Facies analysis and diagenetic evolution of the Dinantian carbonates in the Dutch subsurface: data and analyses well O18-01

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Facies analysis and diagenetic evolution of the Dinantian carbonates in the Dutch subsurface: data and analyses well O18-01

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11. O18-01

11.1 Introduction

The O18-01 well was drilled by Placid Oil between March 18th and May 17th 1991 in the offshore of the Zeeland area, north west of S02-02 and S05-01, west of P16-01 (Figures 11-1 and 11-2, Table 11-2). It reached 3051 m TD in the Silurian shales. The well was drilled for hydrocarbon exploration but was dry.

Figure 11-1: Map showing all the wells penetrating the Dinantian carbonates. Location of the O18-01 well is indicated by a dashed red circle.

Table 11-1: Table summarising the coordinates of the O18-01 well (from www.nlog.nl).

Co-ordinates (x, y in utm31, ed50 format)	494813, 5775857
Lat/Long (°)	52.132125, 2.9242167
Supplied co-ordinates	2.9242167, 52.132125 (ED50-GEOGR)
Depth in meters referred to :	Rotary Table
Total depth (m, along hole) :	3051
Vertical position of Rotary Table :	32.2 meter relative to MSL
Trajectory shape :	Vertical
Deviation in X-direction :	49.41
Deviation in Y-direction :	-5.87
True vertical depth (TVD) in m :	3049.534

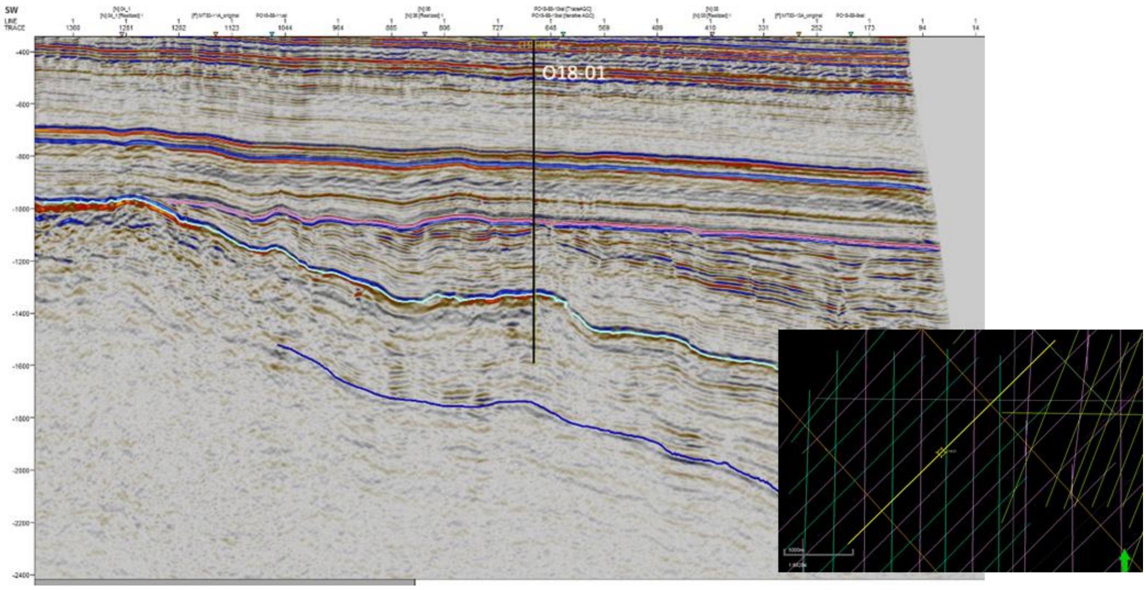

Figure 11-2: The O18-01 well in the seismic line PO18-88-4val. Blue line: base Dinantian; cyan: top Dinantian; Pink line: base Cretaceous unconformity.

11.2 Available dataset

Most of the available data and reports on the O18-01 well are available on "www.nlog.nl" within the following link:

https://www.nlog.nl/nlog/requestData/nlogp/allBor/metaData.jsp?tableName=BorLocation&id=106529427

The most relevant publications discussing and presenting the data obtained from BHG-01 well are as following:

Carlson, T. (2019). Petrophysical Report of the Dinantian Carbonates in the Dutch Subsurfaceacies analysis and diagenetic evolution of the Dinantian carbonates in the Dutch subsurface. SCAN Report, April 2019, 26 p. Report downloadable from www.nlog.nl/scan.

GAPS. (1991). Final Report. Conventional Core Analysis Well O/18a-1. Warmond.

Intergeos. (1991). O/18a-01 Core Petrography Study. Leiderdorp.

Mann, U., Horsfield, B., Littke, R., Radke, M., Rullkotter, J., and Schaefer, R. G. (1991). Organic geochemistry of slected rock samples from well O/18-a1, Offshore Netherlands. Aachen.

