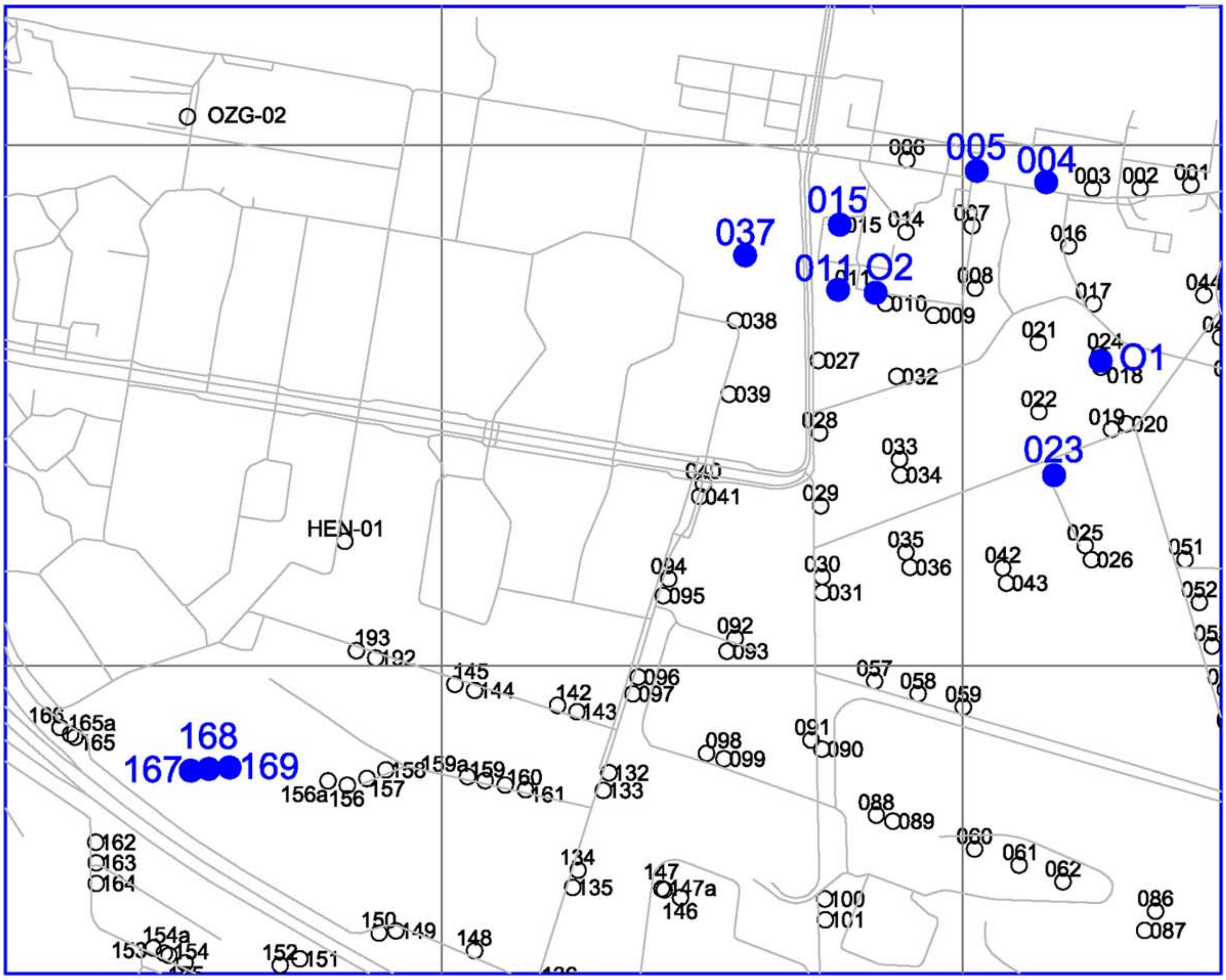
TWR North identification of delamination based on GRlogs



for

Nouryon

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ATTACHMENTS

1. Introduction & Approach

In the northwestern parts of the TWR area significant migration of caverns has taken place. Here a number of wells have been regularly logged from the mid 19sixties and on. Recently a theory has been formed that delamination of sections will occur prior to (further) migration. The theory was based on observations by Nouryon at well B037 (changes between GRlog results between 1979 and 2003) and well B007a (mud losses during drilling but no clear density decrease). This delamination would show on the Gamma Ray logs by a small scale downward movement of boundaries and a thickening of lithological units caused by vertical extension of the layers above a migrating cavern. Further, progressive thickening with depth would be expected. If detailed study of Gamma Ray logs reveals signs of delamination prior to cavern migration, this can be used as a tool for forecasting further migration. Thickening of a certain interval without breaking may lead to earlier than expected ending of the migration process. Once the thickened interval rests upon backfill or on bulked material of broken layers no further migration will occur.

The current study is a pilot study testing the hypothesis that delamination of sections can be deduced from studying Gamma Ray logs through time. This requires an accurate correlation of lithological sections rather than individual Gamma Ray peaks which do not have an identity. The basis for this study are the lithological units defined in earlier studies where necessary complemented with marker beds present within these units.

Data & Approach

Wireline log data for B037, ON1, ON2 and B023 were studied initially. In a later stage wells B004, B005, B011, B015, and the three wells of Series 167 were added to the study (see fig 1.1 for well location). For all wells the 'boorboek' information has been studied and all wireline logs have been incorporated. Whenever more runs are available with the same date, the log with the best quality was selected. Part of the older digitized logs are assumed neutron logs, even though they are named Gamma Ray logs in the header. NGAM in the header appears to be either a Neutron or a Gamma Ray log. No horizontal scale is stated, so it is not known whether the curves are mirrored. Most of these logs have been plotted but they were omitted from the study when the quality appeared doubtful.

The name of the reference log for the stratigraphy is given in **bold** in figures, graphs and data files. The reference log itself is **red** on the Gamma Ray log history panels. Non stratigraphic correlation lines are indicated in **blue** (e.g. casing, markers). The stratigraphy on the reference log originates from the detailed geology of the Hengelo solution mining area, Part 1 (GL10.101). For the summary of the stratigraphy refer to fig 1.2.

The study is based on Gamma Ray logs only. No detail on cavern development and migration was available. Only of Series167 a sonar echo was found in the 'boorboek'. CCL logs and cable tension data have not been included in the analyses.

Wells ON1 and ON2 are drilled in two caverns that had already migrated, the B018 - B024 and B010 - B011 caverns respectively. No wireline logs have been run in the original wells B018, B024, or B010. Only B011, drilled in 1941, has a good set of logs over time starting from 1967.

The Gamma Ray logs are displayed in one panel in chronological order (Attachment A, Gamma Ray history panel). A selected number of boundaries of standard lithological units recognized in earlier studies were indicated on each separate curve. In addition, for some wells a number of conspicuous log markers was added, especially in the deeper parts of the log section. In the study mainly abbreviated lithological names are used (e.g. OU-H for Main Röt Claystone Member unit H). See fig 1.3 for abbreviations and full names.

To better illustrate changes with time, the depths of the markers were plotted on XY graphs (delamination graphs) against time on a linear scale. Thicknesses were calculated to identify trends and to identify differential thickening of units and sections.

The data for the depth of the lithological boundaries and markers are added in an excel format (GL19.401 data.xls). All data refer to the GL/MV datum at the time of logging. This means ground level subsidence has to be added to the reconstructed lithological boundary. Delamination in this study focuses on differential movement below GL/MV.

An attempt is made to incorporate surface subsidence. A coherent historical data set per well is not available and the various 'waterpasmeting' studies and old 'normalisatie' files had to be studied. Within the budgeted time a full study was not possible and the results are tentative (see chapter 4). For several wells a delamination graph corrected for estimated surface subsidence data at the well location is made as well (See chapter 3).

Stretching or shrinking of the logs probably due to varying cable tension does occur and the method can only be used with a relative large data set. For instance, the 1974 Gamma Ray curve of ON1 reads approximately 1m higher compared to the 1967 curve in the upper parts of the Muschelkalk Formation while readings are comparable in the Röt Claystones. Similar effects can be seen in B023. This means that the accuracy is limited when depth figures are used, but the thickness of lithological units should be less affected. On the other hand, differences between tools used and inaccuracies in boundary definition influence the thicknesses of units more than the depth of a particular unit.

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fig 1.1 ; well location

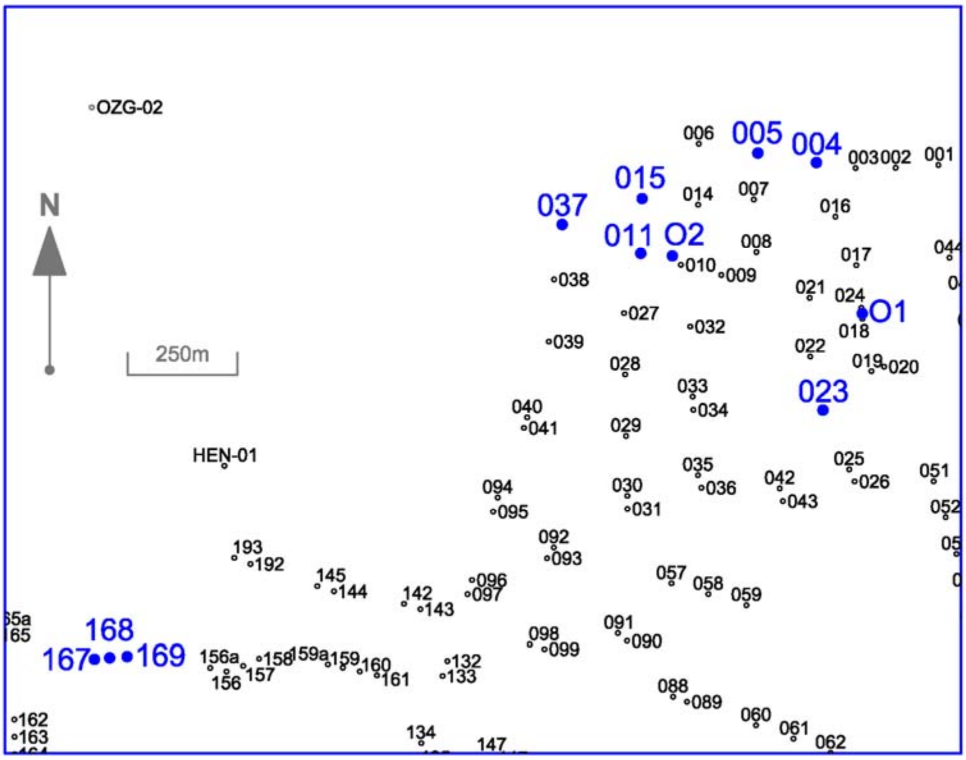


fig 1.2; Stratigraphic summary

Chronostratigraphy		Lithostratigraphy Mid - Eastern Netherlands regional codes				Formation/Member	facies	tectonic phase
		N				North Sea Supergroup	marine	
Quaternary	Pleistocene		NU					
Tertiary	Pliocene			NUOT		Oosterhout Fm.		
	Miocene			NUBA	NUBAS	Upper Breda Sand Mb.		
					NUBAC	Lower Breda Clay Mb.		Savian
	Oligocene		NM	NMRF		Rupel Fm.		Pyrenean
	Eocene		NL	NLFF	NLFFB	Asse Clay Mb.		
					NLFFM	Brussels Marl Mb.		
					NLFFS	Brussels Sand Mb.		
					NLFFY	Ieper Clay Mb.		
					NLFFT	Basal Dongen Tuff Mb.		
	Paleocene			NLLF		Landen Fm.		Laramide
Cretaceous	Upper Cret.		CK	CKGR		Ommelanden Chalk Fm.		Sub-Hercynian
				CKTX		Texel Chalk Fm.		
			KN	KNGL	KNGLU	Upper Holland Marl Mb.		
					KNGLM	Middle Holland Shale Mb.		
					KNGLL	Lower Holland Marl Mb.		
	Lower Cret.			KNNC		Vlieland Claystone Fm.		
				KNNS		Vlieland Sandstone Fm.	marine coastal	
			SK			Niedersachsen Gp.		
				SKCF		Coevorden Fm.	lagoonal	
Jurassic	Malm			SKWF		Weiteveen Fm.		Late Kimmerian
			AT	ATBR		Brabant Fm.		
	Dogger			ATWD		Werkendam Fm.		Mid Kimmerian
	Lias			ATPO		Posidonia Shale Fm.		
				ATAL		Aalburg Shale Fm.		
Triassic	Keuper			ATRT		Sleen Shale Fm.	lagoonal	
			RN	RNKP	RNKPU	Keuper Fm.		Early Kimmerian
					RNKPD	Dolomitic Keuper Mb.		
					RNKPR	Red Keuper Claystone Mb.		
					RNKPE	Red Keuper Evaporite Mb.		
					RNKPM	Mid Keuper Claystone Mb.		
					RNKPS	Main Keuper Evaporite Mb.		
					RNKPL	L. Keuper Claystone Mb.		
	Muschelkalk			RNMU		Muschelkalk Fm.	coastal	
					RNMUE	Muschelkalk Evaporite Mb.		
					RNMUL	Lower Muschelkalk Mb.		
	Buntsandst.			RNRO	RNROU	Upper Röt Claystone Mb.	coastal plain	
					RNRO2	Upper Röt Evaporite Mb.	coastal sebkha	
					RNROM	Intermediate Röt Clayst. Mb.	coastal plain	
					RNRO1	Main Röt Evaporite Mb.	coastal sebkha	
				RNSO	RNSOU	U. Solling Claystone Mb.	coastal plain	
					RNSOS	Solling Sandstone Mb.		
								local hiatus

fig 1.3 ; Abbreviations used in this report

regional stratigraphy	abbreviations official	abbreviations used	local subdivision		
North Sea Supergroup	N	N	N2		
			N1	N1b	
				N1a	
Niedersachsen Group	SK	SK			
Muschelkalk Formation	RNMU	MU-	B	B5	
				B4	
				B3	
				B2	
				B1	
			A	A4h	
				A4g	
				A4f	
				A4c	
				A4c	
				A4c	
				A4b	
				A4a	
			A3		
			A2	A2c	
				A2b	
				A2a	
			A1		
Upper Röt Claystone Member	RNROU	OU-	I		
			H		
			F		
			E		
			D		
			C	C1	
				C2	
				C3	
			B		
			A		
Upper Röt Evaporite Member	RNRO2	O2			
Lower Röt Claystone Member	RNROM	OM			
Main Röt Evaporite Member	RNRO1	MRE	E		Anh-E
			D	D2	Salt D
				D1	
				C2	Salt C
				C1	
				B2	Salt B
				B1	
				A2	Salt A
				A1	

2. Conclusions & Recommendations

Conclusions

Delamination in varying degrees is recognized in most wells in relation to cavern migration. The process can be followed over time if sufficient Gamma Ray logs are available. This delamination is recognized by a progressive thickening of small lithological units with depth. At some point the stratigraphy can not be recognized anymore and correlation is lost. From this depth, the lithology is described as “disturbed formation”. As can be expected, delamination influences the integrity of the casing string as well. Damaged casing is indicated by higher Gamma Ray readings because the formation becomes exposed here. Below these levels of delamination the cavern / local void migrates upward. Based on Gamma Ray logs alone it is not possible to distinguish between the latter two.

ON1
Though disturbed formation is identified in the deeper parts of the logged section, delamination at the levels of Muschelkalk Formation and in the Upper Röt claystones appeared to be inconclusive. Probably most of the migration had already happened before 1965 when the well was drilled and it has stopped even though subsidence continues.

ON2 & B011
From the Gamma Ray history of ON2 it can be concluded that the cavern has collapsed some time before 1967 and that later (1974 – 1978) a further gradual delamination took place. Since 1980, the well cannot be logged below the base of the North Sea Supergroup and the process can not be followed anymore.

B011
The well is a good example of delamination; boundaries of lithological units come in progressively deeper with time and at deeper levels.

B004
In this well only the Tertiary strata and a few meters of Muschelkalk Formation can be logged. Increasing depths of the position of the base of the North Sea Supergroup are an indication for delamination. High Gamma Ray readings in the lowermost part of the curves of 1974 to 1994 may be caused by damaged casing.

B005
The well has a good set of Gamma Ray curves. Delamination is shown by increased thicknesses in the lower Röt claystone units while the Muschelkalk Formation remains more or less constant in thickness. In the years from 1967 - 1975 pronounced cavern migration can be seen. Delamination and slight migration continue up through the last log in 2001.

B015
Gamma Ray curves of B015 indicate delamination in the deeper parts of the Röt claystones together with a slight thickening in the Muschelkalk Formation during the period from 1974 to 1981. Later delamination of lithological units in the Muschelkalk section is not apparent and the lower OU units can not be logged anymore.

B023
Only two logs are available and because of a non linear depth offset, they could not be used for this study.

B037
Though delamination and possibly cavern migration are suggested, it is difficult to prove delamination based on two logs only, especially since the 1979 log only covers the Röt

claystones. In 2003 the Röt Claystone section below base OU-H is 2m thicker compared to 1979, which is mainly attributed to the lowermost OU-C2 and the zone below base C2 to the top of the zone of disturbed formation.

Series B167
Serious migration has taken place in the B167, B168, B169 cavern but only in B168 some delamination can be observed. Faulting has been severe at this location and migration is most likely related to the faults in this area. It is therefore not a good example of delamination: the formation is fractured and disintegrates more easily compared to undisturbed continuous strata.

In B168 indications of delamination are found. Delamination seems to stop in 2013 but some migration continuous.
In B167 a zone of disturbed formation is identified.
At the B169 location no migration has occurred.

Recommendations

. It is advised to make an additional Gamma Ray log of wells B023.

. The method used in this pilot study can only be used if good log markers can be recognized. In featureless parts of the curves, for instance in the Tertiary strata, the CCL logs may have to be used to pinpoint the exact position of the level of the delamination.

3. Results per well

See Attachment A for the Gamma Ray history panel per well.

Please note the original data of the lithological boundaries and markers identified on the GRlogs can be found in the attached xls sheet: GL19.401, delamination data.xls (ref. GL/MV).

Thickness data and delamination graphs are included in this chapter.

Please note the discussion on the surface subsidence is included in chapter 4.

3.1 ON1

The well was drilled in 1965 to investigate the migration of the B018 to B024 cavern. No wireline logs were run in the original wells.

For ON1 ten Gamma Ray logs are available from the period 1965 to 2018 (see Attachment A for Gamma Ray history panel). The 1994 log only covers the top-hole section. Readings of the 1987 GRlog were 1.5m too deep and the entire curve was shifted 1.5m upward. The 1985 log seems to read too deep as well, but has not been corrected. Part of the dogleg in the delamination graph at this year is probably caused by the reference depth. The 1983 log is of poor quality.

In the open hole a GR - Sonic log was ran by Schlumberger in 1965, and also a dip meter which displays the Caliper. The processed results of the dip log are not found. For the current study, the field prints of the Sonic and of the Caliper logs have been digitized. A new final well log has been prepared (ON1, 2019april) on which these curves have been displayed.
The original KNZ end of well report of 1965 interprets from the Sonic log unconsolidated formation which is 'strongly disturbed' in the zones 163.7 – 166.0m, 177.2 – 192.0m, 198.0 – 201.9m, 232.7 – 240.2m, 242.2 – 248.1m, 253.5 – 256.5m, and 258.2 – 261.1m. These are the intervals with the higher interval transit times. Conclusions seem to have been made on the sonic log alone and when the Caliper is displayed next to the Sonic log these higher readings appear to coincide with sections of washed out hole, especially in the lower part of the log, from 233m and deeper. It should be noted that the Caliper curve has a reverse scale. Higher sonic readings in the upper part of the log do not seem to coincide with washed out hole. Most of the high sonic peaks represent cycle skips. High sonic readings from 163 – 167m are caused by a larger hole size which is the 12 1/4" pocket and not by disturbed formation. Of course it cannot be excluded that hole washouts are also (partly) caused by the presence of disturbed formation.
The 13 3/8" surface casing shoe at 43.1m is not recognized on any of the GRlogs. On a number of curves a break is seen several meters below this depth.

In November 2018 a GR-Dens-CAL was run by Schlumberger. The curves were added to the final well log of April 2019 as well. Density readings start from a depth of 258m whereas GR readings begin higher, at 252m. Logs are through the 6 5/8" casing, and above 164.9m also through the 9 5/8" casing. Density readings through the 2 strings caused very high readings, as expected. In these sections also peaks with lower readings are present, which may be related to damaged casing.
Above 107m the Caliper reads slightly higher than below this depth and apparently a different grade of casing has been used here. The density log through only the 6 5/8" casing shows high peaks which coincide with the position of the casing collars. Casing collars also show up well on the Caliper log which has been displayed on an exaggerated horizontal scale. In the lower parts, below 237m, Caliper readings gradually start decreasing which points to collapsed casing. Below 233m, density readings also show very high peaks, which can be related to this phenomenon as well. This depth coincides with the depth at which the hole washouts begin which are concluded from the 1965 Caliper (see above). Schlumberger comments on the poor log quality, and the logs

are re-processed in May 2019. A QC algorithm still indicates the logs of a very poor quality with only a few short intervals with true readings present between 90 and 166m (inside the 9 5/8" casing) and at the bottom of the log between 235 and 252m. However, this latter interval has washed out hole which is also indicated by high interval transit times on the 1965 open hole sonic log.

Delamination and migration

Delamination is difficult to prove in this well, no progressive deepening of lithological boundaries can be observed (see fig 3.1c). The total thickness of the section between the base of the Muschelkalk Formation and the base of the Röt claystone unit E amounts to 68.44m in 1965 and 67.75m based on the 2018 logs (fig 3.1a & 3.1b). A slight but consistent downward trend of some 50cm at the base of the Muschelkalk Formation can be seen from 1965 to 2018. At deeper levels though the trend is less conclusive with small (relative) changes in upward and downward directions . However, the top of the MRE was originally positioned some 70m deeper than the current HUD, and delamination has probably taken place at deeper levels as it is witnessed in the ON2 well.

