1] Fluid escape structures are sedimentary structures that form during the escape of pore fluids from loose, unconsolidated sediments. Most are postdepositional in origin, but some can form during sedimentation. Deformation may result directly from: (1) pore-fluid movement; (2) current-induced shear; or (3) gravity forces acting on density contrasts within low-strength liquefied sediments. In general, fluid escape structures are most common in rapidly deposited, poorly sorted, fine- to medium-grained sands and less common in more slowly deposited, coarser- and finer-grained sediments (Sylvester and Lowe, 1978).

6.2. Core photos

Figure 16: Core 4 box 1. Overview.

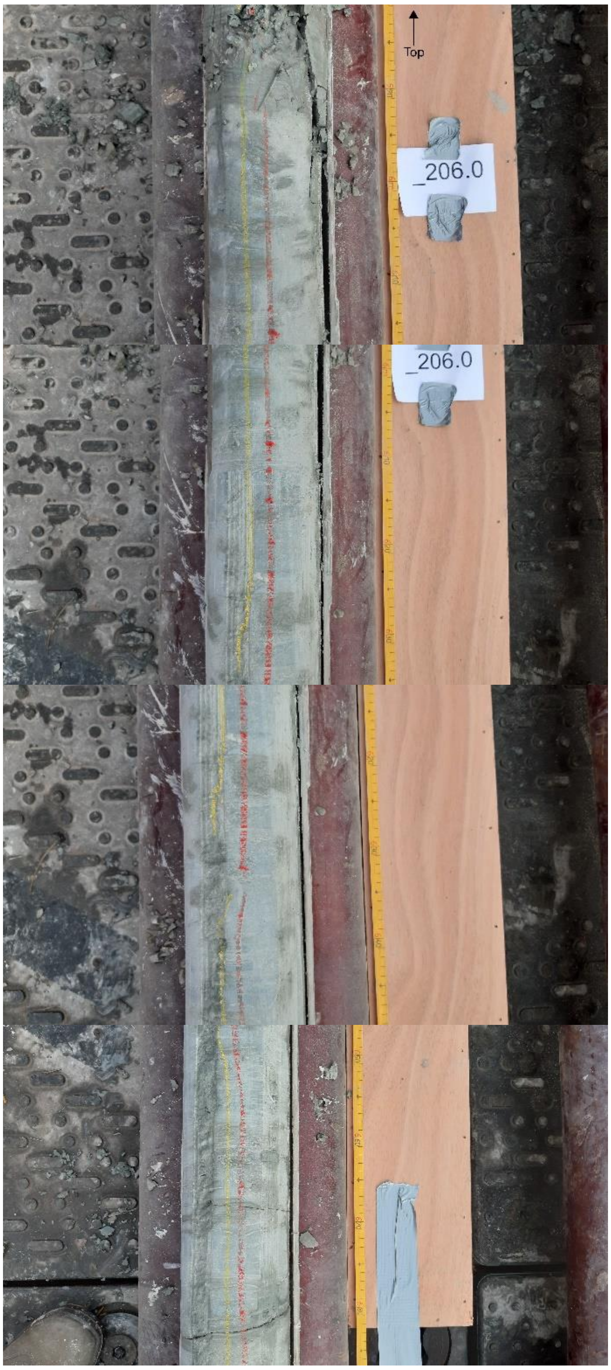


Figure 17: Core 4 box 2. Overview.

Figure 18: Core 4 box 3. Overview.