Muchez, P., Viaene, W. A., Keppens, E., Marshall, J. D., and Vandenberghe, N. (1991b). Vein cements and the geochemical evolution of subsurface fluids in the Campine Basin (Poderlee borehole, Belgium), Journal of the Geological Society of London, 148, 1005-1117.

Nielsen, P., Swennen, R., and Keppens, E. (1994). Multiple-step recrystallization within massive ancient dolomite units: an example from the Dinantian of Belgium. Sedimentology, 41, 567-584.

Oxtoby, N. H. (2002). 4754.50 m & 4757.02 Dinantian, Well UHM-2, Netherlands. Evidence for petroleum emplacement and the conditions of cementation from fluid inclusions. Esher.

Pickard, N. A. H., and Gutteridge, P. (1997). Dinantian depositional systems and exploration potential: offshore and onshore, The Netherlands. Sedimentological study.

Reijmer, J. J. G., Ten Veen, J. H., Jaarsma, B., and Boots, R. (2017). Seismic stratigraphy of Dinantian carbonates in the southern Netherlands and northern Belgium. Geologie En Mijnbouw/Netherlands Journal of Geosciences, 96, 353-379.

Schroot, B. M., V.Bergen, F., Abbink, O. A., David, P., V.Eijs, R., and Veld, H. (2006). Hydrocarbon potential of the Pre-Westphalian in the Netherlands on- and offshore. TNO report.

Swennen, R., and Muchez, P. (1991). Sedimentological and diagenetic study of the Dinantian carbonates and underlying siliciclastics of Placid borehole O-18-1. Leuven.

TNO (2003). Toelichting bij kaartbladen Xl en Xll Middelburg-Breskens en Roosendaal-Terneuzen. Geologische Atlas van de Diepe Ondergrond van Nederland.

Van Amerom, H. W. J. (1991). Report on the Stratigraphic age of the section 3876.00-3995.00 ft of borehole 0-18-1 (Placid International Oil, TLD.) based on macroflora and macrofauna. Heerlen.

Van de Laar, J. G. M. (1991). Palynological investigation of the well O18-1. Heerlen.

Wygrala, B. P. (1991). Final Report. 1-D Modeling Study (Well O18-1). Juelich.

11.2.1 Logs

This well has a complete suite of logs (Figure 11-3) and has been petrophysically evaluated within the framework of the SCAN project (Carlson, 2019).