Lithological units of the section of Röt claystones can be recognized well down to the base of unit RNROU-E. Within unit F, a good low GR peak which represents an anhydrite bed is recognized on all logs (F-bed). In unit E, two log markers are chosen (marker X1 and X2) and in unit D a high GR peak (shale break) can be correlated well (marker X3). Below marker X3 correlation is lost which points to disturbed formation. Thicknesses of the various lithological units do not show a consistent trend at any level.

Low GR readings below 256m on the 1965 curve are caused by local voids which are confirmed by the open hole Caliper (see final well log). These voids form part of the migrated cavern as it is illustrated by the 1967 GR curve which indicates the presence of collapsed formation below these levels.

Figure 3.1d is the delamination graph which is corrected for estimated surface subsidence (Ch 4.1). It shows the deeper position of the log markers with time, but also the top of the void (marker X4) follows this trend. This means that the migration process has stopped but the subsidence continues.

fig 3.1a

ON1	thicknesses (m)						
GRlog	top OU to base OU-E	OU-I	OU-H	OU-H to F-bed	OU-F	F-bed to X1	X1 to X2
1965-06	68.44	22.70	7.10	17.65	4.65	9.96	7.39
1967-09	68.10	22.49	7.05	17.44	4.81	10.21	7.22
1974-04		22.11	7.28	17.85	4.60	10.05	7.33
1983-08	67.98	22.50	6.92				7.84
1985-06	67.37	22.76	7.27	17.35	4.76	10.07	7.10
1987-01	67.80	22.40	7.47	17.52	4.41	9.81	7.80
1995-08	67.30	22.20	7.10	17.60	4.70	10.10	7.40
2018-08	67.87	22.28	7.33	17.57	4.59	10.32	7.07
2018-08 Schl	67.75	22.30	7.00	18.10	4.50	10.05	7.17

fig 3.1b

ON1	thicknesses (m)			
GRlog	OU-E	X2 to X3	base OU-E to X3	X3 to X4
1965-06	3.64	7.12	3.48	8.88
1967-09	3.69	7.05	3.36	9.11
1974-04				
1983-08	3.48	7.21	3.73	
1985-06	2.82	6.78	3.96	9.13
1987-01	2.80	6.61	3.81	8.80
1995-08	2.90	6.70	3.80	9.00
2018-08	3.30	6.88	3.58	9.08
2018-08 Schl.	3.13	6.88	3.75	

fig 3.1c

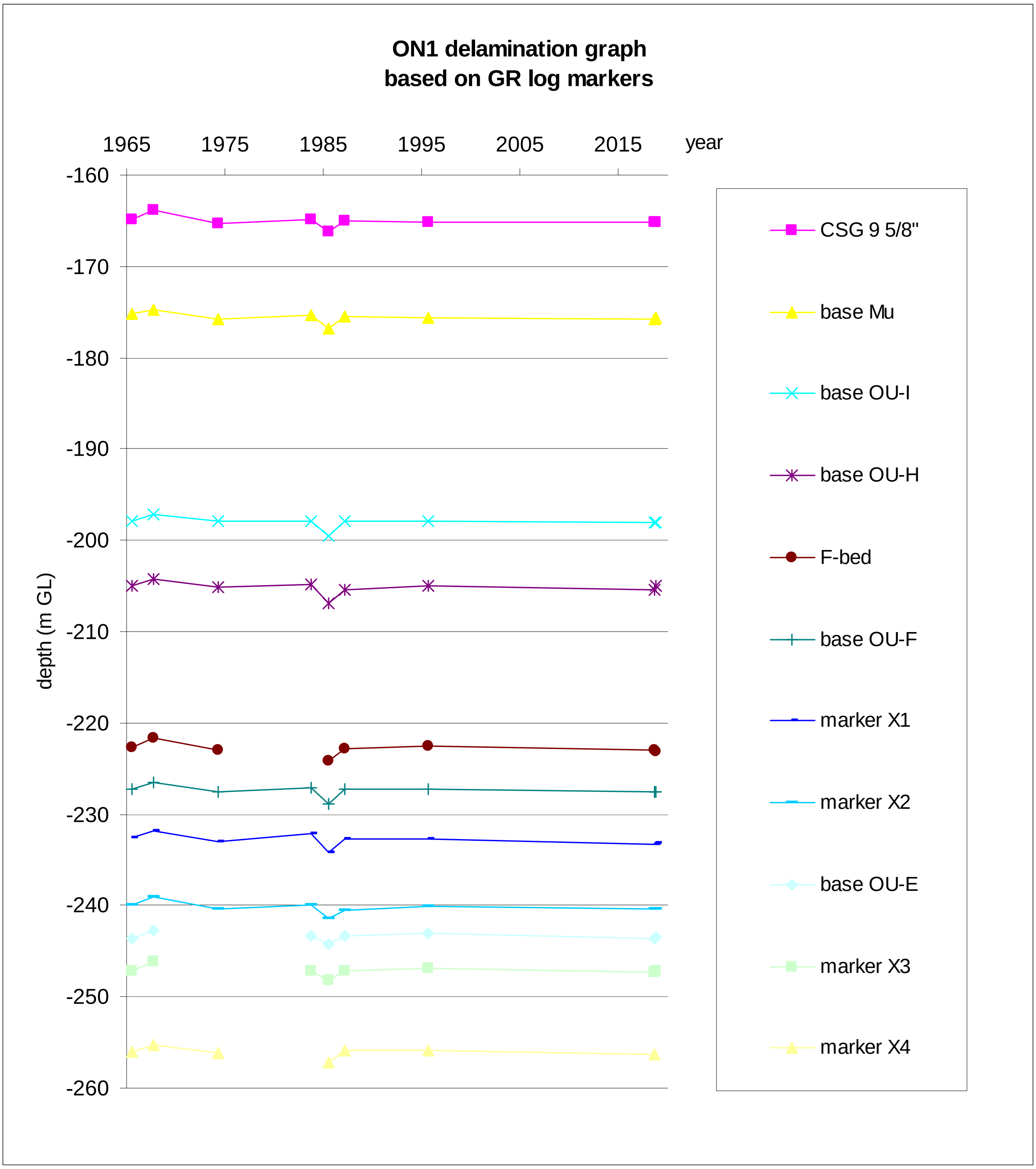
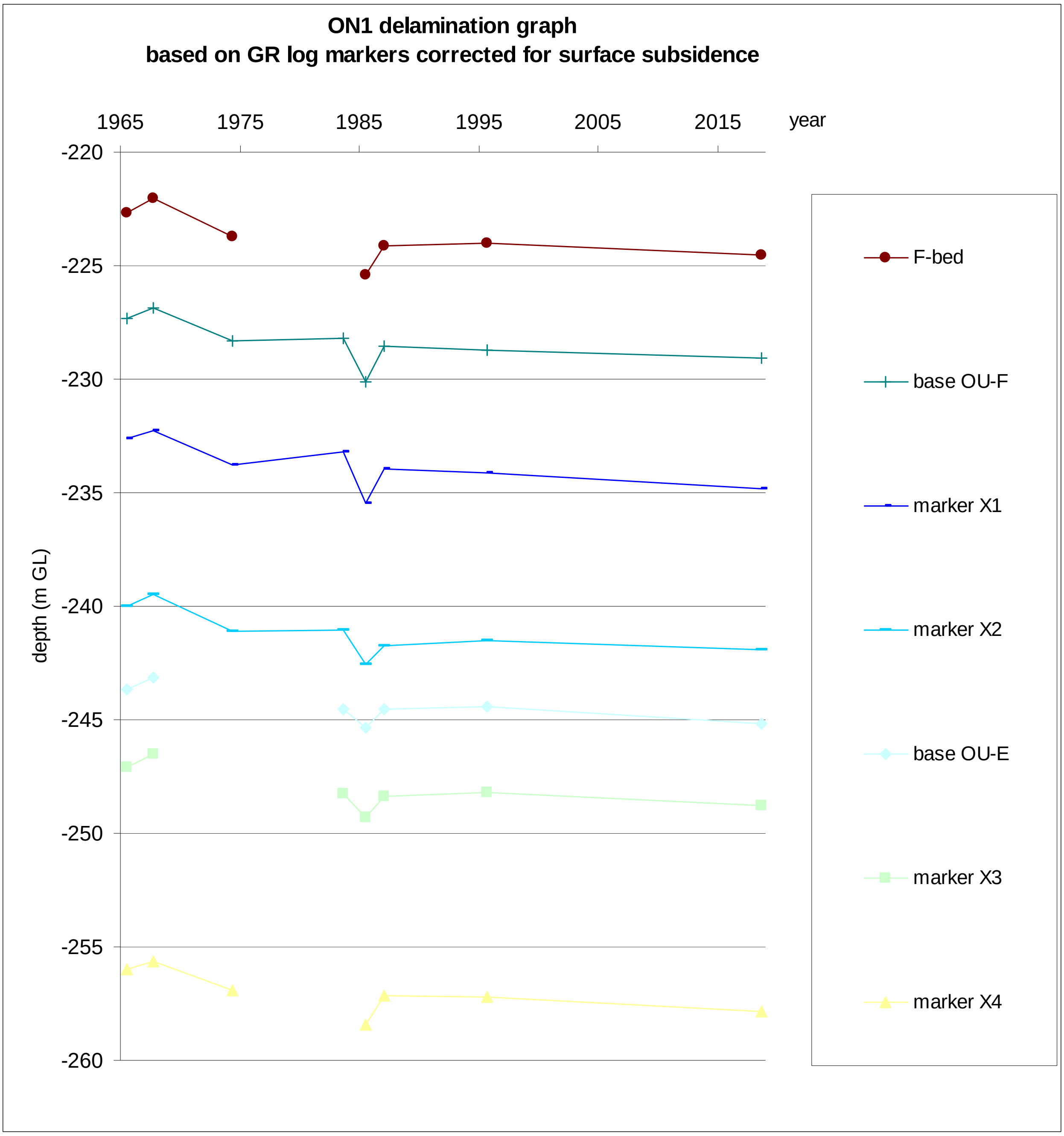

ON1 delamination graph
based on GR log markers
1965
1975
1985
1995
2005
2015
year
-160
-170
-180
-190
-200
-210
-220
-230
-240
-250
-260
depth (m GL)
CSG 9 5/8"
base Mu
base OU-I
base OU-H
F-bed
base OU-F
marker X1
marker X2
base OU-E
marker X3
marker X4

fig 3.1d


ON1 delamination graph
based on GR log markers corrected for surface subsidence
1965
1975
1985
1995
2005
2015
year
-220
-225
-230
-235
-240
-245
-250
-255
-260
depth (m GL)
F-bed
base OU-F
marker X1
marker X2
base OU-E
marker X3
marker X4

3.2 ON2 and B011

3.2a ON2

Sixteen Gamma Ray logs are available from the period 1967 to 2013 (see Attachment A for Gamma Ray history panel).

The ON2 well was drilled in 1967 to investigate the B010 to B011 cavern. The well was drilled to 310.8m and the top of the cavern was found at 280m ('boorboek'). A 7” casing was set at 279m. The Gamma Ray - Neutron log of this year shows high readings in the open hole below the casing. The logging tool did not pass deeper than 290m. Later logs are mainly GR and CCL; Also two logs are available which are probably neutron logs #10 and #12. Since they are named 'GRlogs' and no horizontal scale is stated, they are omitted from the dataset. The 1974, 1976 and 1978 runs could log the Triassic strata down to the Röt claystone unit D, but from 1980 the top of the Muschelkalk Formation could not be reached anymore. The 1990 run found a hold up depth at 127.5m which is 50cm deeper compared to the 1987 run. In 1991 the HUD (hold up depth) was again found shallower, at 127.17m. The nature of the obstruction is probably damaged casing. GRlog quality is not always perfect; especially the logs of 1985, 1987, 1990 and 1991 hardly compare. They are displayed on the Gamma Ray history panel (Attachment A) to illustrate the differences in quality.

Delamination and migration

The 1974 GRlog reads slightly high, probably pointing to a minor problem in the depth reference. On the three GR curves of 1967, 1976 and 1978, boundaries of lithological units are found progressively deeper with depth and time (see figure 3.2c). The North Sea Supergroup and Muschelkalk Formation slightly increase in thickness (fig 3.2a) but in the Röt Formation no significant trend can be observed (fig 3.2b). On the 1974, 1976 and 1978 curves high readings are found below marker X1 at 256.15m, 257.69m and at 258.11m respectively (see GR history panel in Attachment A). These high readings may be related to damaged casing.
The above suggests that the cavern has collapsed some time before 1967 and that later (1974 – 1978) a further gradual delamination took place.

Three Gamma Ray runs that were made later, in 2011, 2012 and 2013 found a hold up depth at some 127m, so the process can not be followed anymore. Only the base of the Tertiary unit N2 is visible, which comes in progressively deeper with a total difference of some 70cm between the 2011 and the 2013 logs. These figures have to be treated with care because this boundary is not well defined on GRlogs only. Adding the estimated surface subsidence data for the well location does not change this picture (fig 3.2d).

fig 3.2a

ON2	depth (m)	thickness (m)								
GRlog	CSG 9 5/8"	N1	base A4f - base MU	A4f	A4e	A4d	A4c	A4a-b	A3	A2c
1967-11	40.20	16.15	52.78	3.13	1.11	3.07	5.94	5.29	4.77	8.32
1974-05	39.43	16.20	53.22	3.12	1.22	3.11	5.74	5.52	4.66	7.92
1976-10	39.60	17.13	53.95	3.03	1.49	3.10	5.77	5.78	4.89	8.22
1978-02	39.70	17.32	54.14	2.95	1.23	3.37	5.85	5.79	4.81	8.39

fig 3.2b

ON2	thickness (m)									
GRlog	A2b	A2a	OU- I - F	A1	OU-1	OU-H	OU-G	OU-F	OU-E	OU-D
1967-11	5.41	10.26	51.71	5.48	22.52	7.43	7.99	13.77	12.68	12.75
1974-05	5.99	10.12	51.80	5.82	22.7	6.65	8.91	13.54	13.27	12.59
1976-10	5.45	10.13	51.99	6.09	22.61	7.40	8.37	13.61	12.98	12.68
1978-02	5.77	10.07	51.85	5.91	22.79	7.07	8.61	13.38	13.19	

fig 3.2c

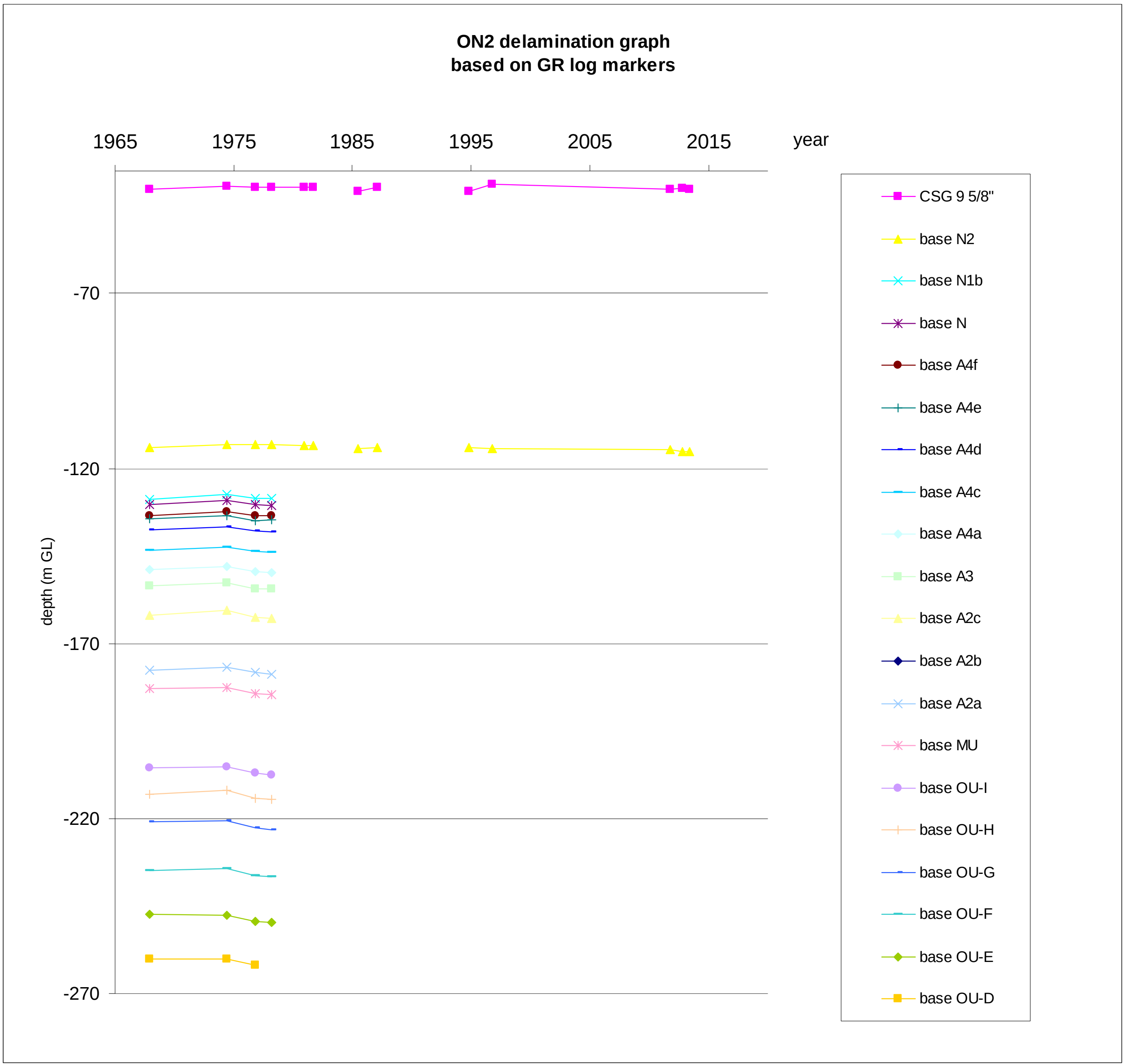
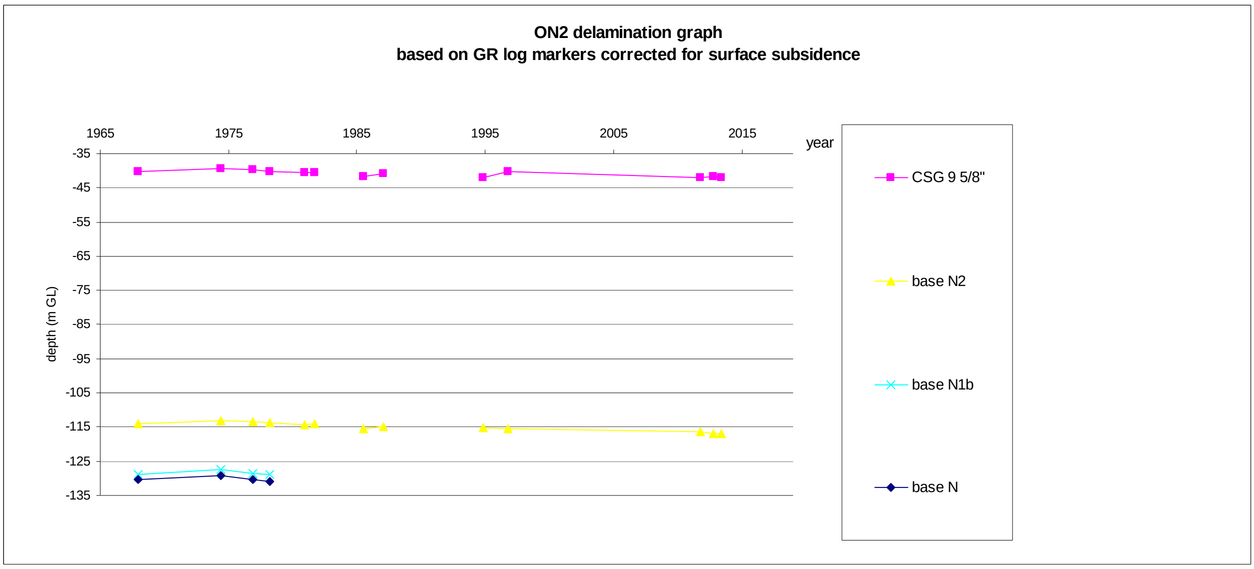


fig 3.2d


ON2 delamination graph
based on GR log markers corrected for surface subsidence
1965
1975
1985
1995
2005
2015
year
-35
-45
-55
-65
-75
-85
-95
-105
-115
-125
-135
depth (m GL)
CSG 9 5/8"
base N2
base N1b
base N

3.2b B011

B011 was drilled in 1941 and the ‘boorboek’ does not state any specific problems. The top of the Muschelkalk Formation was reported at 133.80m and the 9” casing was set at 134.75m. The break on the GRlog at 134.6m is either attributed to this formation change or to the 9” casing. In 1942, the 4” tubing appeared broken at the end of the 7 1/2” casing. In 1943 the bottommost part of the 7 ½” was concluded bend, and some 14.5m was cut. The first GRlog was made in 1967 and the well could be logged into unit RNROU-C until 1990; later wireline runs in 1991, 1994 and 1996 found a hold up depth some 55m shallower. In 2001 the tool could not exceed 95m which is approximately 40m above the top of the Muschelkalk Formation (see Attachment A for Gamma Ray history panel).