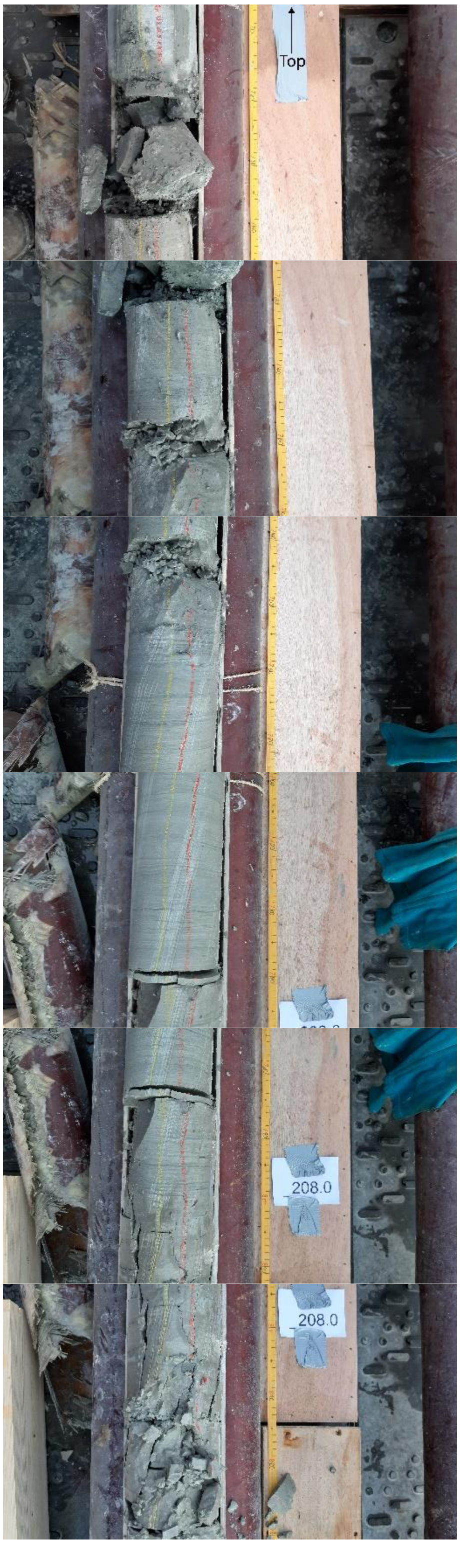


Figure 19: Core 4 box 4

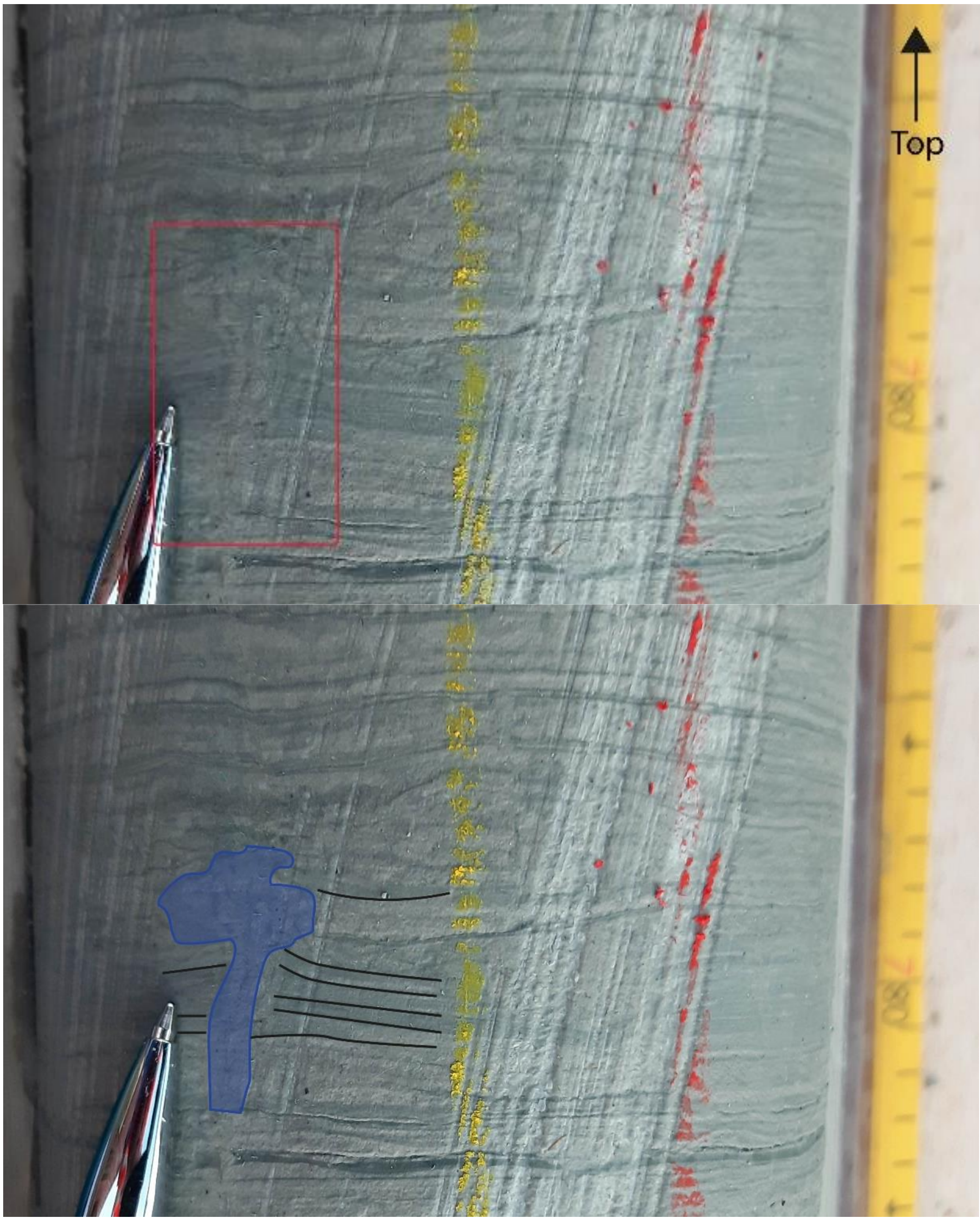


Figure 20: Core 4 box 4. Escape structure around 207.80 m depth. Pen for scale.

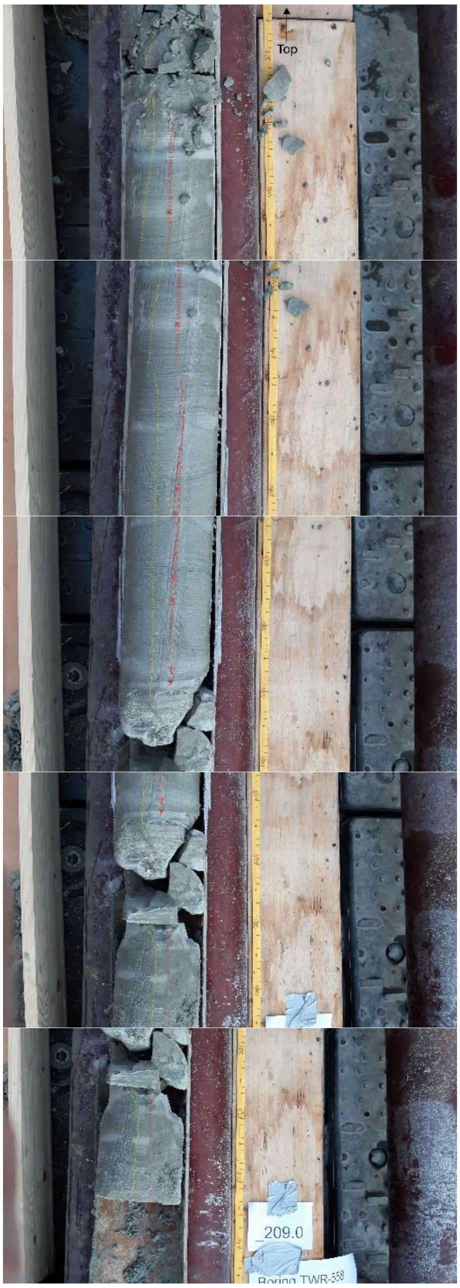


Figure 21: Core 4 box 5. Overview.

Figure 22: Core 4 box 5. Bioturbation structure or escape structure. Pen for scale.

7. References

Geowulf Laboratories. (2016, September). *Detailed Geology of the Ganzebos area Phase 1* (No. GL16.901).

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Sylvester Z., Lowe D.R. (1978) Fluid escape structures. In: Sedimentology. Encyclopedia of Earth Science. Springer, Berlin, Heidelberg

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