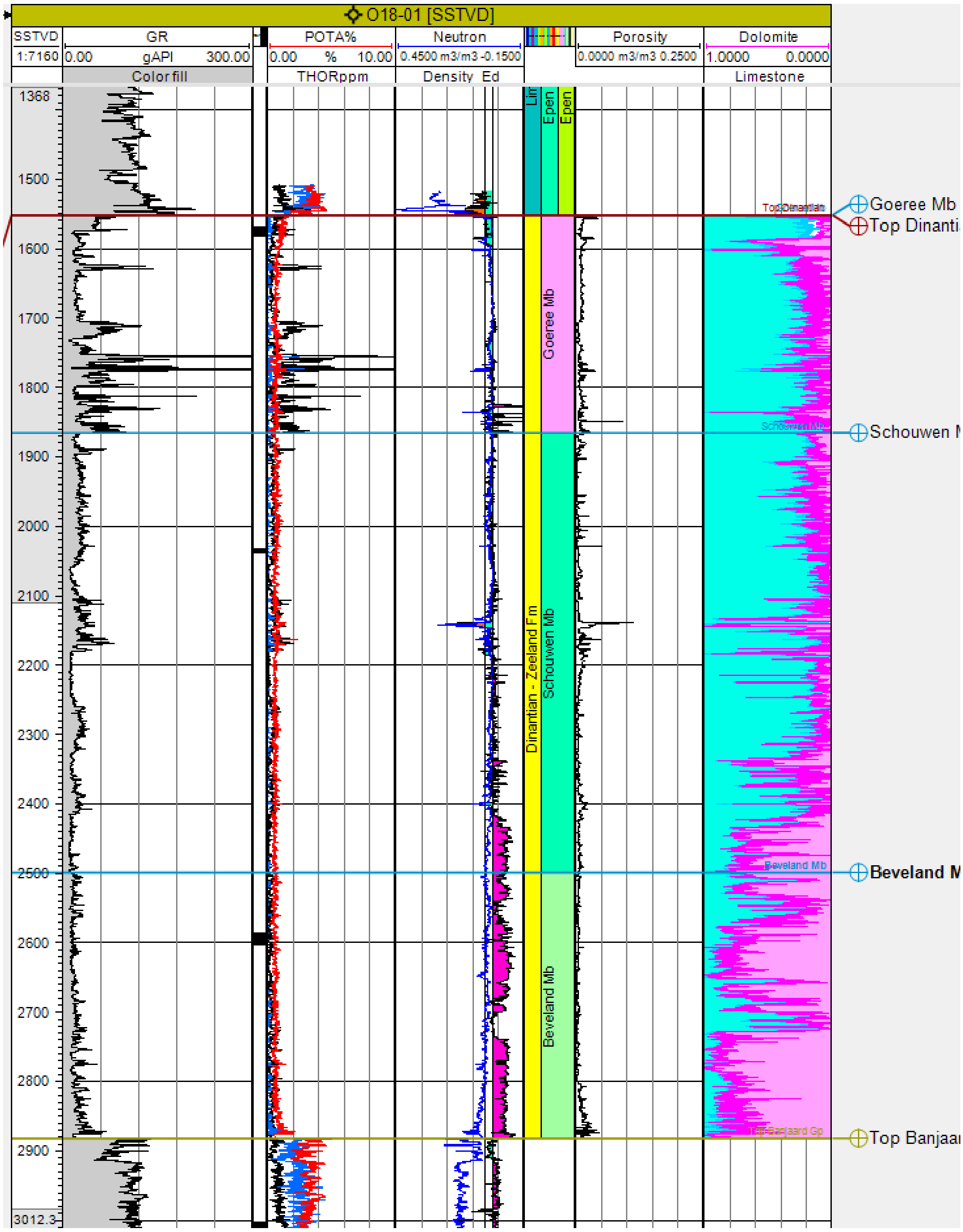

Figure 11-3: Gamma ray, neutron/density, porosity and mineralogical logs in the O18-01 well.

11.2.2 Cores, sidewall cores and cuttings

The O18-01 well includes four cores in the Dinantian (3, 4, 5 and 6) and one core (7) in the Silurian intervals.

11.2.3 Petrography and additional analyses

One thin section is available for diagenetic study (SCAN project). No photomicrographs were taken for microfacies description. Intergeos (1991) undertook a core description and petrographic study of Cores 1 and 2 from the Westphalian A. They concluded that the depositional environments were fluvial channel and associated overbank facies. A microfacies and CL study was undertaken on Cores 3 to 7 by Cambridge Carbonates (2001), commissioned by NAM.

A sample of the dark mudstone karst fill was taken at 5219.10 ft for biostratigraphic analysis and spore colour determination (Scan project). It was found to contain rare dark brown/black degraded organic material with no miospores present so it was not possible to determine the spore colouration. This constrains the age of the vein and cement to post-Namurian. From this vein and the surrounding host rock four stable isotope samples were collected (SCAN project). Microthermometry analysis are mostly available from Oxtoby (2002) but additional analysis was performed on a sample from 5266 ft (SCAN project). This sample is from a vein that cuts the dark mudstone karst fill.

A detailed diagenetic study is also available from Swennen and Muchez (1991).Vitrinite reflectance data is reported in Wygrala (1991) (Table 11-2).

Table 11-2: Vitrinite reflectance data available for the O18-01 well Wygrala (1991).

Depth (m MD)	%Ro
1149	0.63
1152	0.60
1170	0.73
1204	0.76
1231	0.68
1320	0.79
1460	0.81
1561	0.80
2066	0.92
2075	0.95
2623	1.15
3048	3.03
3050	2.45

11.3 Sedimentology

Core 6 (8571-8860 ft) includes dolomitised bioclast wackestone and packstone with layers and lenses of reworked bioclasts (Figures 11-4 and 11-5). These sediments are interpreted as storm reworked bioclastic carbonates deposited on the mid- to distal parts of a carbonate ramp. There are intervals of brecciation and fracturing. Brecciated intervals contain angular, clasts with a fitted fabric; a geopetal accumulation of angular shards of the host rock is present in some brecciated intervals. The breccia and fractures are cemented by coarse calcite crystals.