Delamination and migration

The well is a good example of delamination. The section of Muschelkalk Formation from the base of unit A4f (which is a good log marker) to the base of the formation shows a thickening of 1 meter from 1967 to 1987 which seems mainly caused by the argillaceous unit A2c. The total of the Upper Röt Claystone units I – F increases some 2 meters, although this increase is a bit erratic probably due to varying cable tension. Below unit RNROU-F log correlation is not so good but most lithological units can be recognized. The interval from base F to marker X1 shows an increase of nearly 3m. Below the log marker X1, which is a high GR peak in unit C2, correlation is lost, which indicates disturbed formation. GRlog marker X2 moves up through time and is probably related to cavern migration although consistent low readings are absent. From 1991 no significant delamination is observed.

Addition of surface subsidence accentuates the delamination graph. Fig 3.2b-d shows an increased deepening of all lithological boundaries with depth. This graph also shows the decrease in thickness between the two markers pointing which indicates migration.

fig 3.2b-a

B011	base Mu-A4f	thickness Muschelkalk Formation (m)								
GRlog	to base Mu	A4e	A4d	A4c	A4a	A3	A2c	A2b	A2a	A1
1967-09	50.37	0.81	3.07	5.73	4.10	7.40	7.60	5.50	9.51	6.65
1974-05	50.12	0.74	3.13	5.39	4.21	7.10	7.84	5.71	9.56	6.44
1976-04	50.23	0.84	3.06	5.51	4.44	6.88	7.69	5.43	9.56	6.82
1976-10	50.52	0.78	3.09	5.36	4.64	6.85	8.24	5.17	10.02	6.37
1978-02	50.51	0.84	2.85	5.59	4.21	6.84	8.41	5.60	9.91	6.26
1983-08	51.18	0.85	2.92	4.89	5.05	6.54	8.64	6.18	9.10	7.01
1985-06	51.03	0.59	3.08	5.50	4.48	6.66	8.27	6.37	9.18	6.90
1987-01	51.37	0.78	3.02	5.78	4.13			5.69	9.67	6.64
1990-01										
1990-07	51.31	0.53	3.38	5.81	4.11	7.15	8.08	6.58	9.32	6.35
1991-04	51.26	0.77	3.01	5.74	4.49	6.38	8.77	6.27	9.65	6.18
1994-09	51.27	0.73	3.14	5.72	4.35	7.06	7.95	6.34	9.56	6.42
1996-07	51.27	0.63	3.25	5.80	4.16	7.21	8.00	6.28	9.41	6.53

fig 3.2b-b

B011	thicknesses RNROU (m)								base F	X1
GRlog	I - F	I	H	G	F	E	D	C3	to X1	to X2
1967-09	51.67	21.95	7.39	9.04	13.29	13.70	13.24	12.26	43.07	21.09
1974-05	51.79	22.16	7.19	9.30	13.14	13.31	13.52	12.36	45.96	17.15
1976-04	53.62	23.48	7.27	9.38	13.49	14.04	13.11	11.92	45.55	14.71
1976-10	54.04	22.89	7.73	9.34	14.08	13.49			44.48	15.03
1978-02	53.80	22.74	7.96	9.11	13.99	12.99	13.14	12.18	44.75	13.73
1983-08	53.02	22.45	7.98	9.33	13.26	13.23			45.14	16.10
1985-06	53.07	22.63	7.48	9.62	13.34	13.54	12.07		45.01	14.93
1987-01	53.07	22.62	7.72	9.23	13.50				45.82	15.35
1990-01			9.00	8.39	13.59	13.94				
1990-07	52.95	22.79	7.60	8.91	13.65	13.85	12.82	11.70	45.69	12.03
1991-04	52.89	22.81	7.55	8.78	13.75					
1994-09	53.04	22.79	7.71	8.93	13.61					
1996-07	53.72	22.85	7.50	9.26	14.11					

Comparison ON2 and B011

In B011, indications for disturbed formation begin at 281m on the 1967 curve and the top of the cavern is interpreted at 302m. In the ON2 well the top of the cavern was found at 280m ('boorboek'). Possibly this does not really represent the void since low GR readings are missing, but indicates collapsed formation as found in B011 at a similar depth.

Both ON2 and B011 subsidence graphs show a pronounced dogleg between 1974 and 1976.

fig 3.2b-c

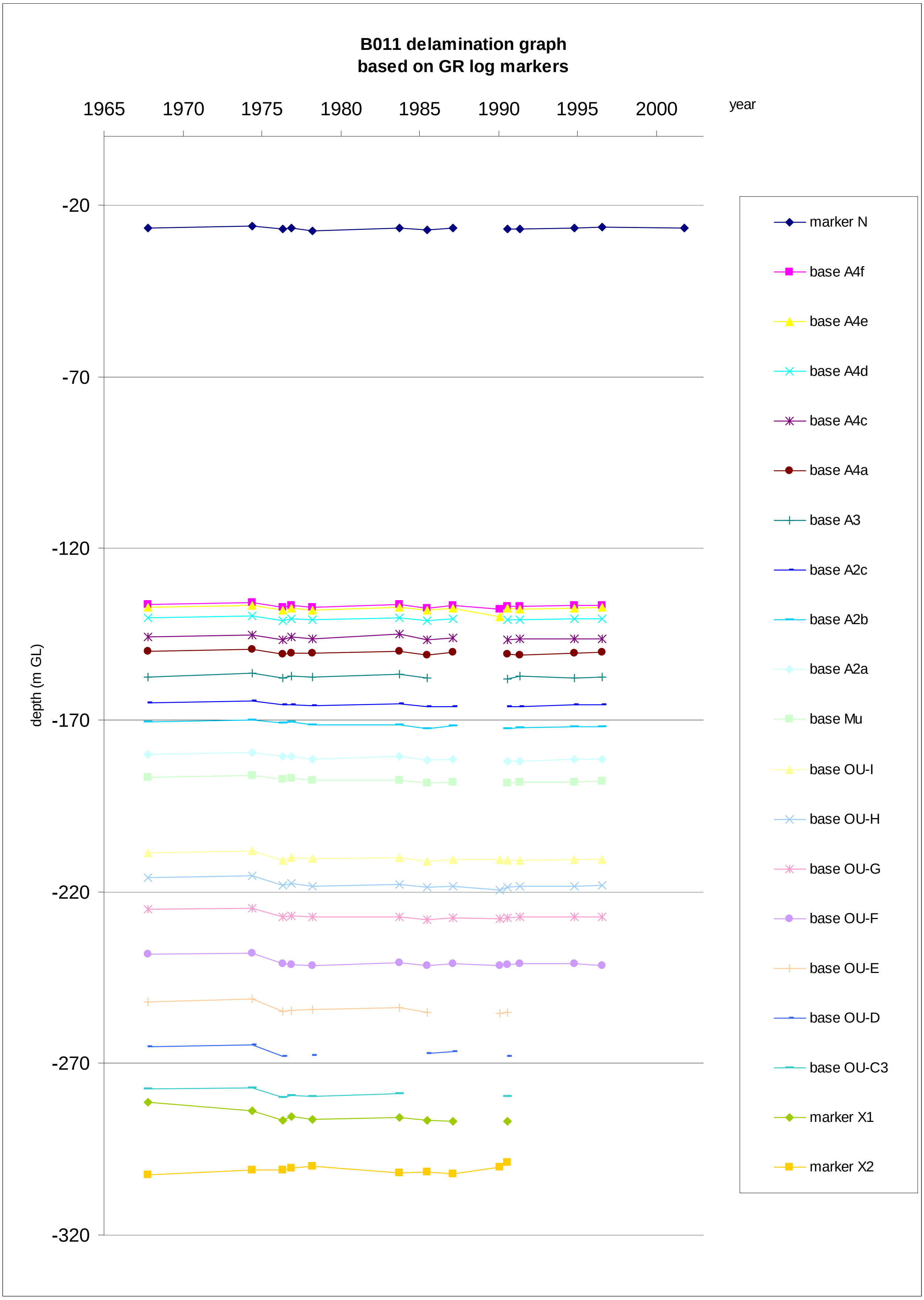
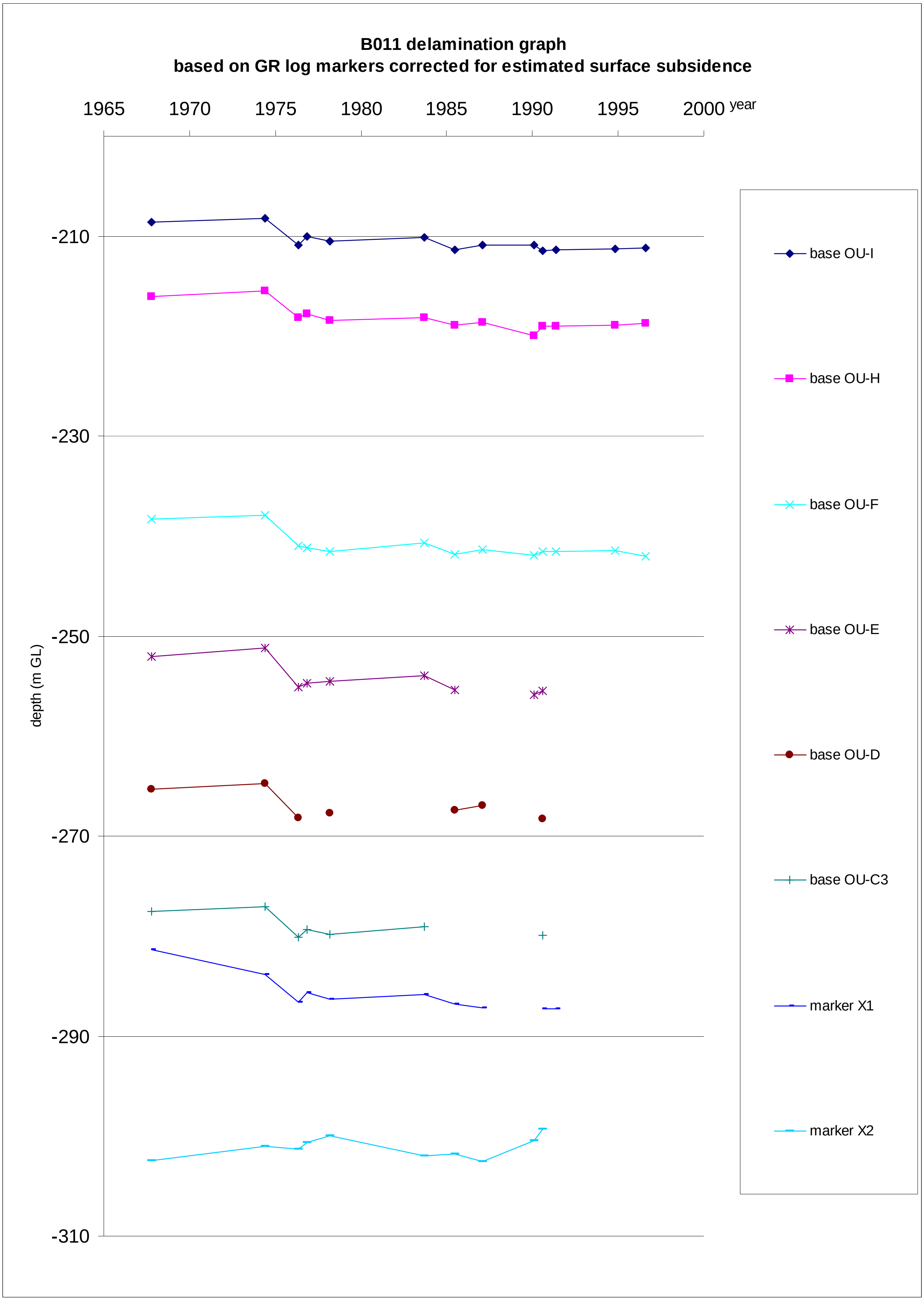

B011 delamination graph
based on GR log markers
1965
1970
1975
1980
1985
1990
1995
2000
year
-20
-70
-120
-170
-220
-270
-320
depth (m GL)
marker N
base A4f
base A4e
base A4d
base A4c
base A4a
base A3
base A2c
base A2b
base A2a
base Mu
base OU-I
base OU-H
base OU-G
base OU-F
base OU-E
base OU-D
base OU-C3
marker X1
marker X2

fig 3.2b-d


B011 delamination graph
based on GR log markers corrected for estimated surface subsidence
1965
1970
1975
1980
1985
1990
1995
2000
year
-210
-230
-250
-270
-290
-310
depth (m GL)
base OU-I
base OU-H
base OU-F
base OU-E
base OU-D
base OU-C3
marker X1
marker X2

3.3 B004

The well was drilled in 1935 and problems with bend or broken tubing and casing started in 1949. In 1951, a connection with B001, B002 and B003 was concluded. In 1956 the cavern appeared connected with B005. In 1960 the well was partly plugged back and top cement was tagged at 284.65m. The first Gamma Ray measurements are from 1967. This curve shows a hold up depth (HUD) at 236.7m in unit RNROU-C3. The HUD of the later logs are all around 145m which is in the basal Muschelkalk units.

Muschelkalk Formation largely disappeared due to Tertiary erosion; only the basal units RNMU-A2a and A1are left. The base of the North Sea Supergroup was reported at 133.2m and the 9 5/8” was set at 133.77m, so it is not clear whether the break on the GR curve is caused by the base of the N1a sand bed or by the casing. Nevertheless, the break has been correlated (see Attachment A for Gamma Ray history panel).

Delamination and migration

The boundaries of the Tertiary N1b unit are not sharp and well defined on GR curves. Figure 3.3a suggests a slight increase in thickness of this unit but this may not be conclusive. The depth of base North Sea Supergroup or the 9 5/8” casing shoe is a sharp boundary which is recognized on all GR curves and fig 3.3a indicates a thickening of approximately 2m of the Tertiary strata. The exact position of the level of delamination is unknown. Possibly, this can be indicated by a study of the CCL curves.

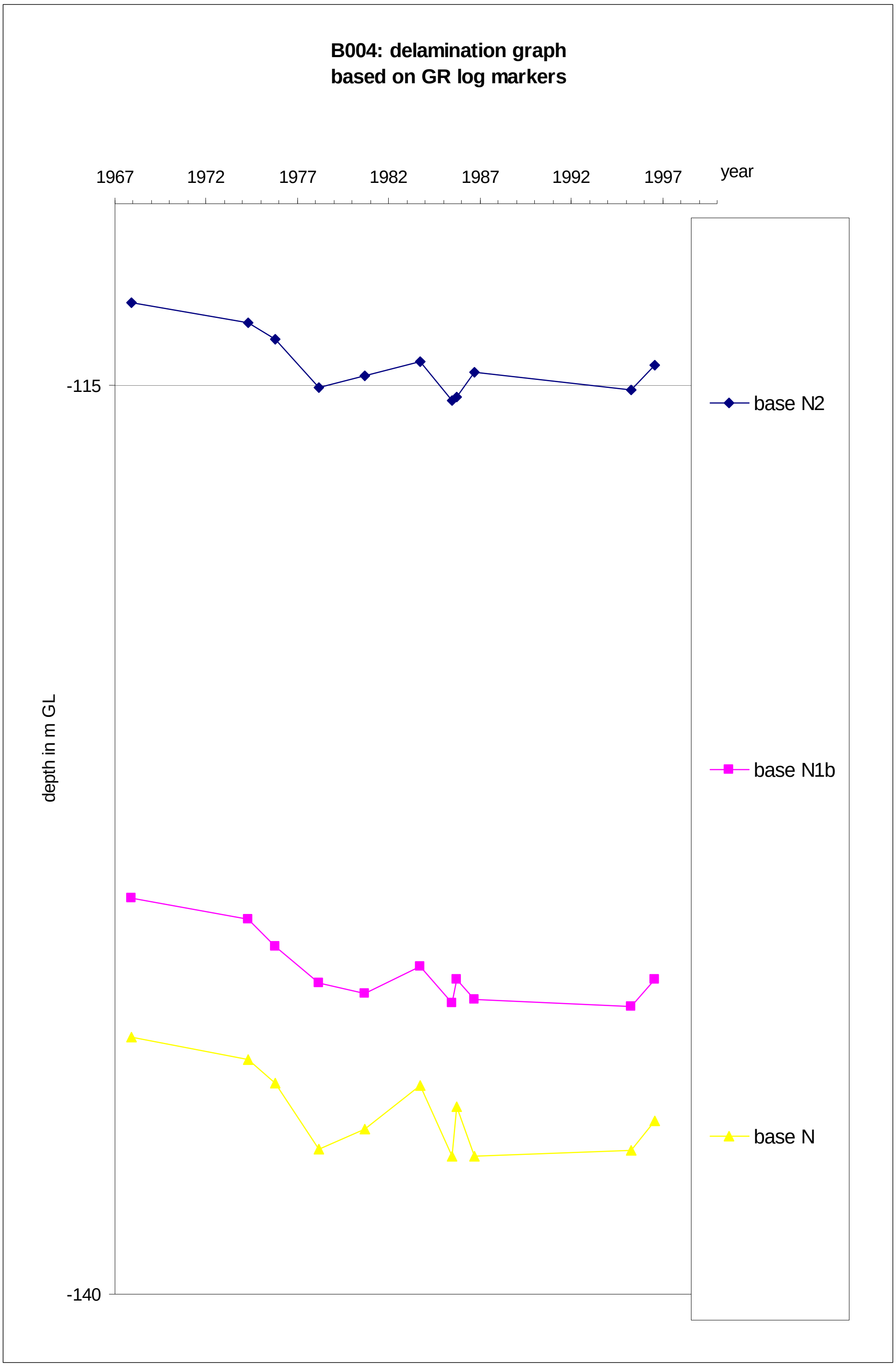
The surface subsidence could not be unambiguously reconstructed (See Ch 4) and a delamination graph corrected for surface subsidence was not made.

The basal Muschelkalk unit A1 is recognized on the 1967 curve, but it has disappeared on the 1974 log. Instead, the 9 curves from 1974 to 1994 end with high GR readings which may be caused by damaged casing exposing the formation. The 1995 and 1996 curves end with low readings at 144.3m and 144.5m respectively, which may represent a local void.

fig 3.3a

B004	thickness (m)		depth (m)
GRlog	N1b	N1a	base N
1967-11	16.35	3.84	132.93
1974-04	16.39	3.85	133.53
1975-10	16.70	3.76	134.19
1978-02	16.39	4.56	136.00
1980-08	16.98	3.75	135.47
1983-08	16.61	3.28	134.25
1985-06	16.57	4.21	136.21
1985-08	16.02	3.49	134.83
1986-08	17.26	4.31	136.21
1995-03	16.96	3.96	136.04
1996-07	16.90	3.89	135.23

fig 3.3b


B004: delamination graph
based on GR log markers
1967
1972
1977
1982
1987
1992
1997
year
-115
-140
depth in m GL
base N2
base N1b
base N

3.4 B005

The well was drilled in 1935; the 9” casing was set at 134.96m, some 60cm below the base of the North Sea Supergroup. The base of the low GR peak at this level either represents the casing or the basal sand unit N1. Already in 1938 the 4” tubing was broken “er moet een instorting hebben plaatsgehad” and the 7 ½” casing was cut at 353.83m, which is 3.5m above the top of Salt-A. In 1947 the cavern appeared connected with B007 and by 1955 the caverns of B005, B006, B007, B008, B009, B010 and B011 were connected.

Delamination and migration

Changes in thickness of the Muschelkalk Formation and of the upper part of the Röt claystone section I – F are not apparent (fig 3.4a). However, in the deeper and less competent parts of the Röt claystones an increase in thickness indicating delamination is found (fig 3.4b). The total of the units D – C2 shows an increase of more than 2m from 1967 until 1990, hereafter thickness remains constant. Units C3 and C2 show an increase in thickness of 1m each in the same period (fig 3.4b). Although these differences are not spectacular, delamination is demonstrated well in combination with the migration of the void or cavern.

The field print of the 1967 log indicates the top of the cavern at 296.8m (marker X), which was confirmed by the Prakla Sonar measurement. Below the void on the 1974 log an erratic GR pattern indicating collapsed formation is found. On the 1975 GRlog, marker X is found at 280.9m. This means a migration of 15.8m is in evidence from 1967 up to 1975, after which the depth of the marker remains more or less constant. The thickness from base C2 to the top of the void (marker X) decreases 6m from 1974 to 1975 and another 2m from 1975 until 2001 which is due to disintegration of the OU-C1 unit. (See also Gamma Ray history panel, Attachment A). This means that although marker X remains at the same apparent depth, it moves up in the stratigraphy.

From 1967 to 2001 a surface subsidence of 31cm is recorded; adding these values to the delamination graph did not show different results (fig 3.4c & 3.4d). The deeper depths figures for the logs from 1992 and 1994 may be caused by variations in the depth reference for the GRlog.

fig 3.4a

B005	thickness	thickness	thickness RNROU				
GRlog	N1	RNMU	I - F	I	H	F	D + E
1967-11	20.64	16.92	52.44	22.57	7.49	22.38	28.75
1974-01	20.11	16.56	52.77	22.52	7.88	22.37	28.82
1975-10	20.28	16.64	52.88	22.78	7.32	22.78	28.59
1976-11	20.76	16.39	52.70	23.03	7.18	22.49	28.53
1978-02	20.40	16.94	53.12	22.92	7.42	22.78	28.33
1980-08	20.86	17.11	52.63	22.53	7.33	22.77	28.55
1983-08	19.55	17.92	52.86	22.16	8.23	22.47	28.21
1985-08	20.21	17.48	52.78	22.37	7.97	22.44	28.22
1990-10	20.97	16.73	52.73	22.69	7.70	22.34	28.85
1991-07	20.25	16.88	52.88	22.84	7.42	22.62	28.88
1992-10	19.73	17.42	52.86	23.03	7.16	22.67	28.93
1994-10	19.66	17.01	53.00	22.77	7.56	22.67	28.84
1995-07	21.36	16.79	52.57	22.63	7.37	22.57	29.04
1996-10	21.01	16.81	52.63	22.94	7.16	22.53	29.03
2001-11	20.73	16.87	52.66	22.88	7.16	22.62	29.17

fig 3.4b

B005 GRlog	thickness RNROU D-C2	C3	C2	base C2 to marker X
1967-11	56.35	13.40	14.20	36.35
1974-01	56.68	13.98	13.88	26.17
1975-10	56.24	13.49	14.16	20.06
1976-11	56.48	14.39	13.56	18.92
1978-02	55.78	13.87	13.58	19.43
1980-08	57.37	14.96	13.86	17.91
1983-08	56.57	13.79	14.57	18.72
1985-08	57.72	14.33	15.17	18.84
1990-10	58.83	14.14	15.84	18.37
1991-07	58.58	14.47	15.23	17.65
1992-10	58.57	14.06	15.58	18.33
1994-10	58.76	14.85	15.07	17.46
1995-07	58.99	14.88	15.07	17.50
1996-10	58.66	14.41	15.22	17.76
2001-11	58.84	14.62	15.05	17.74

fig 3.4c

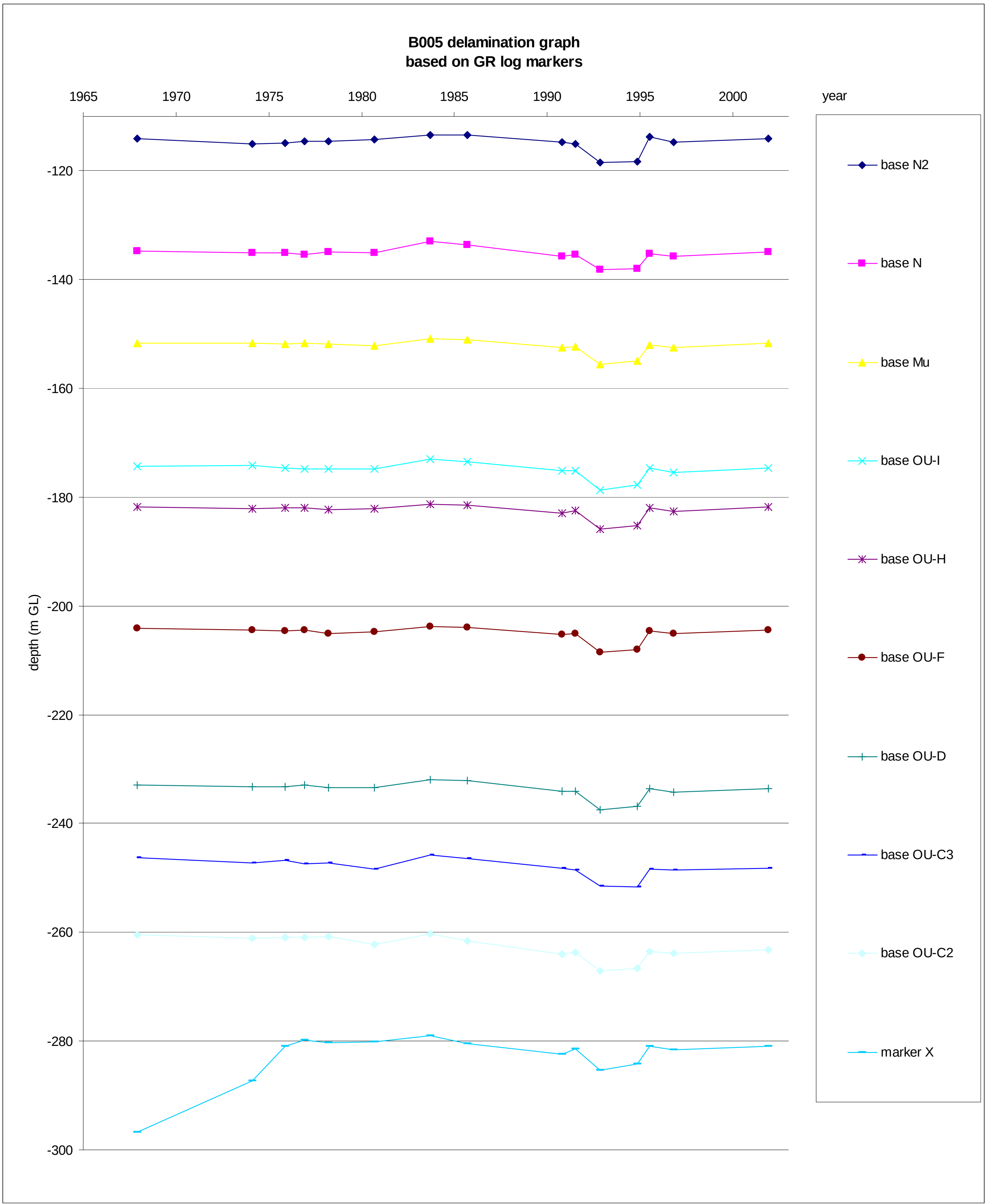
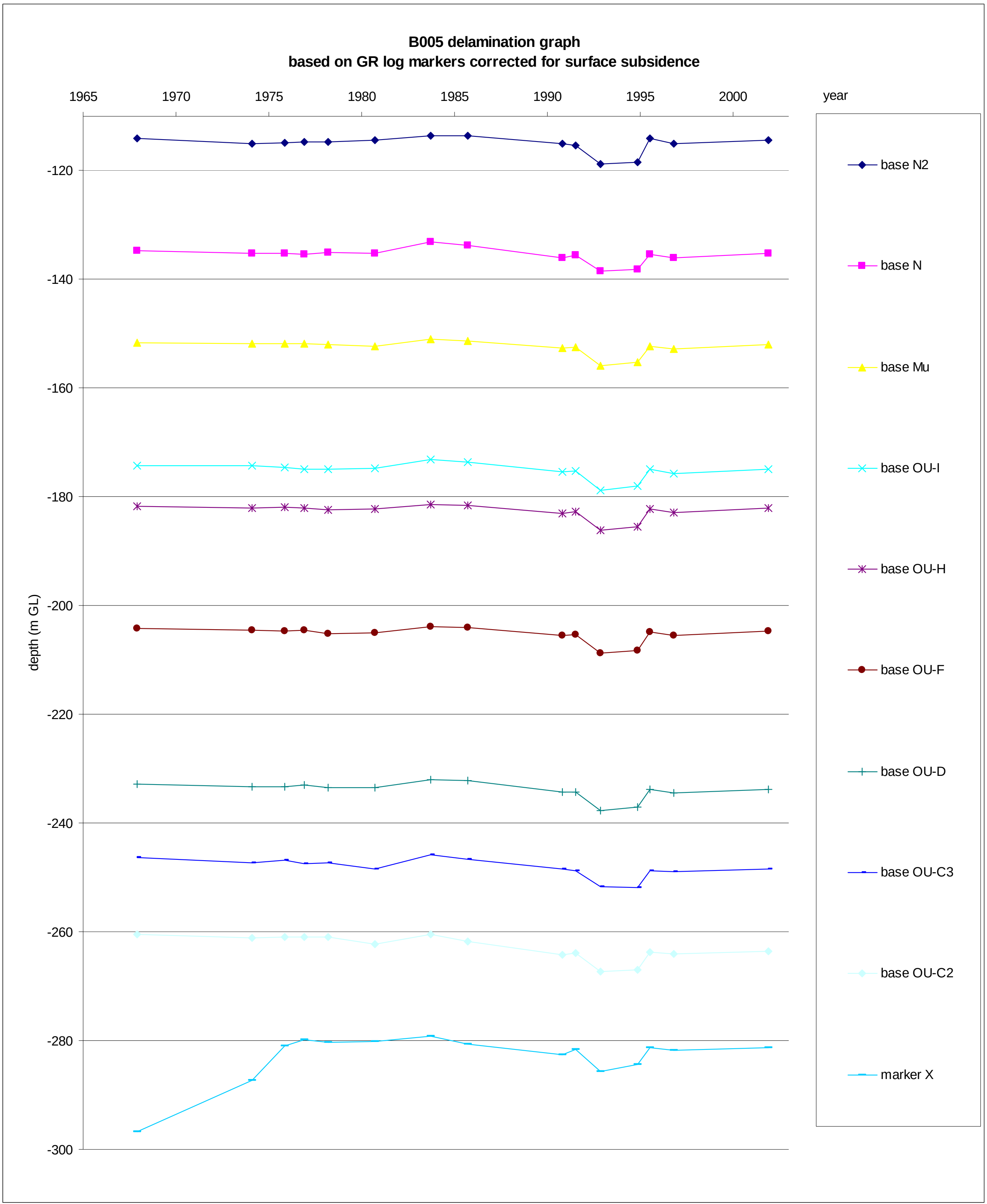

B005 delamination graph
based on GR log markers
1965
1970
1975
1980
1985
1990
1995
2000
year
-120
-140
-160
-180
-200
-220
-240
-260
-280
-300
depth (m GL)
base N2
base N
base Mu
base OU-I
base OU-H
base OU-F
base OU-D
base OU-C3
base OU-C2
marker X

fig 3.4d


B005 delamination graph
based on GR log markers corrected for surface subsidence
1965
1970
1975
1980
1985
1990
1995
2000
year
-120
-140
-160
-180
-200
-220
-240
-260
-280
-300
depth (m GL)
base N2
base N
base Mu
base OU-I
base OU-H
base OU-F
base OU-D
base OU-C3
base OU-C2
marker X

3.5 B015

B015 was drilled in 1948, attempts were made to pull the 9” casing, but only 3.60m could be retrieved and the casing was cemented in place at 133.4m. The top of the Muschelkalk Formation was reported at 134.7m. Gamma Ray correlation at this level probably follows the 9” casing. Problems with the 4” tubing began in 1959; the 7 ½” casing appeared to be bend at 342.35m, which is 3.40m above the top of the salt. The well produced until 1960, where after the cavern was used for backfilling with brine purification slurry. In 1976 Prakla sonar measurements were carried out after extensive well repairs. The 1985 GR – CCL run indicated the 7” casing broken at 122.07m and at152.50m ('boorboek').

The 1976 to 1981 runs found a hold up depth at progressively shallower levels and from 1983 and the base of the Muschelkalk Formation could just be logged. In 2001 the logging tool again reached deeper into the Röt claystone unit H.

Delamination and migration

Low readings on the 1974 GR curve indicates a void at 275.68m below some 7m of very high readings which may be caused by damaged casing. In the 1976 and 1978 logs correlation is lost below base OU-E. The high Gamma Ray readings in the lowermost parts of these curves can also be related to damaged casing.

In the period from 1974 until 2001, the base of the Muschelkalk Formation has descended 3.18m and the base of the Röt claystone unit I 3.70m. The thickness of the Muschelkalk has increased with 1m and the thickness of unit RNROU-I with 52cm. The 9” casing is found 90cm deeper on the 2001 curve compared to the 1974 curve. Of course all this has consequences for the integrity of the 9” and 7” casing strings and a study of the CCL logs will give more detail.

Deeper parts of the section are found on the 1974 – 1981 curves only. During this period clear signs of delamination can be seen. Increase in the thickness of the Muschelkalk Formation is 89cm during this period while the OU I to F units thickness increase is 2.27m. As can be seen from the delamination graph (fig 3.5c & b) the Röt units increase in thickness downward and through time in this period.

The 2001 log again finds the RNROU-H unit, showing a clearly recognizable unit I, and OU- I to H boundary. Unit OU-I seems slightly thicker than in 1981. The GR values of unit H are a bit on the high side which may indicate damaged casing. This may point to a slight ongoing delamination, but is not conclusive.

No details are known about cavern development and migration could not be related to the delamination process.

Cumulative subsidence at the well location is estimated at approximately 50cm. Correcting for this subsidence does not influence the results (fig 3.5d).

fig 3.5a

B015	thicknesses (m)					
Grlog	base N2 to CSG	CSG to base A4b	base A4ab to base Mu	unit A4ab	unit A3	unit A2c
1974-05	17.74	1.94	35.50	1.13	6.82	7.81
1976-10	17.34	2.49	35.49	0.95	6.69	8.53
1978-02	17.65	2.32	35.58	0.90	7.20	8.15
1981-09	17.35	2.43	35.94	0.93	7.00	8.18
1983-08	16.68	2.53		1.99	7.06	8.85
1985-06	17.56	2.96	36.16	0.86	7.44	7.84
1987-01	17.20	3.36	35.90	1.44	7.24	8.31
1990-01	17.55	3.17	36.51	1.44	6.94	8.91
1994-09	17.88	2.87	36.34	1.64	7.14	8.46
1995-08	17.71	3.70	36.23	0.98	7.19	8.64
1996-07	18.16	3.80	36.17	0.70	7.15	8.69
2001-10	18.00	3.13	36.51	1.21	7.23	8.85

fig 3.5b

B015	thicknesses (m)						
Grlog	unit A2a	unit A1	unit OU (I - F)	unit OU-I	unit OU-H	unit OU-G	unit OU-F
1974-05	9.78	5.51	38.79	22.81	7.13	8.85	12.53
1976-10	9.56	5.44	38.71	22.95	7.08	8.68	12.54
1978-02	9.66	5.56	38.75	22.91	7.03	8.81	12.36
1981-09	9.44	5.56	41.06	23.09	7.77	10.2	12.08
1983-08	10.35						
1985-06	9.09	5.79					
1987-01	9.14	5.7					
1990-01	9.98	5.54					
1994-09	10.38	5.45					
1995-08	10.57	5.35					
1996-07	10.28	5.45					
2001-10	9.49	5.34		23.33			

fig 3.5c

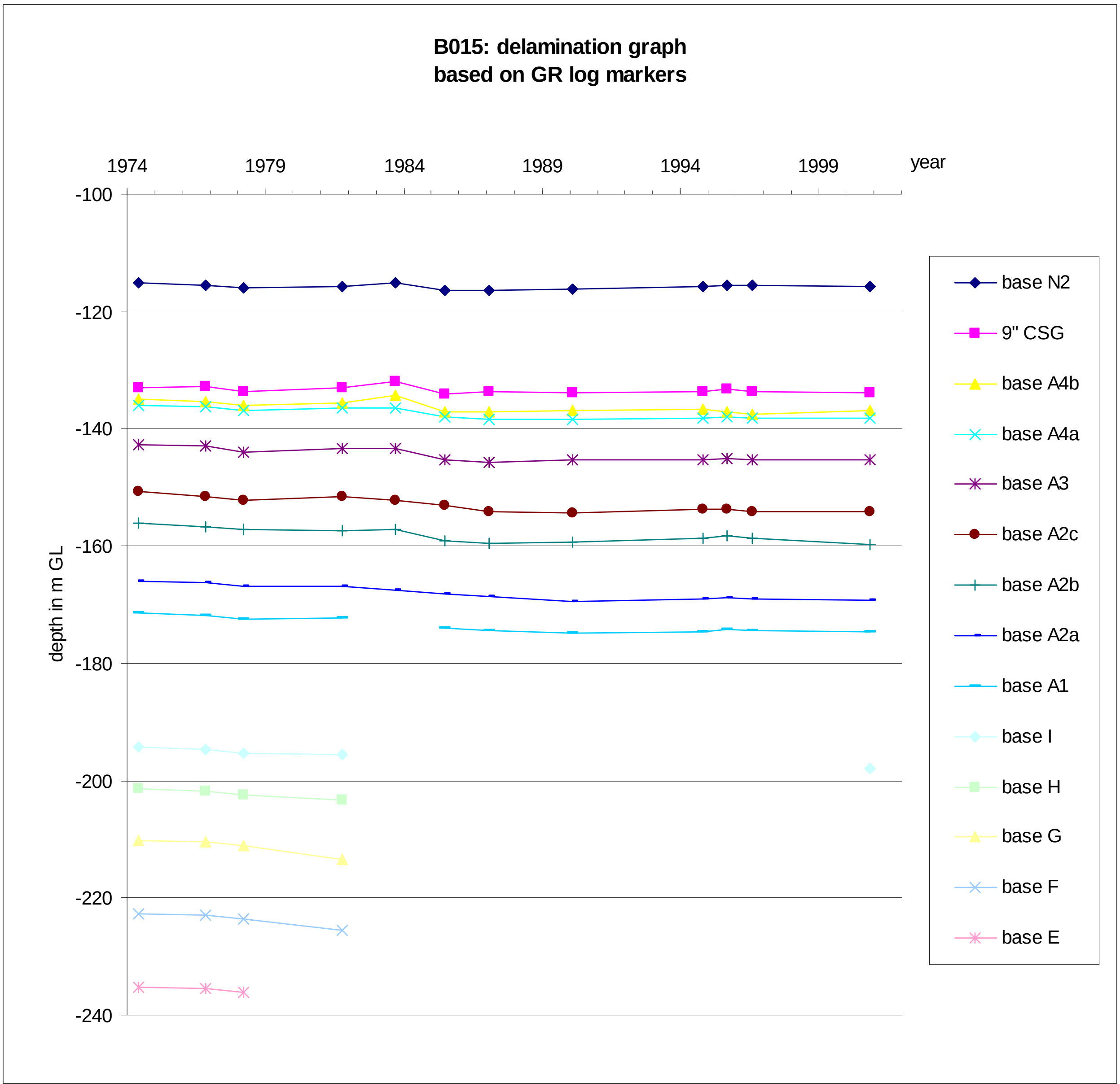
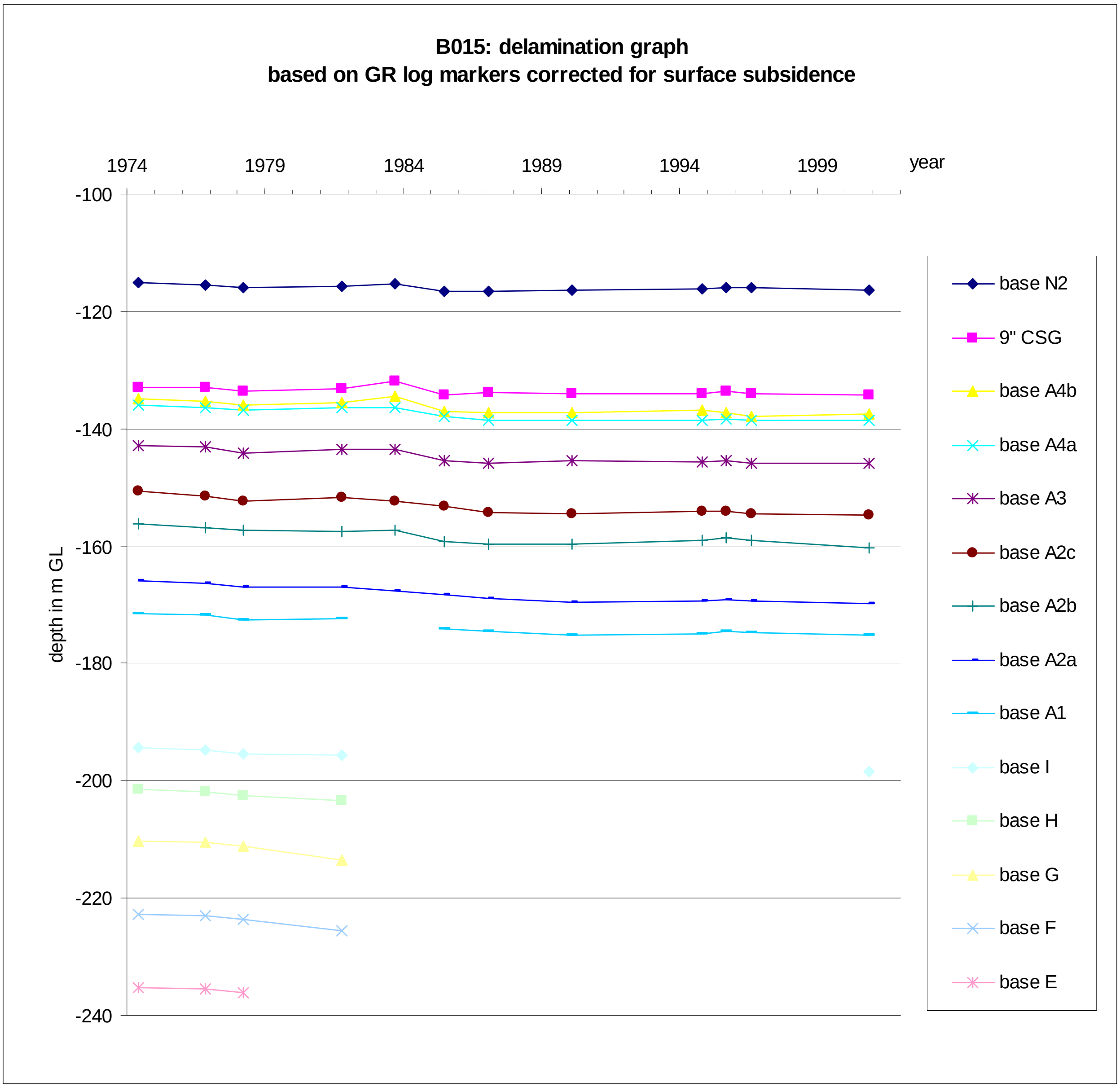

B015: delamination graph
based on GR log markers
1974
1979
1984
1989
1994
1999
year
-100
-120
-140
-160
-180
-200
-220
-240
depth in m GL
base N2
9" CSG
base A4b
base A4a
base A3
base A2c
base A2b
base A2a
base A1
base I
base H
base G
base F
base E

fig 3.5d


B015: delamination graph
based on GR log markers corrected for surface subsidence
1974
1979
1984
1989
1994
1999
year
-100
-120
-140
-160
-180
-200
-220
-240
depth in m GL
base N2
9" CSG
base A4b
base A4a
base A3
base A2c
base A2b
base A2a
base A1
base I
base H
base G
base F
base E

3.6 B023

The well was drilled in 1950 but already in 1951 problems with the 4” tubing suggested an “instorting”. Production from the well was stopped in 1959. The “boorboek” mentions the 9” casing at 127.97m, but the GRlogs do not show indications for a casing shoe at this depth.
Of B023 only two Gamma Ray logs are available. The one from 1981 which was used in the part 1 study (GL10.1001) and a new curve from 2018. Correlation between the logs is good in general but there is a non-linear depth offset. The 2018 curve reads 3.0m higher at the top of the Muschelkalk Formation but 4.3m higher at the base of the Formation. Deeper, at the base of the Röt claystone unit C3, the offset has increased to 5.2m. It is not known which of the curves is incorrect, possibly something has gone wrong in the digitizing process of the 1981 log. A new GR run will have to be made to confirm the 2018 log. A final well log with both GRlogs has been added, a delamination graph has not been made.