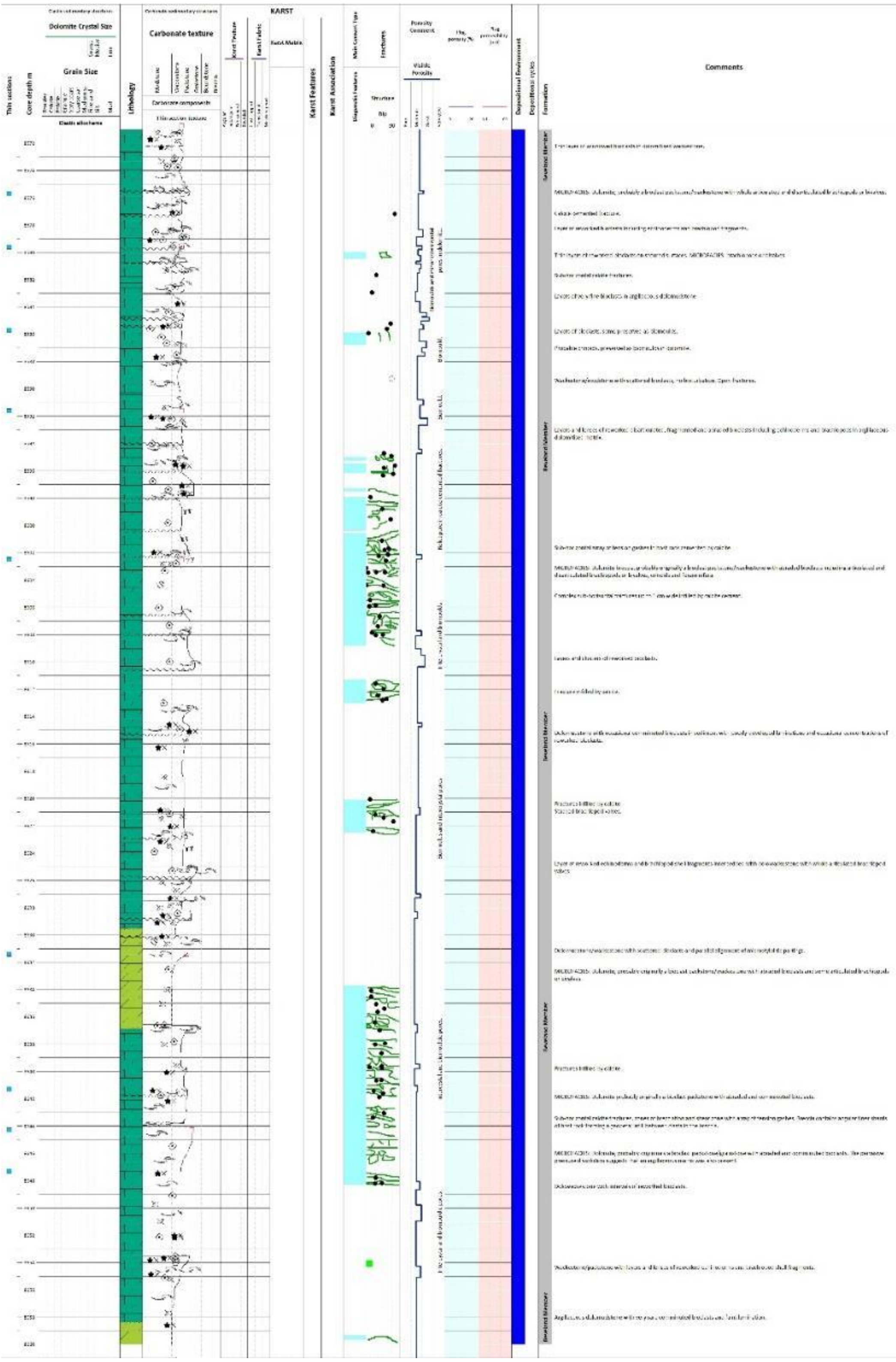

Figure 11-4: Overview of the sedimentological log constructed for Core 6, well O18-01 (an image of higher resolution is available in Appendix B).

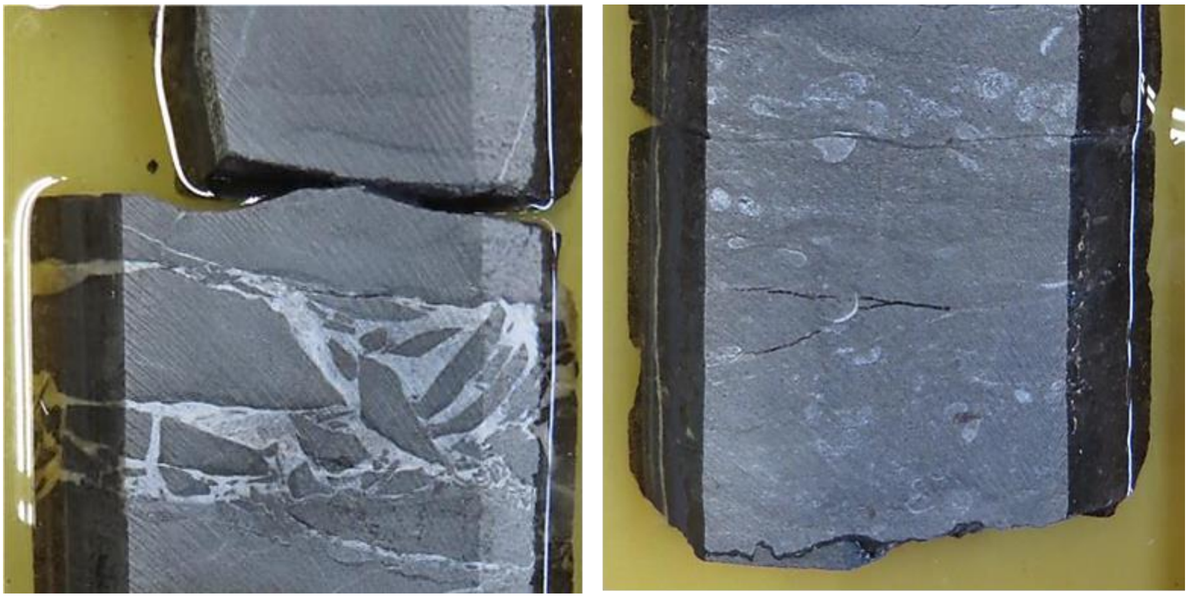

Figure 11-5: Core photo example of Core 6 (8646.0 and 8624.5 ft) in the O18-01 well.

Core 5 (6674-6811 ft) comprises bioclast wackestone and packstone with layers and lenses of reworked bioclasts (Figures 11-6 and 11-7). These sediments are similar to the ones in Core 6 and are interpreted as a storm reworked bioclastic carbonates deposited on the mid- to distal parts of a carbonate ramp.

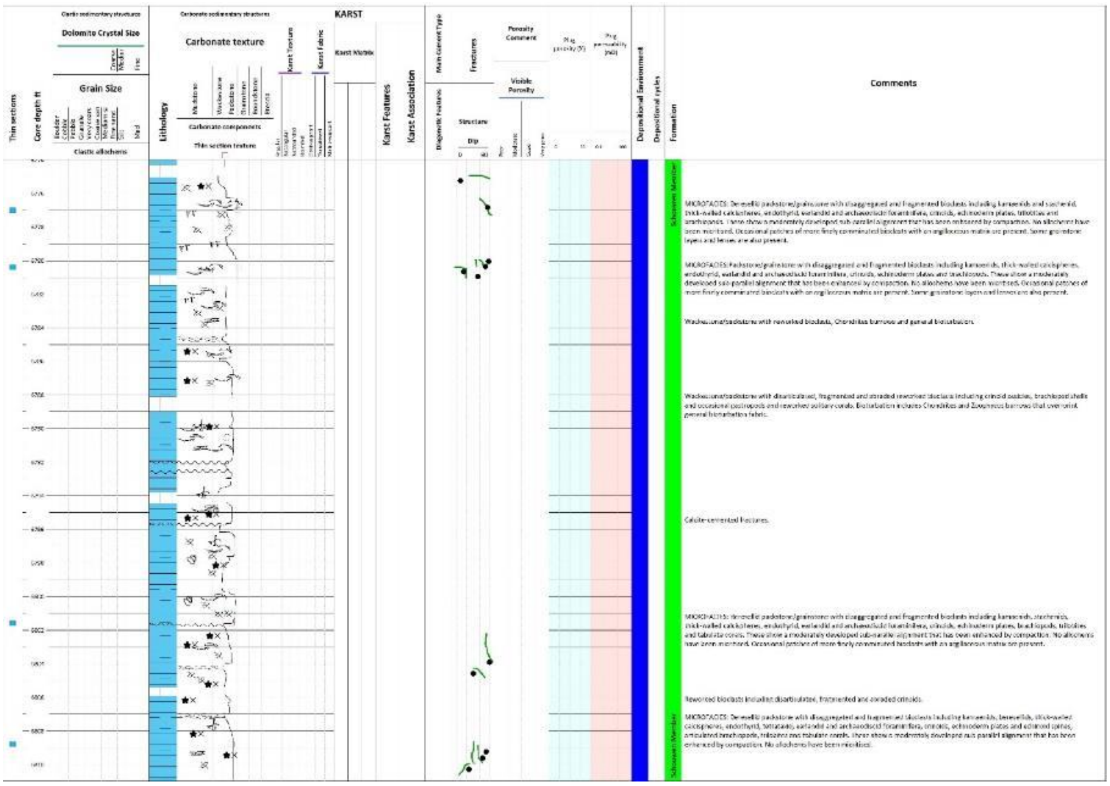

Figure 11-6: Overview of the sedimentological log constructed for Core 5, well O18-01 (an image of higher resolution is available in Appendix B as a supplementary document).

Figure 11-7: Core photo example of Core 5 (6794.5 and 6804.5 ft) in the O18-01 well.

Cores 3 and 4 (5250-5298 ft) consists mainly of bioclast wackestone/carbonate mudstone with whole fenestrate bryozoan sheets, articulated brachiopods, gastropods, bivalves and a goniatite (Figure 11-8). The micritic matrix generally has a micropeloidal texture. Common irregular cm- to dm-sized cavities lined by fibrous calcite cement that are also partly infilled by peloidal geopetal and bioclastic sediment. These cavities may represent stromatactoid cavities that formed as modified shelter cavities in a micrite matrix around fenestrate bryozoan sheets. The depositional setting is interpreted as carbonate mud mounds that may be associated with a carbonate shelf margin.

Some depositional cavities, fractures and internal cavities of bioclasts are infilled by dark grey siliciclastic silty mudstone which is interpreted as a sub-Limburg group karst fill (Figure 11-9).