3.7 B037

The well was drilled in 1955. In 1967 the cavern appeared to be connected with those of B038, B039, B040 and B041. A Prakla measurement was carried out in 1971, and production was continued until 1979. In 1977 the cavern was found connected with B094 and B095 as well. The details of the Prakla measurement are unknown. The oldest GRlog dates back to 1979 but it covers the section of the Röt claystones only. The 20030211-4 GRlog was used as a reference originally (GL10.1001).

For B037 various logs from 2003 and one log from 1979 are available. All logs from 2003 have been displayed on the panel; the 2003 logs are of a good quality and most of them compare well. The logs of 12th June and 13th June do not correlate with the other ones, the readings of the latter are also 70cm high compared to the other curves.

Correlation is good down to the level of marker X1, which represents the top of the zone of disturbed formation. The base of unit OU-C2 is found 80cm deeper and marker X1 is found 2m deeper on the 2003 log. On the 1979 log, the interval 319.8 – 326.9m represents a local void or (part of) the cavern, below which collapsed formation is present again.

Especially low GR peaks should be correlated with care because they do not always represent formation, but can also be caused by voids or washed out hole.

delamination and migration

In 1979 migration had reached into unit RNROU-C.

Thicknesses from base H to marker X1 show an increase in thickness of 2m between the logs. This difference can mainly be attributed to the lower unit OU-C2 and the section below base C2 to marker X1. Though this seems to point to delamination, it is difficult to prove delamination with any confidence based on two logs only.

Low readings in the lowermost part of the log of June 17th may indicate the local void below the X2 marker. On the logs of 12th and 13th June only disturbed formation can be seen at this depth. This would bring the top of the void 5.8m shallower on the 2003 log.

An attempt has been made to add surface subsidence to the delamination graph (fig. 3.7c). Based on extrapolation of the available data surface subsidence proved to be small (Ch. 4.7; fig 3.7c & d).

fig. 3.7a

B037	thickness (m)							
GRlog	base H to marker X1	OU-H	OU-G	OU-F	OU-E+D	OU-C3	OU-C2	base C2 to marker X1
1979-08	80.09	7.45	8.53	11.61	25.20	12.57	11.09	11.09
2003-02 no4	82.13	7.89	8.07	11.81	25.53	12.52	11.94	12.26

fig. 3.7b

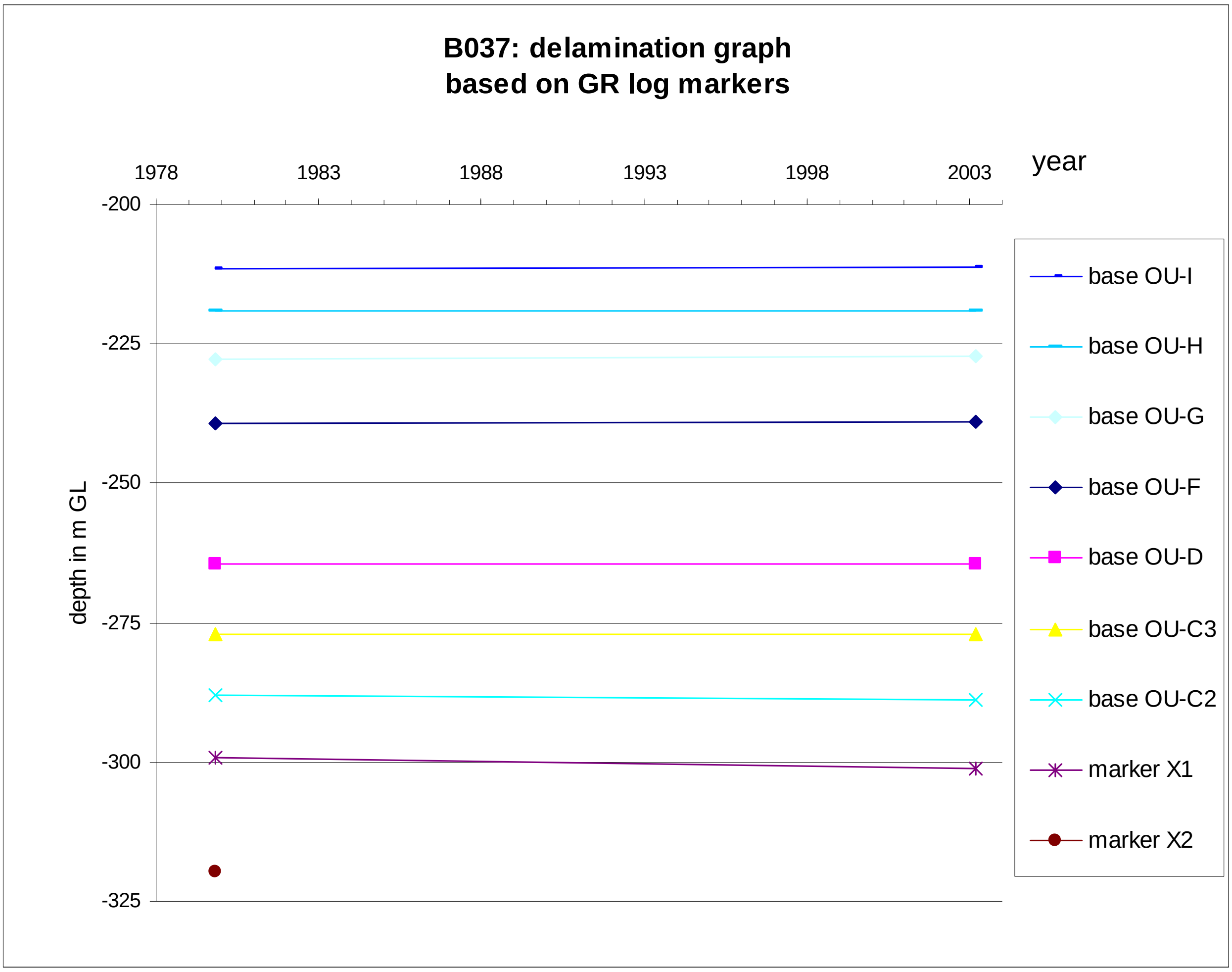
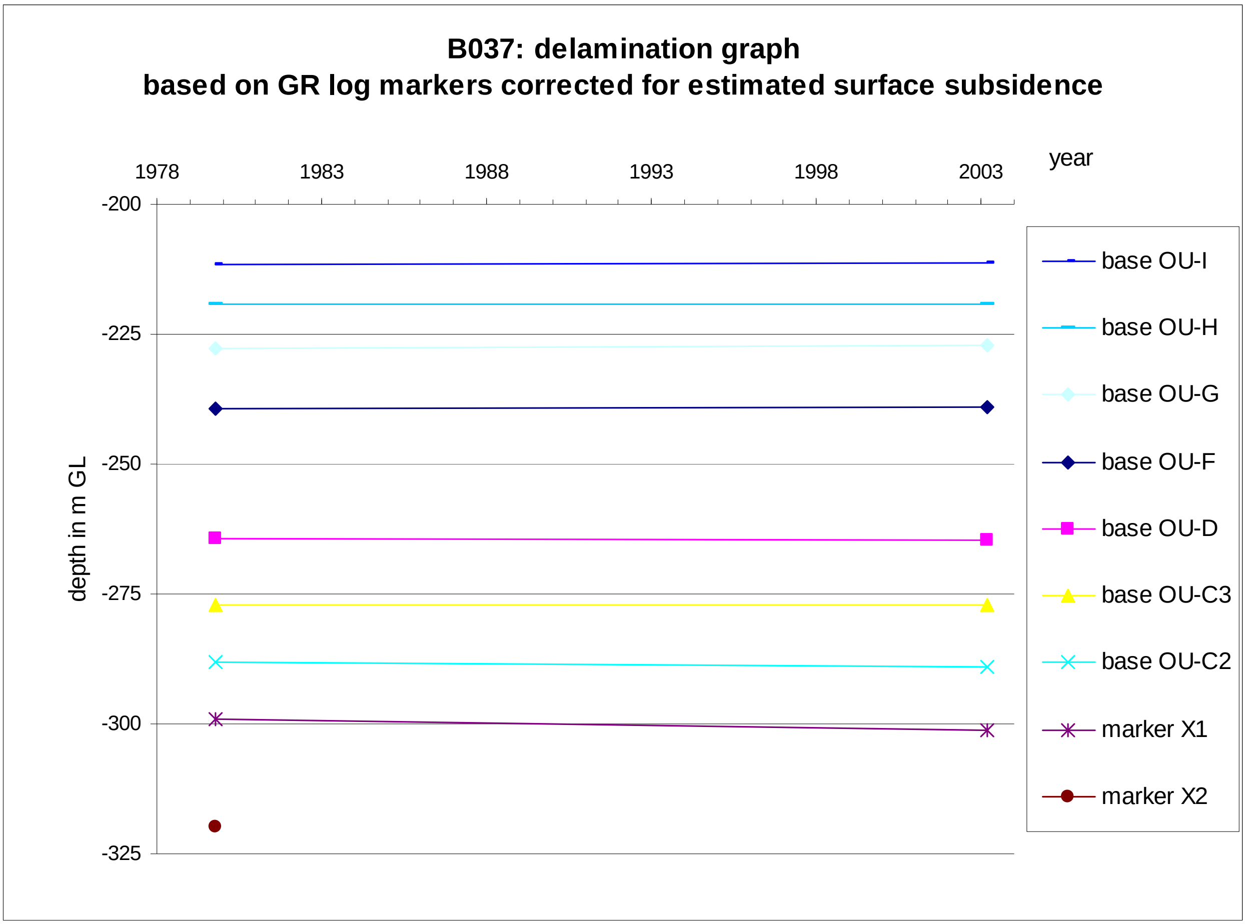

B037: delamination graph
based on GR log markers
year
1978
1983
1988
1993
1998
2003
-200
-225
-250
-275
-300
-325
depth in m GL
base OU-I
base OU-H
base OU-G
base OU-F
base OU-D
base OU-C3
base OU-C2
marker X1
marker X2

fig. 3.7c


B037: delamination graph
based on GR log markers corrected for estimated surface subsidence
year
1978
1983
1988
1993
1998
2003
-200
-225
-250
-275
-300
-325
depth in m GL
base OU-I
base OU-H
base OU-G
base OU-F
base OU-D
base OU-C3
base OU-C2
marker X1
marker X2

3.8 Series B167

The cavern of series B167 has been developed in a complex faulted area, similar to the neighboring cavern B156 to B158. These faults are of a composite nature and the total amount of off-sets in the Muschelkalk and Röt sections is considerable, up to 65m. Because of the complex nature of the fault patterns in this part of the area, faults have been indicated schematically In report GL10.101.

Delamination and migration

The delamination graphs clearly show significant migration for B167 and B168 with the latter also showing progressive delamination. The collapse of the cavern at the B168 location is most likely related to the faults in this area; the formation is fractured and disintegrates more easily compared to undisturbed continuous strata. Problems were already recognized in 1980 when the roof of the cavern had migrated into the upper Anhy-E unit, but production went on until 1994.

Since subsidence was considered negligible by Nouryon, surface subsidence data have not been accounted for.

3.8a B169

The well was drilled in 1970 and it produced until 1994. A total of some 58m of Muschelkalk and Röt section is found cut-out in the well trajectory. The oldest GRlog dates back to 1990, but it covers the salt section only and readings on this curve are 1.6m high to the next GRlog of 1994. In 2002 the well was logged to surface for the first time and this run was taken as the reference in the 2009 study (GL10.1001). From this time onward the well has been regularly logged.

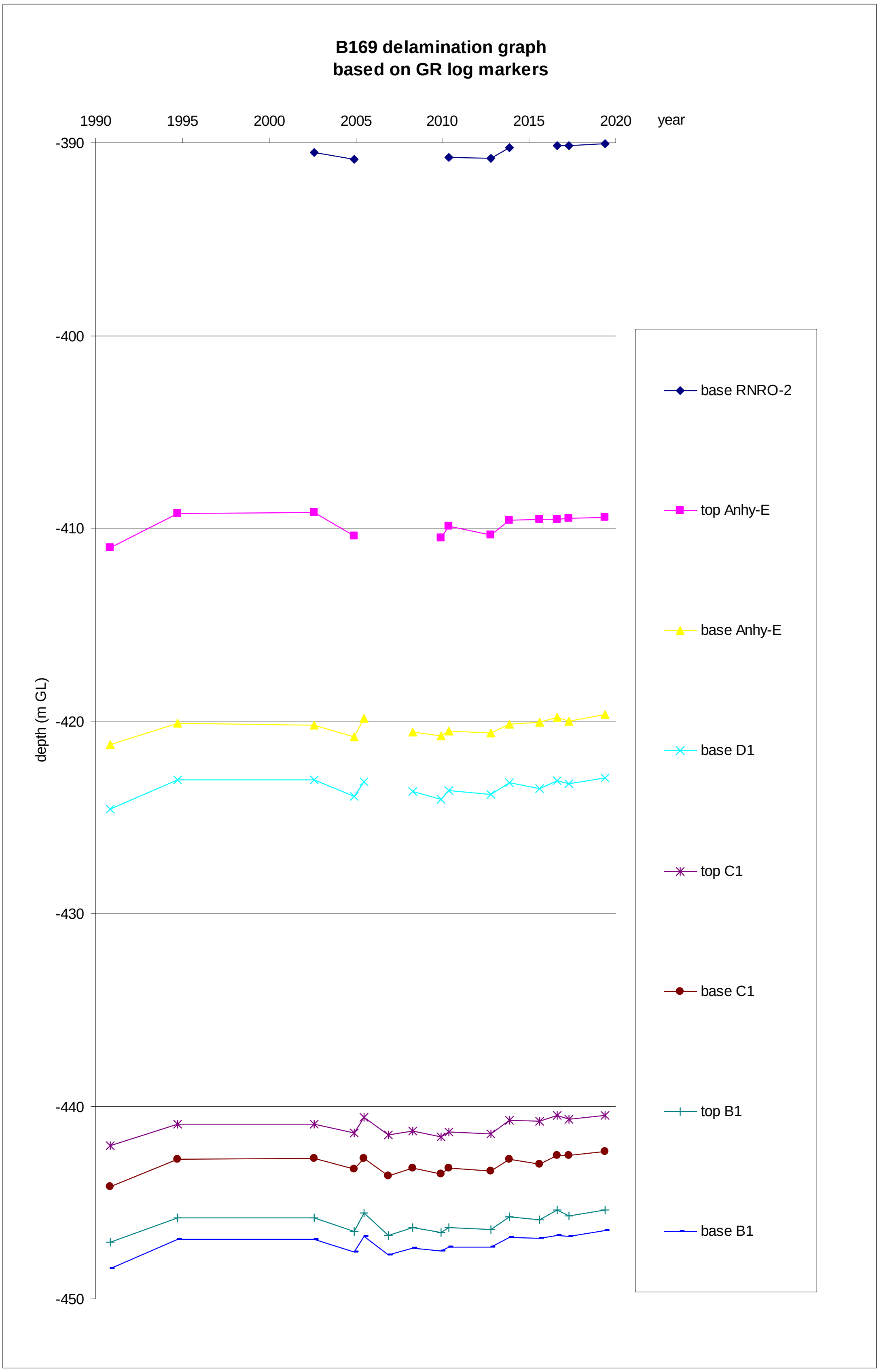
Indications for delamination have not been found. At the levels of base Muschelkalk Formation, Upper Röt Evaporite Member, top MRE and top Salt C no differential thickening or deepening occurs. Boundaries are found either slightly higher or slightly lower compared to the 2002 reference curve. Formation thicknesses do not change with time (fig. 3.8a-a). Also within the salt section itself, at the levels of B1 and C1 no consistent thickening is seen.
Remarkably, from 2010 the units within the MRE come in shallower with time (fig. 3.8a-c).

The roof of the cavern was determined at 469.90m in 1994 by Socon. This does not show as a major break on the GRlog.

fig 3.8a-a

B169										
	9 5/8" CSG	thickness	thickness RNRO							
Grlog	to base SK	RNMU	OU+O2	O2+OM	Anhy-E	D1	Salt C	C1	Salt B	B1
1990-10					10.22	3.38	17.46	2.13	2.88	1.35
1994-08					10.91	2.93	17.86	1.83	3.07	1.10
2002-07	147.73	97.47	97.71	18.71	11.00	2.85	17.89	1.77	3.07	1.12
2004-11	148.23	97.62	97.69	19.55	10.47	3.04	17.51	1.86	3.24	1.06
2005-06						3.26	17.45	2.11	2.83	1.22
2006-11								2.12	3.08	1.05
2008-03						3.07	17.64	1.91	3.06	1.09
2009-12					10.29	3.28	17.50	1.91	3.06	0.97
2011-05	147.49	97.47	98.00	19.10	10.65	3.10	17.73	1.83	3.10	1.04
2012-09	147.81	97.16	97.61	19.56	10.28	3.17	17.62	1.96	3.01	0.95
2013-10	147.63	97.42	97.54	19.34	10.56	3.03	17.53	2.03	3.01	1.03
2015-07					10.57	3.42	17.28	2.23	2.89	0.96
2016-07	147.19	97.48	97.37	19.36	10.29	3.30	17.39	2.07	2.84	1.31
2017-03	147.11	97.17	97.76	19.35	10.54	3.21	17.42	1.87	3.17	1.03
2019-05	147.17	97.07	97.82	19.39	10.27	3.28	17.53	1.87	3.04	1.06

fig 3.8a-b


B169 delamination graph
based on GR log markers
1990
1995
2000
2005
2010
2015
2020
year
-390
-400
-410
-420
-430
-440
-450
depth (m GL)
base RNRO-2
top Anhy-E
base Anhy-E
base D1
top C1
base C1
top B1
base B1

3.8b B168

In 1994, the cavern at the B168 location had migrated into the top of Anhy-E. This is illustrated on the 1994 echo, included in the 'boorboek' and can also be seen on the GRlog. Cavern migration is probably related to faults present in this area. The total fault cut-out in the well trajectory in the Muschelkalk and Röt sections amounts to some 65m. The first GRlog to surface was made in 2002. The well was in use as the injection well until 1985 when part of the tubing was lost in the cavern and injection was taken over by B167.

delamination and migration

The depth of the base of the Muschelkalk Formation remains unchanged through time. Also the bases of the Röt claystone units F and C3 remain at the same depths. But at deeper levels the situation changes.
On the 1994 GR curve, the roof of the cavern is found at 416.0m (marker X3), but on the 2002 log collapsed formation is present at this level with a local void from 384-392m. On 2006 log the void has migrated to 379.8m but on the later logs collapsed formation is found at this level. Since 2002 the marker X3 which represents the top of the void or the top of collapsed formation ascended approximately 4m.

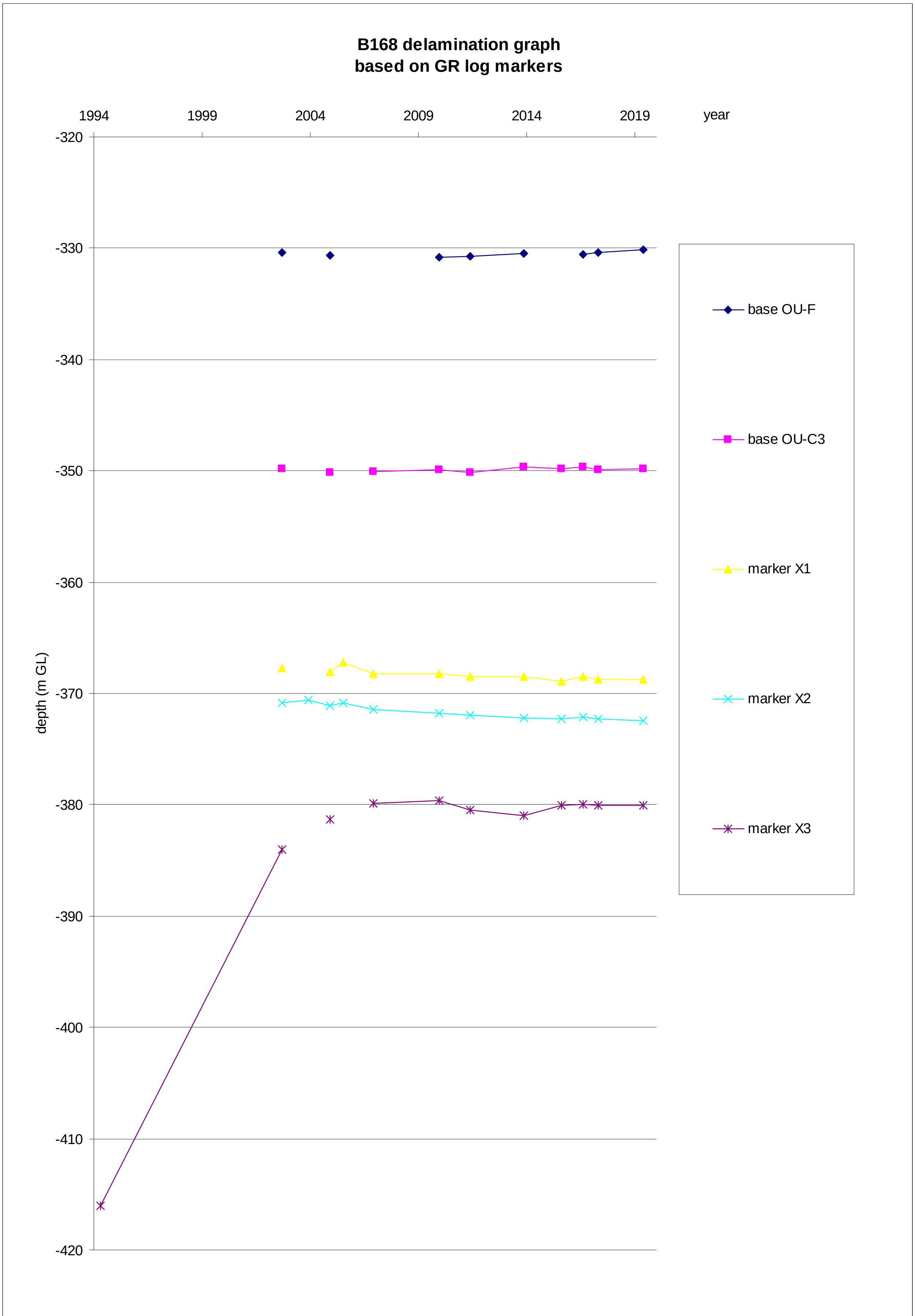
The base C2 boundary is not very well defined on all GRlogs and two high GR peak markers are therefore added to identify delamination (X1 and X2). In 2019 the high GR peak marker X1 is found approximately 1m deeper than on the 2002 curve. In the same time the distance between the two markers increases 70cm (fig 3.8b-a). From the data in fig 3.8a it can be concluded that though delamination seems to stop in 2013 (delta base C3 to X1 and delta marker X1-X2), migration continuous (delta marker X2-X3).

Figure fig 3.8b-b shows the progressive delamination in combination with migration.

fig. 3.8b-a

B168	thickness (m)							
Grlog	CSG to base SK	RNMU	units OU-I + H	unit OU-F	units C3+D+E	base C3 to X1	marker X1 - X2	marker X2 - X3
2002-08	148.35	98.54	15.18	20.09	19.50	17.91	3.06	
2004-11	147.59	98.82	14.79	20.53	19.46	17.95	3.04	10.17
2005-06							3.60	
2006-11						18.10	3.25	8.41
2009-12		98.89	14.72	20.63	19.12	18.31	3.51	7.85
2011-05	147.97	98.78	14.82	20.40	19.38	18.33	3.48	8.53
2013-10	147.93	98.79	15.04	20.17	19.21	18.81	3.70	8.79
2015-07						19.07	3.38	7.79
2016-07	147.87	98.58	14.79	20.75	19.10	18.84	3.58	7.91
2017-03	147.82	98.12	14.90	20.56	19.51	18.83	3.58	7.79
2019-05	147.48	98.69	14.62	20.39	19.69	18.92	3.70	7.57

fig 3.8b-b


B168 delamination graph
based on GR log markers
1994
1999
2004
2009
2014
2019
year
-320
-330
-340
-350
-360
-370
-380
-390
-400
-410
-420
depth (m GL)
base OU-F
base OU-C3
marker X1
marker X2
marker X3

3.8c B167

In the B167 well trajectory a total of 65m is cut-out in the Muschelkalk and Röt sections due to normal faulting (earlier reports).

The six logs run from 2011 correlate well in the upper section, no thickness differences can be seen here (fig 3.8c-a). Below the marker X1 in unit OU-I, correlation between the logs is lost, pointing towards disturbed formation. The thickness of base MU to marker X1 varies little and no trend can be seen. The thickness between the X1 - X2 marker decreases significantly showing the upward migration of the cavern (fig 3.8c-c). 3.8c-b seems to show a slight thickening in the salt units from 1980 to 2002, but this is thought not to be conclusive.

On the 2002 GRlog which is the first GRlog to surface, a void is indicated from 331.2m to 356.9m in the Röt Claystone Member (maker X2 - X3), but deeper, a complete section of lower RNROU, RNRO2, RNROM and RNRO1 is present again. The local void here is probably an extension of the collapsed cavern at the B168 location. Later GR curves show the top of this void at progressively shallower levels until 2011, when the migration process seems to stop at 312.7m. The base of the void only shows on the 2002 and 2006 GRlogs. From 2011 and on, the HUD is stable around 311m (see also GRlog history, attachment A).

Formation tops come in slightly shallower with time, which may be related to surface subsidence (fig 3.8c-d).

fig 3.8c-a

B167	thickness (m)								
GRlog	CSG to base SK-C	unit SK-A +B	CSG to base MU	unit B3	unit A4h	units MU A4e + A4f	unit A1 + A2	unit OU-I	unit OU-H
2002-07	122.62	22.91	243.74	19.81	14.46	10.78	20.88	16.52	7.27
2005-06	123.37	22.85	244.62	19.76	14.50	10.83	20.72	16.14	7.11
2008-03	123.79	22.89	245.18	19.82	14.68	10.73	21.02		
2011-05	123.44	22.82	244.57	19.80	14.44	10.83	20.88		
2012-09	123.00	22.90	244.18	19.78	14.49	10.75	20.82		
2013-10	123.19	22.94	244.56	19.65	14.61	10.83	21.01		
2015-07						10.86	21.18		
2016-07	123.50	22.91	244.47	19.77	14.47	10.79	20.72		
2017-03	124.09	22.69	245.31	19.92	14.14	11.02	21.08		
2019-05	122.99	22.73	244.21	19.64	14.49	10.83	20.83		

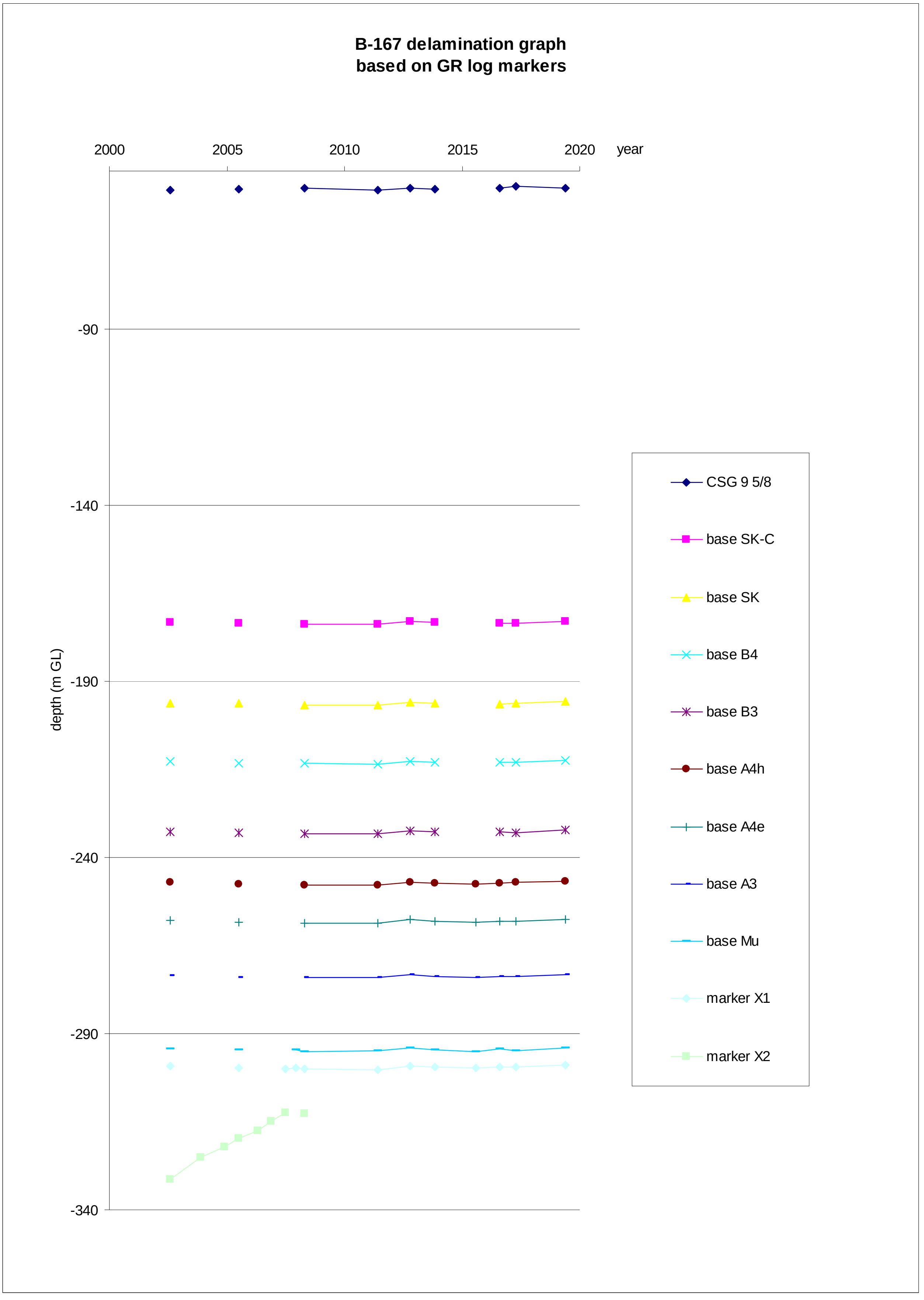
fig 3.8c-b

B167	thickness RNRO1 (m)					
GRlog	Anhy-E	D1	C1	B1	Salt C	Salt B
1980-01	9.38	3.09	1.37		17.86	
1994-03				1.05	16.88	3.30
1998-05	9.85	3.15	1.72	0.64	17.74	4.31
2002-07	9.31	3.09	1.12	0.84	18.23	4.37

fig 3.8c-c

B167	thickness (m)	
	base MU	marker X1
GRlog	marker X1	to X2
2002-07	5.03	31.94
2011-05	4.99	20.10
2016-07	5.18	
2017-03	4.86	12.67
2019-05	5.23	

fig 3.8c-d


B-167 delamination graph
based on GR log markers
2000
2005
2010
2015
2020
year
-90
-140
-190
-240
-290
-340
depth (m GL)
CSG 9 5/8
base SK-C
base SK
base B4
base B3
base A4h
base A4e
base A3
base Mu
marker X1
marker X2

4. Surface Subsidence data

The reference depth for the wireline logs is CF or MV/GL, meaning surface subsidence may affect this depth. Therefore an attempt was made to include surface subsidence data to come to a corrected reference value per wireline log.

Surface subsidence data were made available by Nouryon in the normalisatie.xls file for the period before 1996, in the Oranjewoud 'waterpasmetingen' 2001 & 2008, reports for data from 1996 to 2008, and in the (concept) MUG report for the period to 2018.

Especially from the older data it proved difficult to obtain a reliable subsidence level at the well locations at the different times of logging. For most wells several measurement points are available at the exact well location in the normalisatie.xls file. They often are for different periods but in the overlapping periods different absolute and delta values can be observed even when the coordinates are exactly the same. Later new measurement points were added, which were not always located at the well location. This means extrapolation is unreliable in some cases. Especially after 2008 only limited data is available for the exact location of the wells included in this study.

Especially with older data deviating values were identified, which were sometimes caused by erroneous measurements. But sometimes the physical measurement point was moved (fallen down, dug up by roadwork and/or re-positioned). After study of the reports, the Oranjewoud data appeared to have the best quality data, and they are used as main reference.

Forward extrapolation to 2018 and backwards to the year of the first wireline log required data for several measurement points to be linked. Per well the data have been studied, and an attempt has been made to find an acceptable series of data for the well location. (see discussion per well). The year of the first wireline log has been taken as '0' and subsidence with time is represented as a cumulative change in 0.00m to every GRlog.

Whenever possible delamination graphs have also been made with surface subsidence included (see chapter 3).

Some inconsistencies were found in the Nouryon normalisatie.xls file. The period stated (column E) is 10 (October) or 4 (April) in the Date column (J) both months are stated as April. For a number of wells a dedicated sheet had been added with cumulative surface subsidence graphs. Some of these graphs are erroneous. E.g. for B025 the data for the years 1963 to 1965 were used twice, once from measurement point B25.1 (C12 - C15) and once from measurement point B25 (C15 - C17). This erroneous data set had been used to prepare the graph in the normalisatie file.

As can be seen from the discussion per well below results are very tentative and only give an indication of the impact of subsidence at the exact well location. Accurate reconstruction of the effect of surface subsidence on the GRlog reference depth falls outside of the scope of this study.

4.1 ON1

No subsidence data for ON1 are available. ON1 is drilled between B018 and B024; only for the latter location subsidence measurements are stated for the period of interest. For B024 three values are available B24 (meetpunt 1024), B24.1 and B24.2 (meetpunt 91551 & 91375). The coordinates of all measurement points are exactly the same (two decimals), but NAP values and delta values are different. The Oranjewoud report uses point number 1024 (report 2001). Therefore the B24/#1024 meetpunt measurements are also used, from 1972 to 1998. The Oranjewoud report states a starting value of 19.926 for 1972 and a delta of -842mm until April 1996, which is the same as stated by the normalisatie.xls file for meetpunt 1024. Also the deltas for the years to 1998 are similar, with the normalisatie file using one decimal more. The Oranjewoud delta values to October 2001 are added to the series. For 2018 the value of 2001 is added.

No new measurements are stated in the Oranjewoud 2008 report or in the 2018 MUG report.

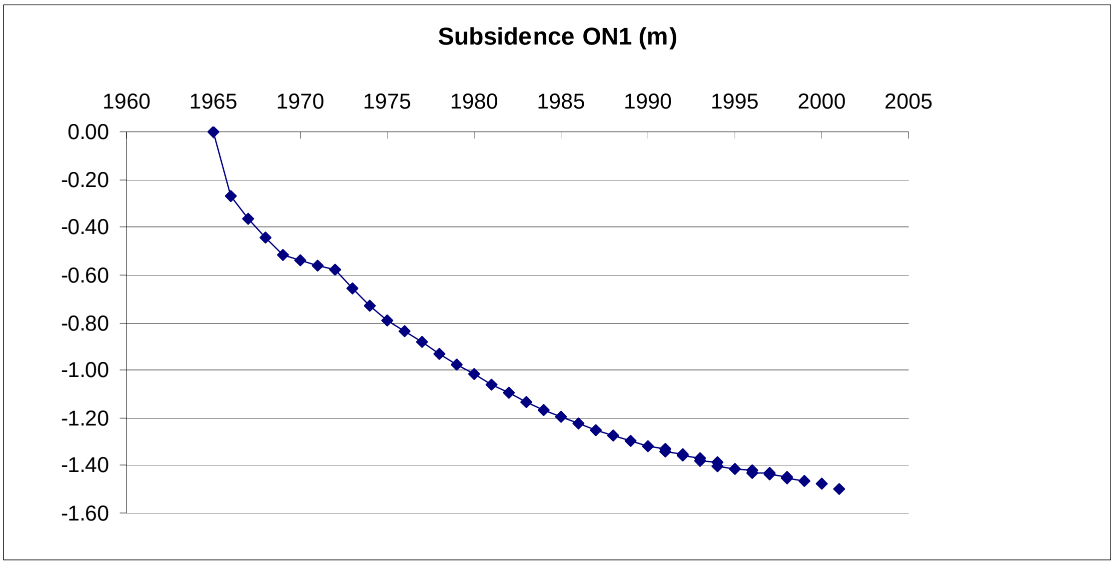
To extrapolate the data back to 1967 the delta measurements of point B24.2 have been used, for 1970 and 1971 the value of 1969 has been taken.

The subsidence was calculated relative to the year of the first wireline log in 1965.

fig 4.1a

ON1 date Grlog	Subsidence (m)
1965-06	0.00
1967-09	-0.36
1974-04	-0.73
1983-08	-1.14
1985-06	-1.20
1987-01	-1.25
1994-10	-1.40
1995-08	**-1.42**
2018-08	-1.50
2018-11	-1.50

fig 4.1b



4.2 ON2

No data are available for ON2. For well B010, data is available in the normalisatie.xls file. No data in the Oranjewoud & MUG reports is available for nearby measurement points like 5601 - 5604. The B010 data shows periods with probably erroneous data, for instance 1981. The B011 data seem more consistent, but here subsidence is much less than shown for the B010 location. Therefore the B010 data are used with the obviously erroneous data omitted. To extrapolate data from 1996 onwards the nearest available measurement point 5659 is used, which is positioned towards the northeast of well B011.

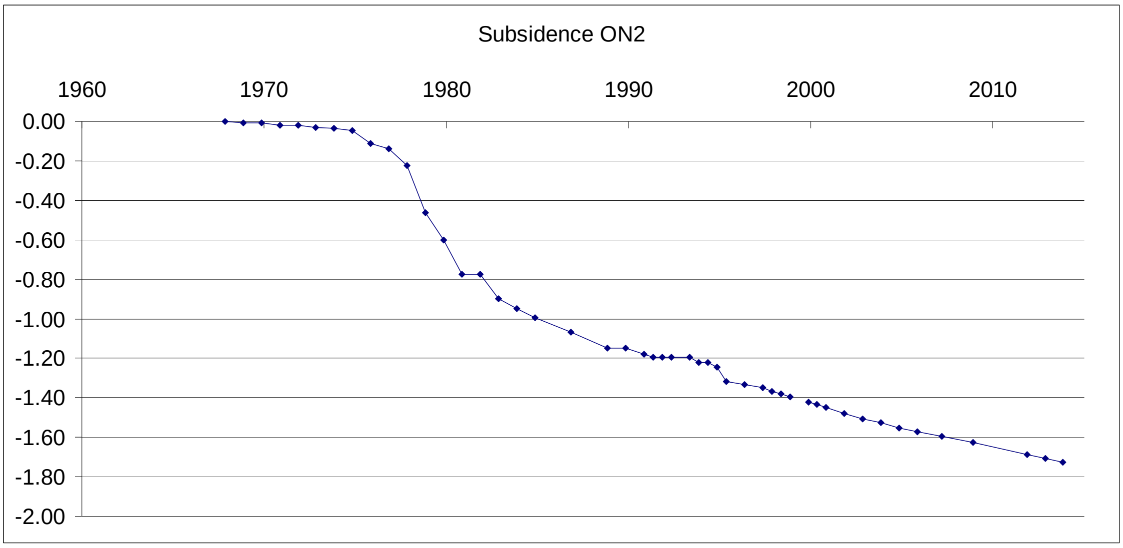
From the year of the first GRlog the data of measurement point 1010 are taken, as a reference for the surface subsidence at the ON2 location. From 1996 onwards delta values from measurement point 5659 are used. It must be noted that the actual subsidence in the location of B010 and ON2 is probably higher than stated for point 5659, which is closer to the B011 location.

No data is available for these measurement points in the MUG report (2018). From 2001 the 20mm per year realized from 2003 to 2008 is used to calculate the subsidence for the period of the later wireline logs.

fig 4.2a

ON2 date Grlog	Subsidence (m)
1967-11	**0**
1974-05	-0.05
1976-10	-0.14
1978-02	-0.46
1980-12	-0.77
1981-08	-0.83
1983-08	-0.95
1985-06	-1.03
1987-01	-1.11
1990-03	-1.18
1991-04	-1.19
1994-10	-1.32
1996-09	-1.33
2011-09	-1.69
2012-09	-1.71
2013-05	-1.73

fig 4.2b


Subsidence ON2
1960
1970
1980
1990
2000
2010
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
-2.00

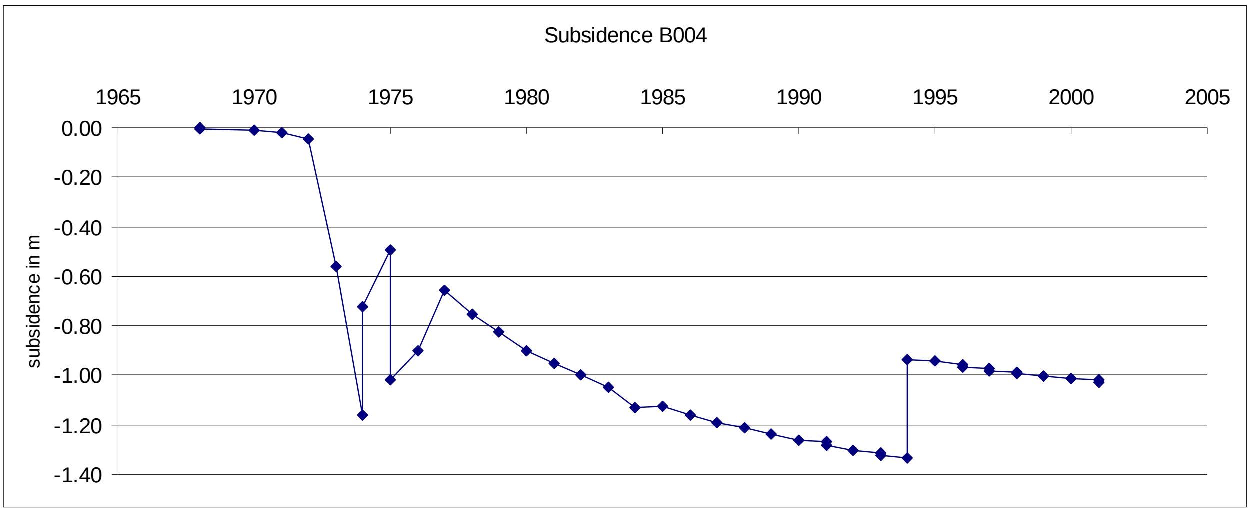
4.3 B004

The normalisatie file contains data for B4, B4.1, B4.2 and B4.3. All four measurement points have exactly the same coordinates (two decimals). Only B4 (meetpunt 1004) has continuous data from 1968 to 1998. The other three measurement points only cover the period from 1941 until 1963. The normalisatie file shows partly erroneous data with unlikely delta values of + 115 to +393 (see figure).

According to the boorboek the 7" casing had subsided and in 1974 an extension was made on top of the 7" casing flange which brought up the "waterpaspunt" 52.6cm. However, the 7" casing again appeared to sink in the 9" casing.