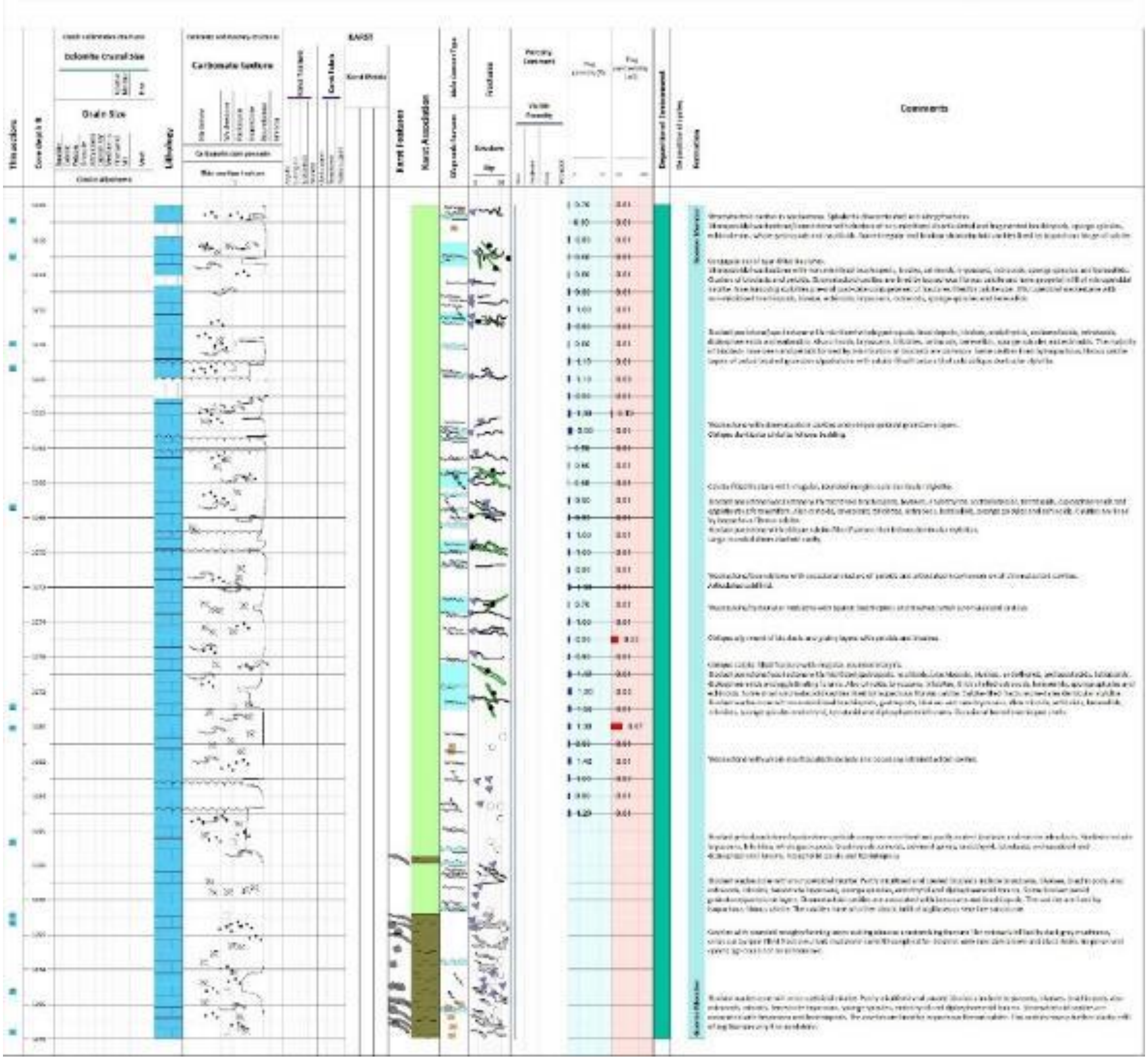

Figure 11-8: Overview of the sedimentological log constructed for Cores 3 and 4, well O18-01 (an image of higher resolution is available in Appendix B as a supplementary document).

Figure 11-9: Core photo example of Core 3 and 4 in the O18-01 well.

11.4 Stratigraphy

The succession of the O18-01 well spans from Quaternary to the Silurian times (Table 11-3), encountering the Cretaceous unconformity at 1129 m MD.

Table 11-3: Stratigraphy of the O18-01 well (from www.nlog.nl).

Stratigraphical unit	Top interval	Base interval
Upper North Sea Group	0	209
Lower North Sea Group	209	902
Ommelanden Formation	902	1129
Baarlo Formation	1129	1237
Epen Formation	1237	1584
Goeree Member	1584	1898
Schouwen Member	1898	2532
Beveland Member	2532	2915
Banjaard group	2915	2952
Silurian	2952	3051

11.4.1 Dinantian interval

The Beveland, Schouwen and Goeree Members of the Zeeland Formation have been recognised in the Dinantian intervals encountered in the well O18-01. The Dinantian is overlain by the Limburg Group of Westphalian age. A correlation of the O18-01 well with successions in the Campine Basin has been performed by Swennen and Muchez (1991).