The Oranjewoud report uses meetpunt number 1004, with the starting point chosen at April 1977 and a cumulative delta of -466mm to find a NAP value for April 1996. Both values are the same for both files. The Oranjewoud delta values are used to extrapolate the NAP from 1996 to April 2001. Because of the presence of unreliable data from April 1974 until 1996 these figures have not been added to the delamination graph.

fig 4.3a



4.4 B005

For B005 there are two measurement points available in the normalisatie file: B5 at the exact well location and B5.1 which lies18m to the southeast. For the latter a continuous series is available from 1941 until November 2008. The B5 measurement point is introduced in 1979 and data is available until 2001. Both series show a similar trend. The B5.1 point is used here, because it shows a continuous trend and it is also used by Oranjewoud.

fig 4.4a

B005 date Grlog	Subsidence (m)
1967-11	0
1974-01	-0.06
1975-10	-0.07
1976-11	-0.08
1978-02	-0.09
1980-08	-0.10
1983-08	-0.12
1985-08	-0.14
1990-10	-0.20
1991-07	-0.21
1992-10	-0.23
1994-10	-0.25
1995-07	-0.26
1996-10	-0.27
2001-11	-0.31

4.5 B011

For B011 the data for measurement point 1011 is used for the period from 1983. To extrapolate back to 1967, when the first GRlog was made, the delta values of the B11.2 measurement point are used.

fig 4.5a

B011 date Grlog	Subsidence (m)
1967-09	0
1974-05	-0.03
1976-04	-0.06
1976-10	-0.06
1978-8	-0.08
1983-8	-0.15
1985-6	-0.24
1987-1	-0.27
1990-1	-0.37
1990.7	-0.37
1991-4	-0.39
1994-9	-0.47
1996-7	-0.52
2001-9	-0.65

4.6 B015

In 1997 Oranjewoud added a measurement point 5664 (“meetlijn”), no coordinates are available for this point, but in the 2001 report it is stated to be positioned at the B015 well location. The older normalistie.xls file shows meetpunt B15 (# 1015) and B15.1 - B15.3 all at the well location. The latter three give data up to 1974 and are not used. The B15 data are used for the period from 1972 - 1996. From 1996 the delta of measurement point 5664 from the Oranjewoud reports to come to cumulative subsidence for the last log of 2000. The value of +29 for 1983 is considered erroneous and omitted from the dataset. To calculate a value for 1983 and 1985 a surface subsidence rate of 1 mm/year is used.

fig 4.6a

B015 date Grlog	Subsidence (m)
1974-5	0
1976-10	-0.02
1978-2	-0.04
1981-9	-0.07
1983-8	-0.09
1985-6	-0.11
1987-1	-0.15
1990-1	-0.2
1994-9	-0.32
1995-8	-0.34
1996-7	-0.37
2000-10	-0.49

4.7 B037

For B037 three measurement points have been used: 37.1 (from 1955 until 1988), 37.2 from 1955 until 1966 and 37.3 from 1955 until 1958. All three points are at the exact well location. The data show some subsidence in the early 60's of approximately 8mm/year and again in 1977 and 1980. Total surface subsidence from 1955 to 1981 is 8.6cm.

No data for the years 1982 - 1986, and a plus 669mm delta is shown for 1987. The latter probably is caused by a re-adjustment of the physical position of the measurement point. It has not been measured after 1988. It is measured again from 1998 when it was renamed number 103702. It is not clear whether this is exactly the same measurement point. This indicates a surface subsidence of 70cm in 10 years. If the B37.1 NAP value from 1981 is used, the subsidence would be 6cm.

Measurement point 103702 shows 2mm/year subsidence from 1998 until 2001, later it has not been measured again. This is in line with the average 4mm/year for the period from 1961 – 1981 for B37.1. The most likely surface subsidence trend seems to be 2mm per year with occasional discontinuities when up to 9mm per year is in evidence.

To come to a (minimum) subsidence from 1979 until 2003, which is the period for which wireline logs are available, a subsidence of 3mm per year has been used, which gives a total surface subsidence of 7cm for the 2003 log relative to the 1979 log.

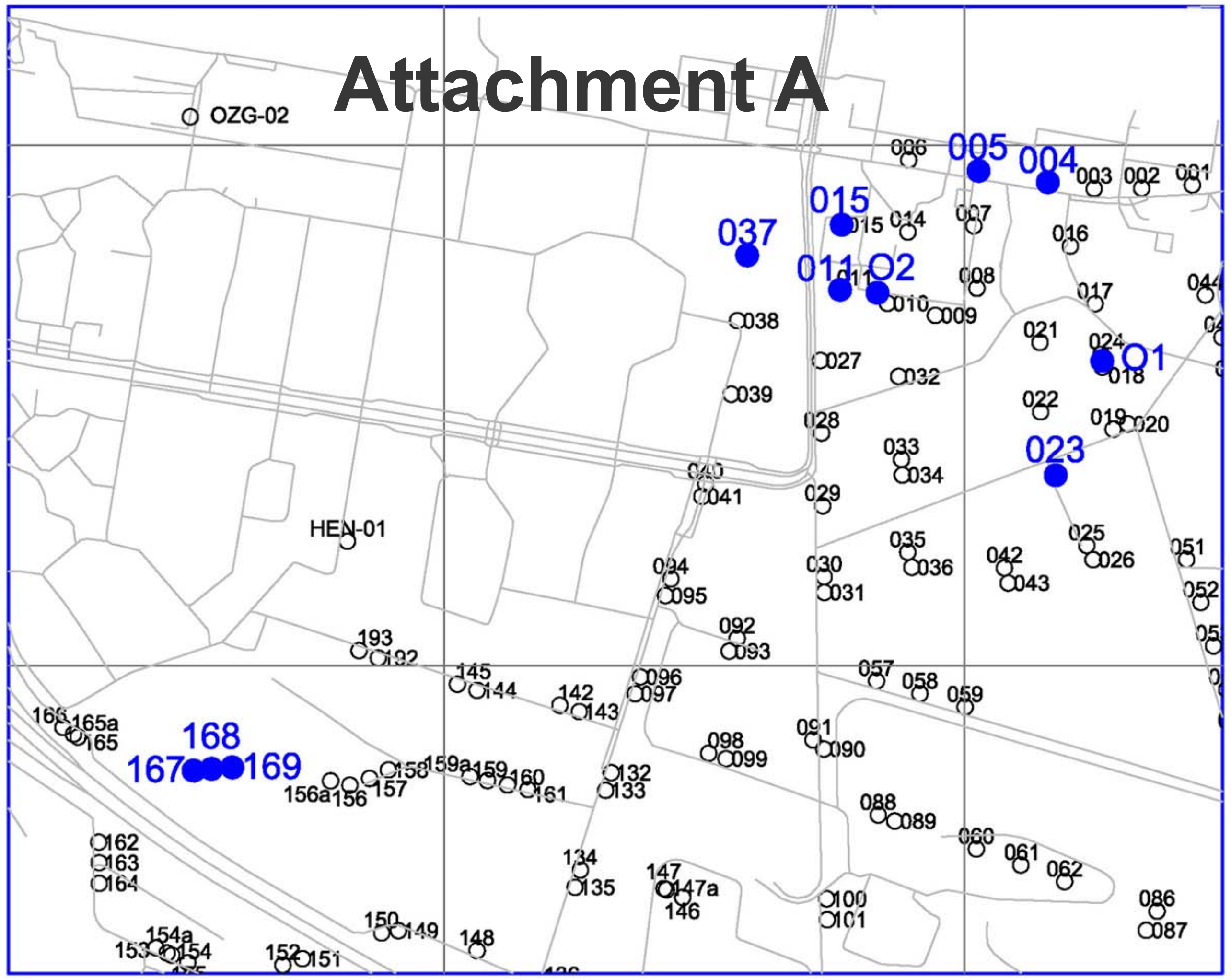
4.8 Other wells

B023 ; For measurement point 102301 no data is available after 2001. Only two GRlogs are available for this well which have a considerable depth offset and extrapolating data to 2018 seems not realistic.

Series B167
Limited surface subsidence in the area is stated by Nouryon and the subsidence data have not been included in the study.

TWR North

identification of delamination based on GRlogs



for

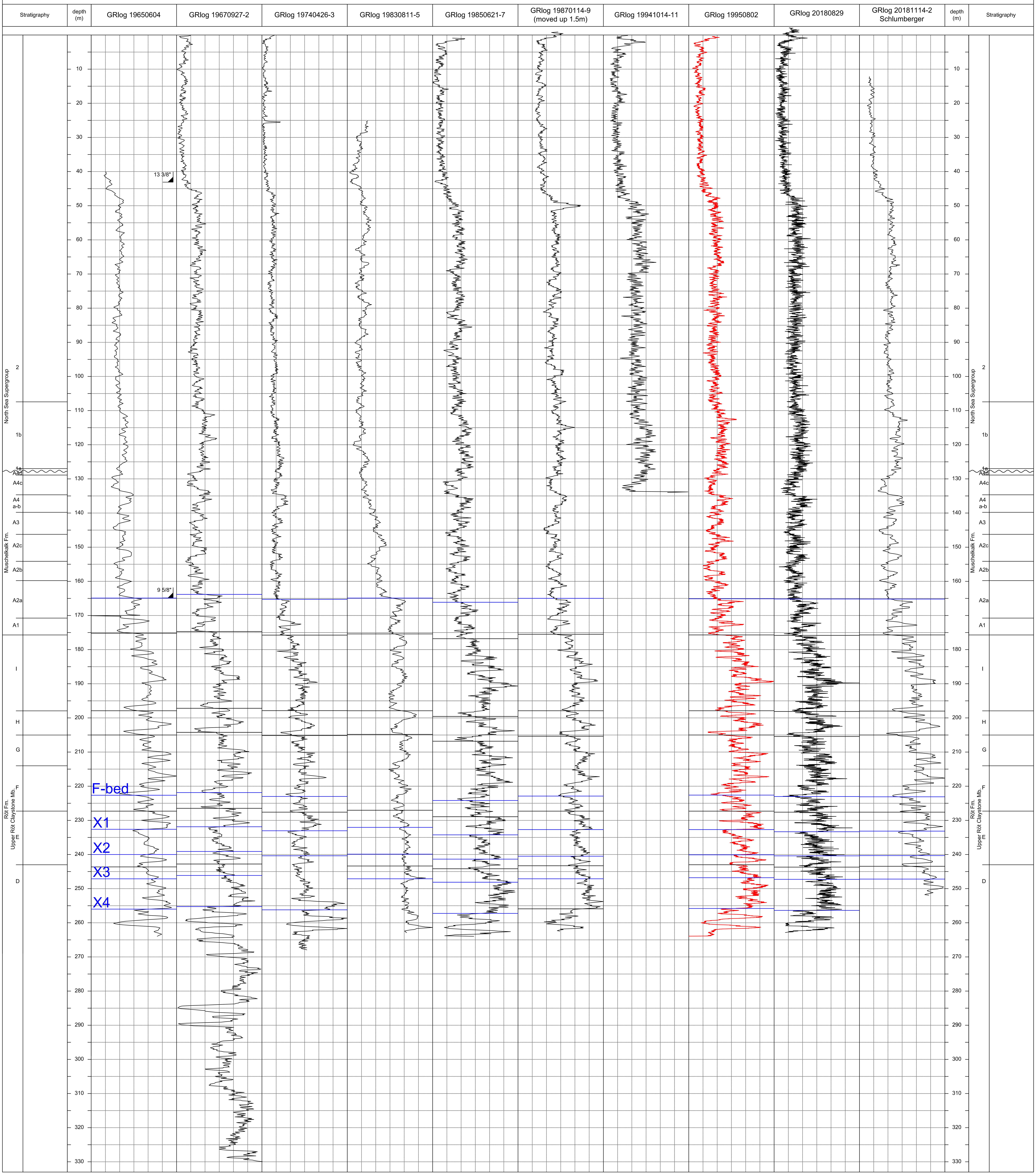
Nouryon

prepared by:
GEOWULF*Laboratories,* the Netherlands
April 2019, report no: GL19.401
info@geowulf.nl

Well ON1: Gamma Ray history panel

Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

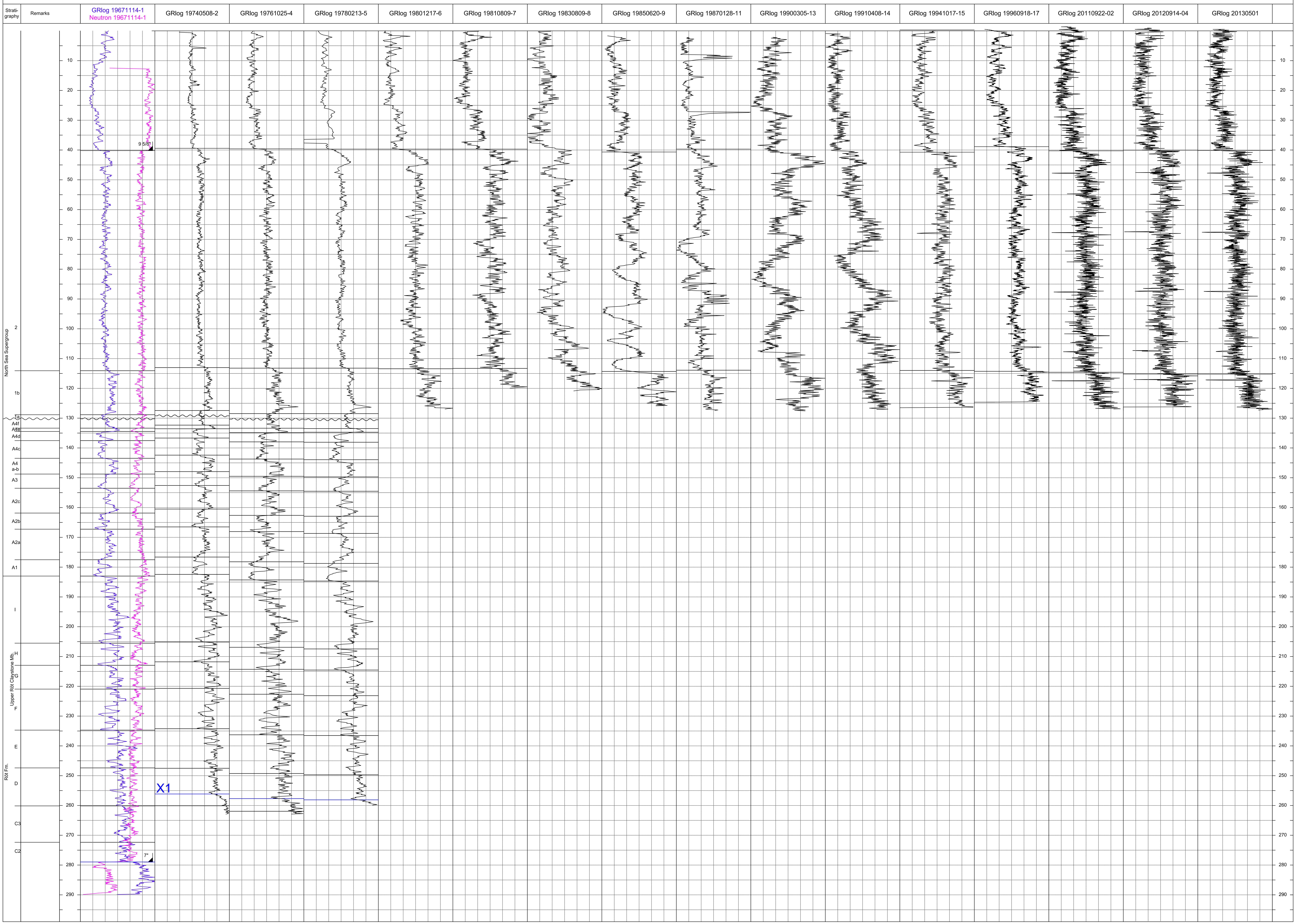
Attachment A; report GL19.401
prepared by:
GEOWULF*Laboratories*, the Netherlands



Well ON2: Gamma Ray history panel

Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

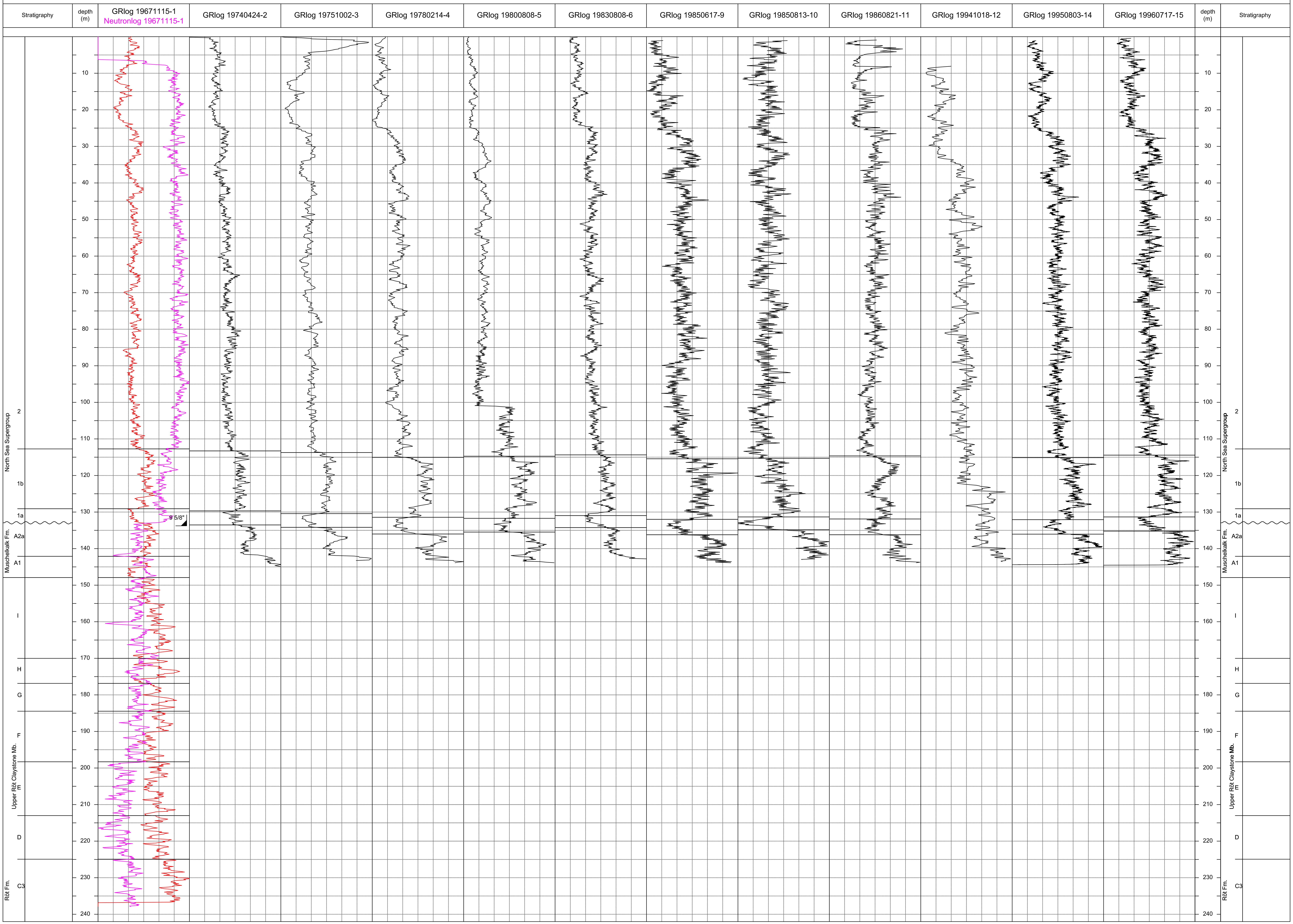
Attachment A; report GL19.401
prepared by:
GEOWULF *Laboratories*, the Netherlands



Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

Well B004: Gamma Ray history panel

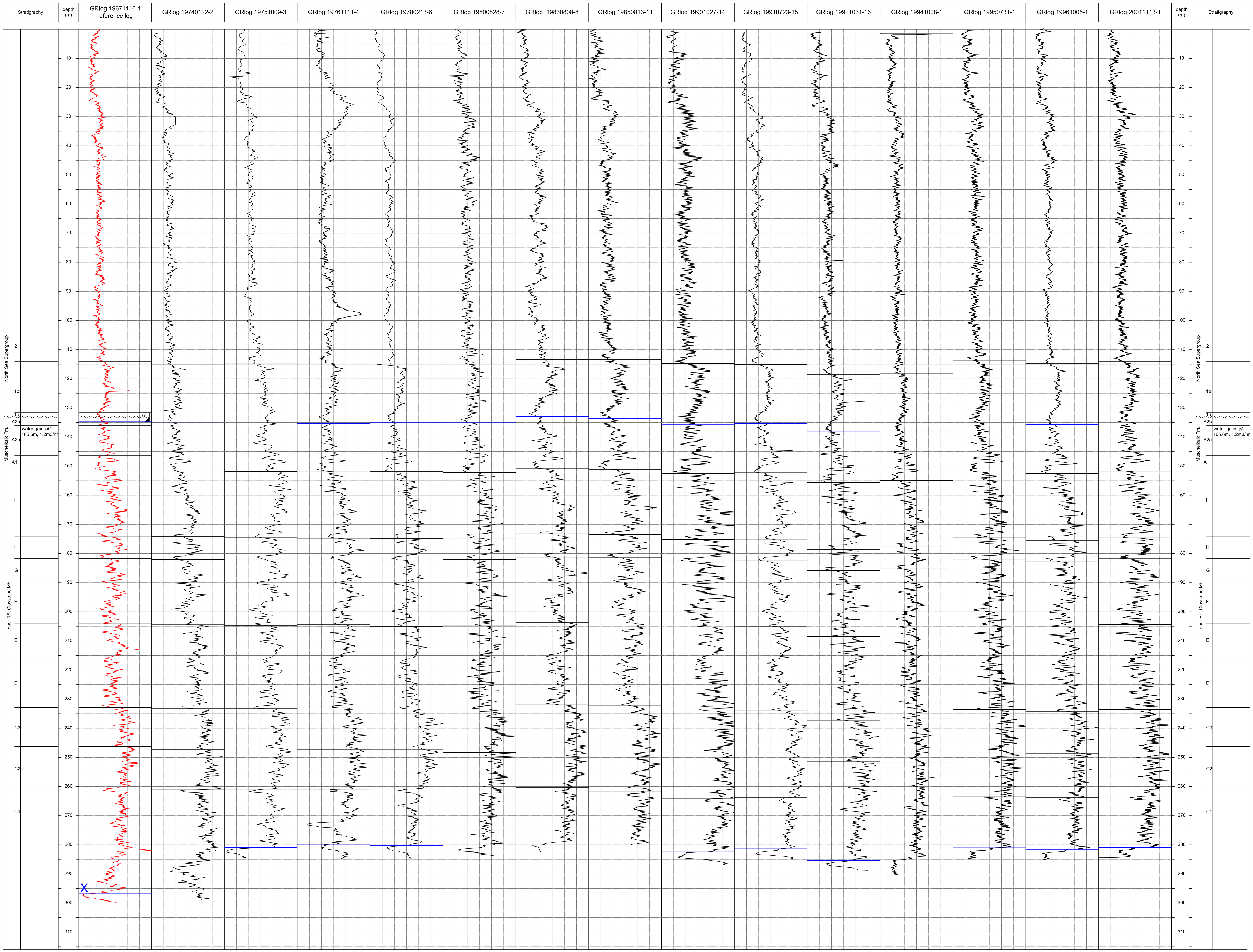
Attachment A; report GL19.401
prepared by:
GEOWULF *Laboratories*, the Netherlands



Well B005: Gamma Ray history panel

Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

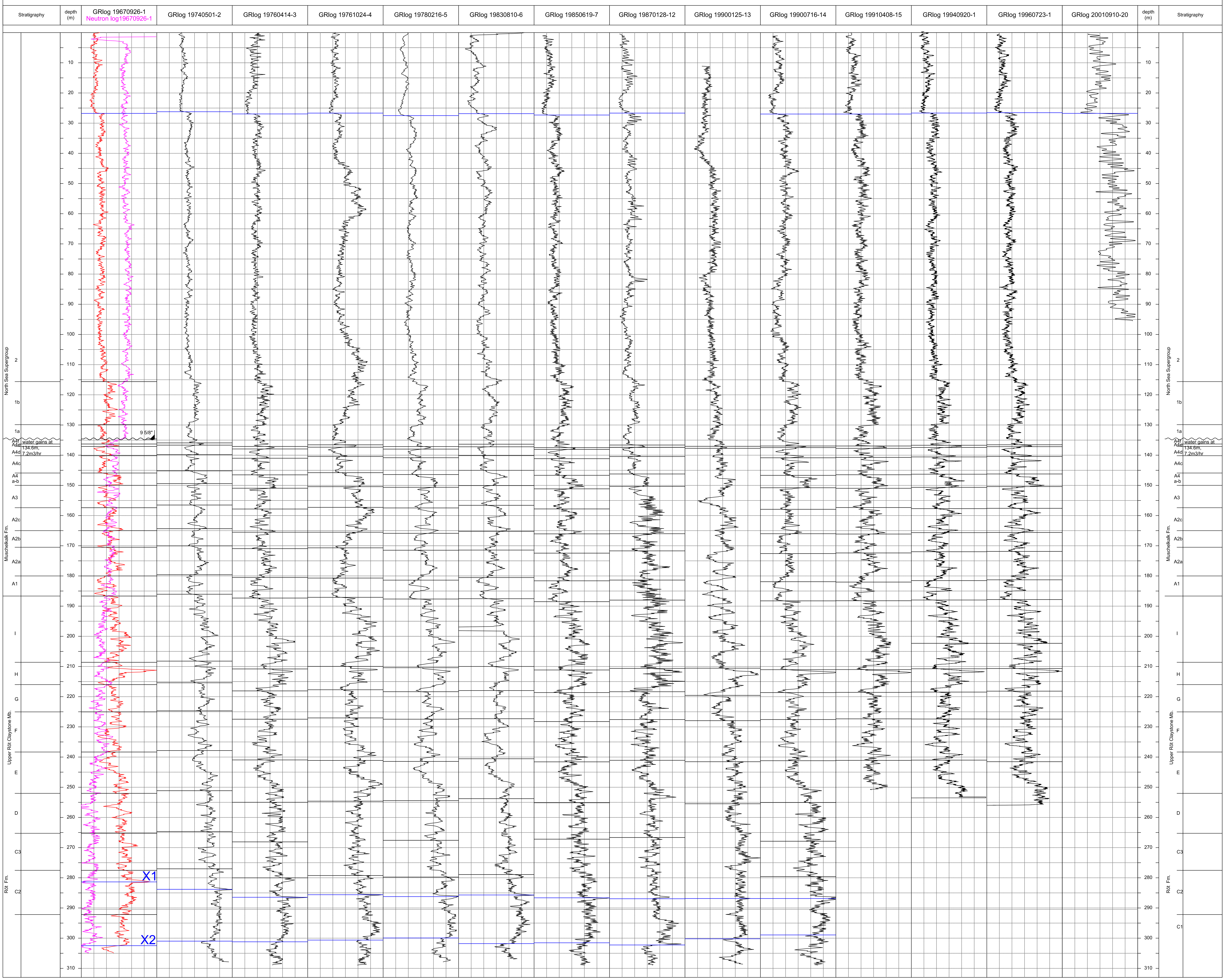
Attachment A; report GL19.401
prepared by:
GEOWULF*Laboratories*, the Netherlands



Well B011: Gamma Ray history panel

Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

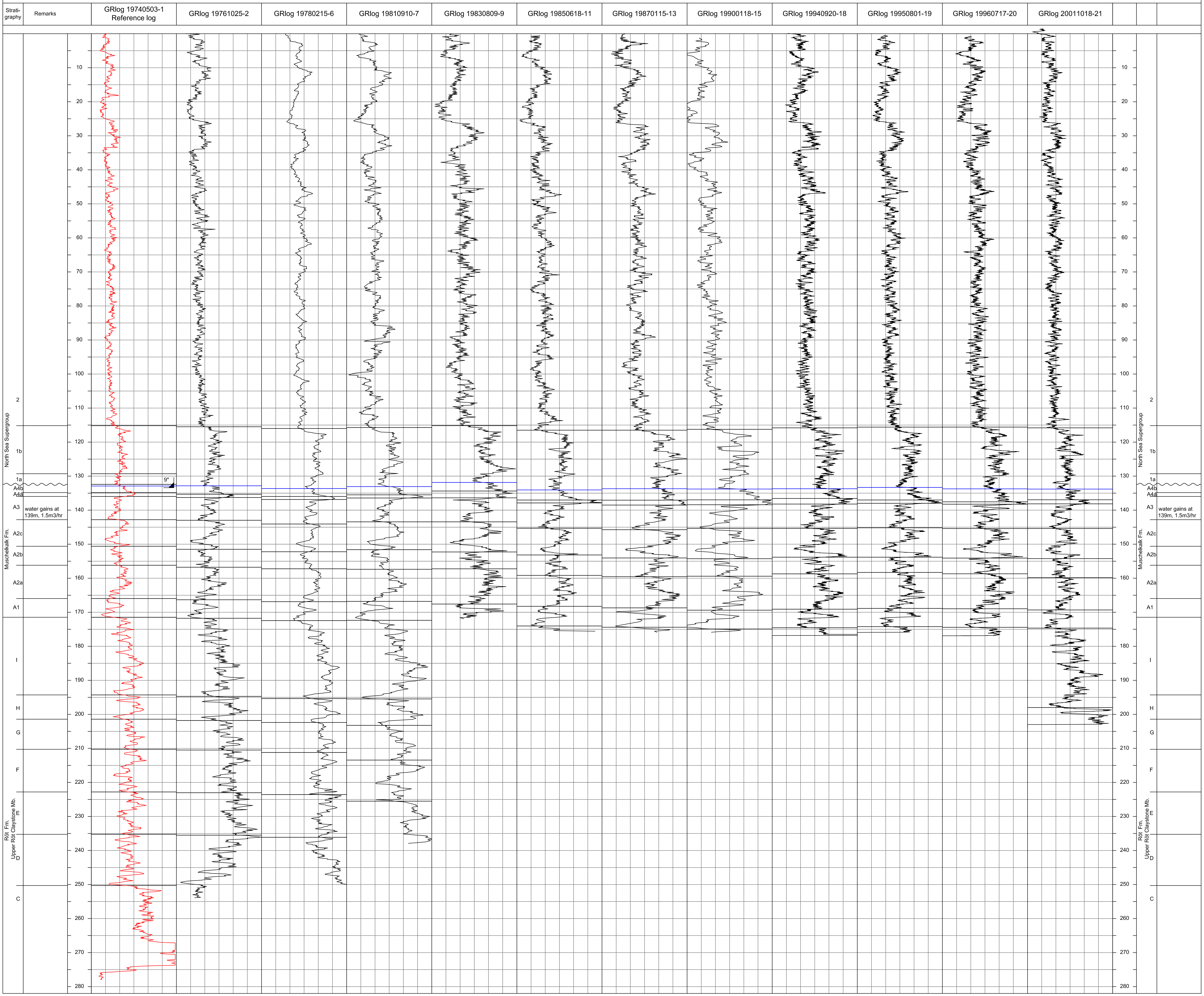
Attachment B; report GL19.401
prepared by:
GEOWULF *Laboratories*, the Netherlands



Well B015: Gamma Ray history panel

Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

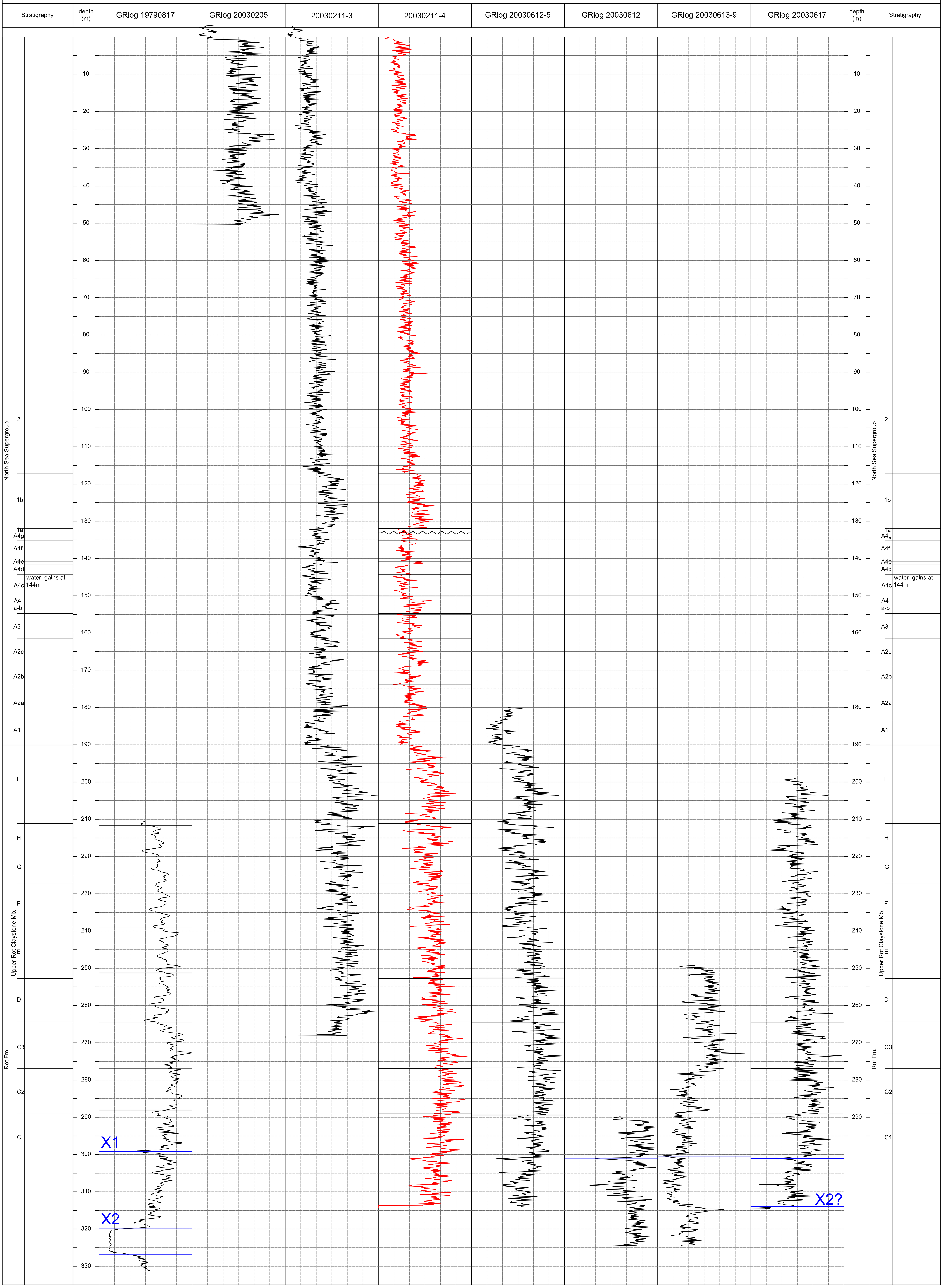
Attachment A; report GL19.401
prepared by:
GEOWULF *Laboratories*, the Netherlands



Well B037: Gamma Ray history panel

Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

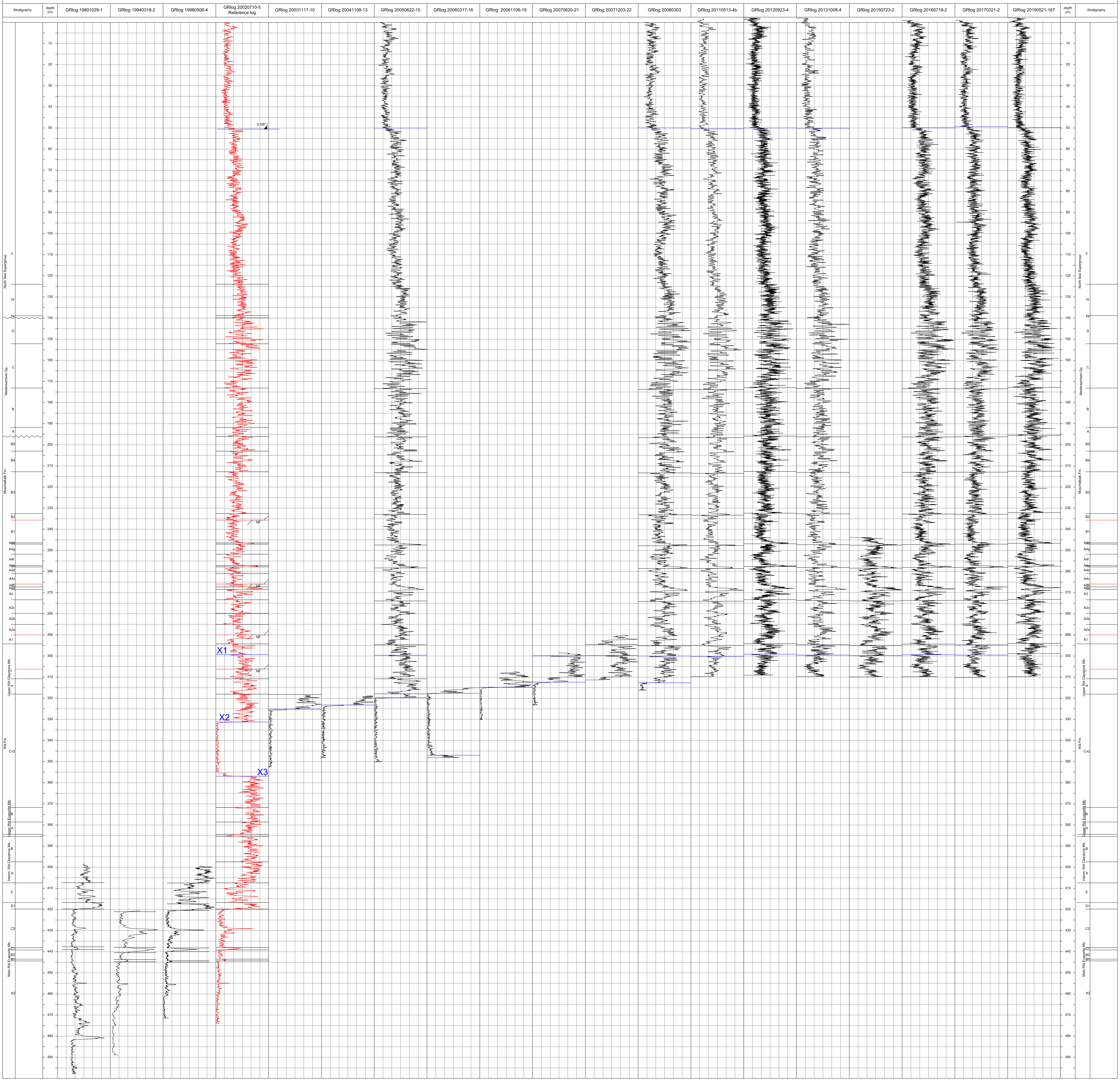
Attachment A; report GL19.401
prepared by:
GEOWULF *Laboratories,* the Netherlands



Well B167: Gamma Ray history panel

Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

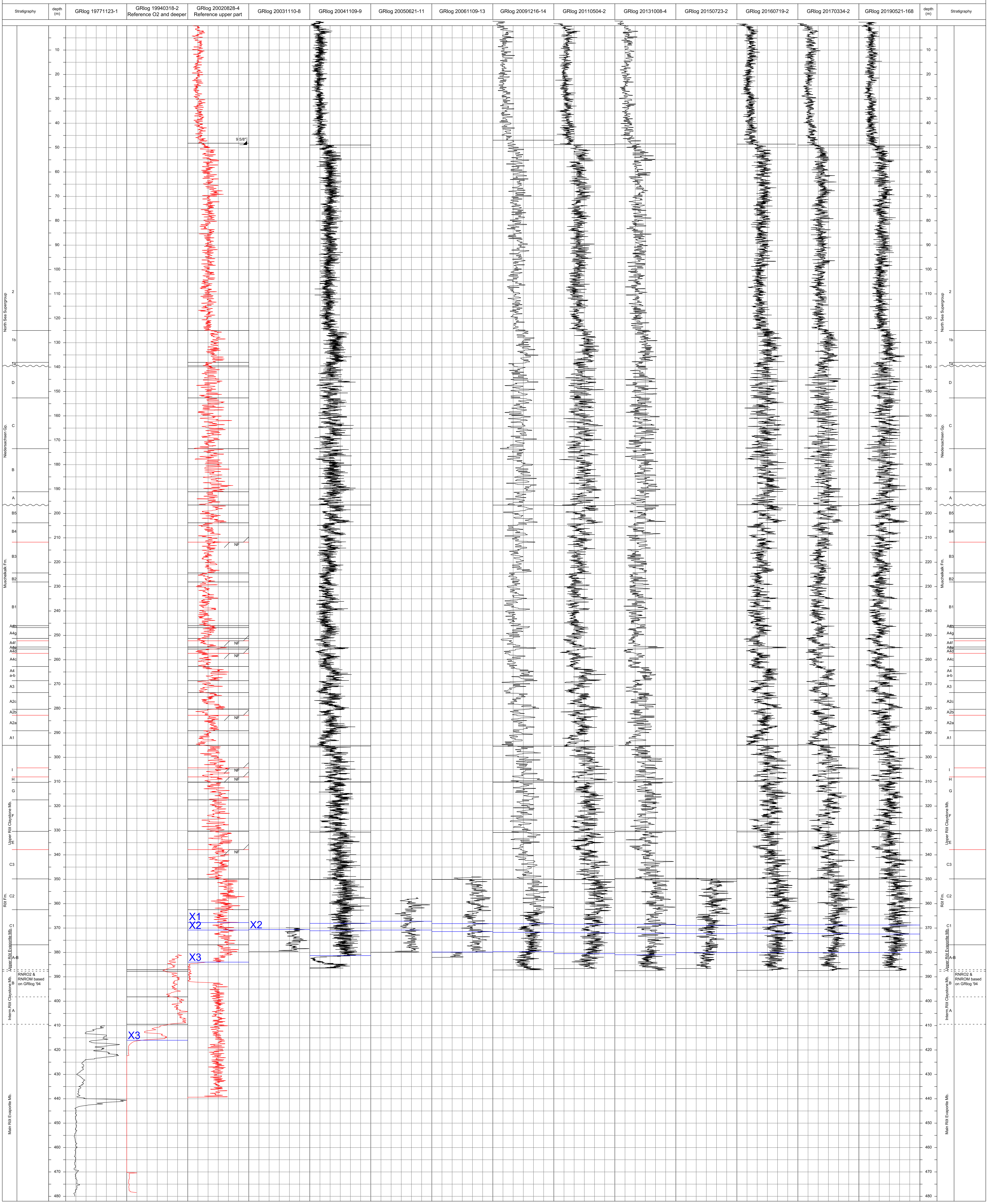
Attachment A; report GL19.401
prepared by:
GEOWULF *Laboratories*, the Netherlands



Well B168: Gamma Ray history panel

Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

Attachment A; report GL19.401
prepared by:
GEOWULF *Laboratories*, the Netherlands



Well B169: Gamma Ray history panel

Gamma Ray through casing (CPS - 100%)
Scale 1 : 500

Attachment A; report GL19.401
prepared by:
GEOWULF *Laboratories*, the Netherlands