11.5 Biostratigraphy

Core 7 (9955-10,009 ft): Late Silurian (Wenlockian-Ludlovian) (composite log).
Core 6 (8571-8660 ft): Early Carboniferous (Tournaisian/Lower Visean); Tn1B/V1A (composite log).
Core 5 (6774-10,009 ft): Early Carboniferous (Middle Visean); V2BB (composite log).
Cores 3 and 4 (5250-5298 ft): Coral and foraminiferal assemblages (Swennen and Muchez, 1991) indicate RB7β-RC8 which are attributed to Warnantian (Belgium) and Asbian/Brigantian (UK).
The host carbonates were dated as late Visean, V3Bγ (composite log). As part of this study, the dark grey mudstone matrix that infills karst cavities at 5,219.10 ft was sampled for age dating but only rare dark brown/black degraded organic material was found with no miospores and so the age could not be determined. The post-Dinantian biostratigraphy includes: 3876-3995 ft Westphalian A; 3937-3938 ft Westphalian A; 3750-4790 ft late Westphalian A and 4790 -5170 ft early Westphalian A.

11.6 Sequence stratigraphy

The sequences recognised in the well O18-01 are shown in Figure 11-10.
Cycle 1a: This cycle represents the initial flooding of the basin; the thin TST is interpreted as deposition of clean carbonates in shallow water. This is followed by increasing gamma ray interpreted as deposition of more muddy carbonates in deeper water. The HST consists of thinly-bedded cyclic inner ramp carbonates.
Cycle 1b: This cycle comprises a thick TST passing up into an HST that has a moderately high gamma ray signature. This cycle may represent initial deposition on the distal to mid-carbonate ramp, followed by progradation into a shallower carbonate ramp setting.
Cycle 1c: This cycle comprises a thick TST passing up into an HST that has a moderately high gamma ray signature. This cycle may represent initial deposition on the distal to mid-carbonate ramp, followed by progradation into a shallower carbonate ramp setting.
Cycle 1d: This cycle has a relatively uniform low to moderate gamma ray character. The core was taken in the late TST to maximum flood of the light green cycle. It represents storm beds deposited in a distal carbonate ramp setting.
Cycle 2a: This cycle consists of moderate gamma ray TST passing up into a high gamma ray interval interpreted as a maximum flooding interval passes up into a low gamma ray HST deposited in a high energy inner carbonate ramp setting.
Cycle 2b: This cycle consists of a thin TST with increasing-upward gamma ray towards a high gamma ray maximum flooding interval with an overlying decreasing-upwards gamma ray HST. This characteristic suggests that 2b cycle was initially deposited in a moderate to low energy setting in a deep ramp or slope setting followed by progradation during the HST to a high energy setting above or near normal wave base on a carbonate shelf interior or shallow carbonate ramp.
Cycle 2c: This cycle has a thick high gamma ray TST with increasing gamma ray with a thickly bedded low gamma ray HST. This cycle has a more uniform gamma ray signature and is interpreted as distal ramp or carbonate slope facies, possibly associated with a transition from

carbonate ramp- to flat-topped carbonate platform. The low gamma ray intervals interpreted as influx of resedimented carbonates during high stands.

Cycle 2d: This cycle is characterised by a TST with a high gamma ray signature suggesting deposition in a deep water slope or distal carbonate ramp. The clean low gamma ray HST may represent deposition in a high energy, carbonate shelf interior or shallow ramp setting.

Cycle 3a: This cycle includes the TST to maximum flooding interval comprising bioturbated carbonate mudstone and wackestone with some interbedded packstone interpreted as storm deposits on a distal carbonate ramp or slope. The HST is interpreted as a generally shallow water carbonate shelf or ramp setting.

Cycle 3b: This cycle consists mainly of bioclastic wackestone/carbonate mudstone with whole fenestrate bryozoan sheets, articulated brachiopods, gastropods, bivalves and a goniatite. The micritic matrix generally has a micropeloidal texture. Common irregular cm- to dm-sized cavities lined by fibrous calcite cement that are also partly infilled by peloidal geopetal and bioclastic sediment. These cavities may represent stromatactoid cavities that formed as modified shelter cavities in a micrite matrix around fenestrate bryozoan sheets. The depositional setting is interpreted as carbonate mud mounds that were associated with a carbonate shelf margin. The gamma ray signature is generally low, but a number of gamma ray spikes are interpreted as mudstone-filled karst cavities that penetrated the top of the Dinantian carbonates. The overall stratigraphic relationships in the well O18-01 suggest that this karst was sub-Limburg and probably of Namurian or Westphalian age.

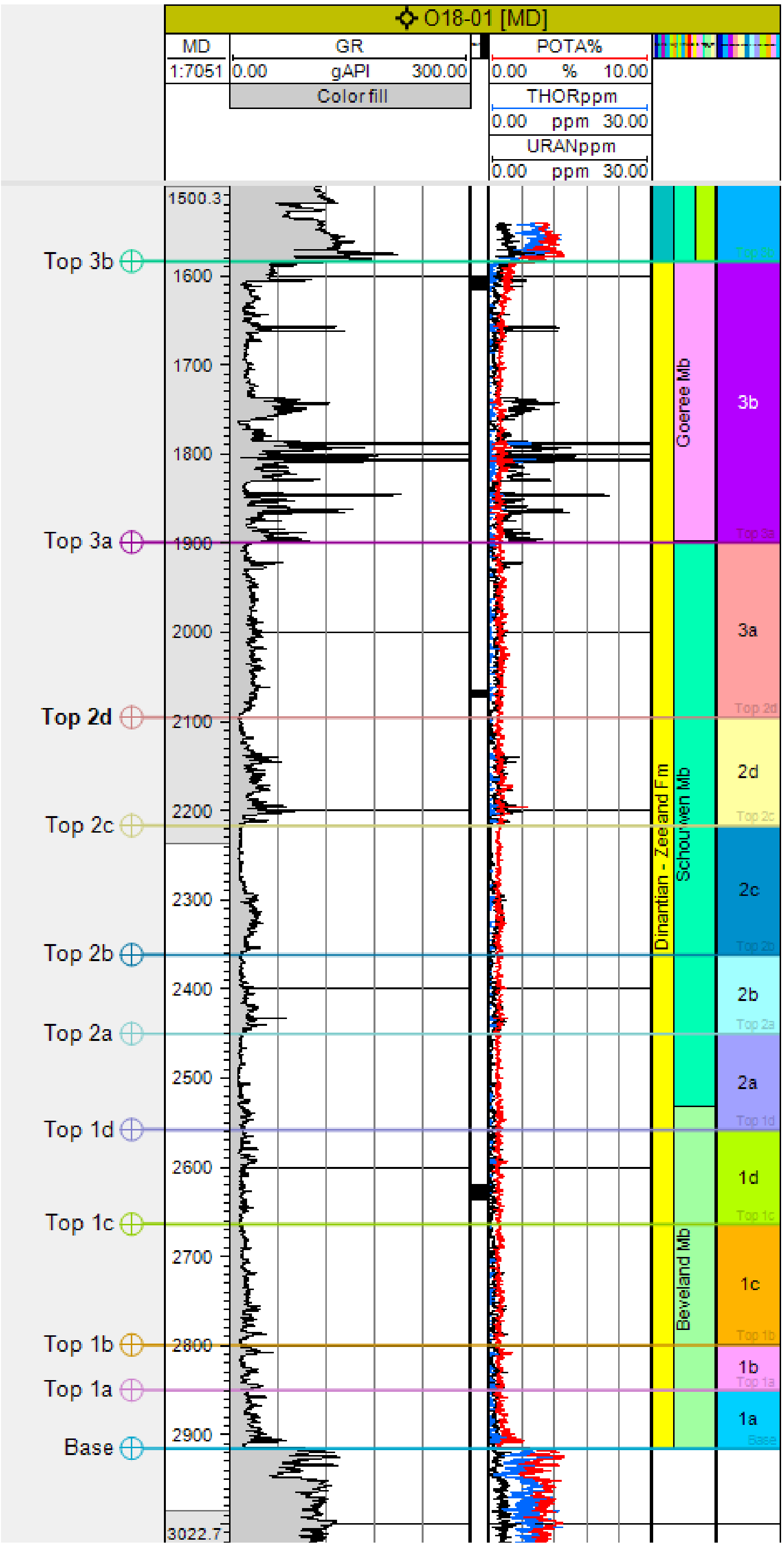

Figure 11-10: Depositional cycles recognised in the well O18-01.

11.7 Diagenesis

A sedimentological, biostratigraphic and diagenetic study was performed by Swennen and Muchez (1991). The diagenetic part of their study emphasised the history of fracturing and the cementation of fractures (structural diagenesis) in the carbonate cores. The diagenetic evolution can be subdivided into two main stages, pre-, syn- and post-fracturing diagenesis. The pre-fracturing diagenesis is as following:

Cores 3 and 4: These cores contain significant syn-depositional porosity in the form of stromatactoid cavities that have been largely cemented by marine cement and later calcite spar. stromatactoid cavities formed as part of carbonate mud mounds, probably in a shelf margin setting. Porosity was most likely occluded during Visean/Namurian exposure or during early Namurian burial.

Core 5: In this core the depositional porosity has been largely destroyed by compaction and calcite cementation, the latter probably occurred during shallow burial (100s of meters). These rocks were probably compacted by Namurian times. A later phase of aragonite dissolution was later occluded by calcite cementation.

Core 6: This core consists mainly of dolomite with intercrystal and biomouldic pores infilled by minor dolomite cement. Bulk rock stable C and O isotopes indicate either formation or re-equilibration in the burial realm; dolomitisation is most likely to have occurred during the Dinantian.

Core 7: This core consists of severely compacted fine siliciclastics with no porosity.

The Syn- and post-fracturing diagenesis includes:

Core 4: This core contains two phases of fracturing infilled initially by non-ferroan calcite (dull orange CL) and later ferroan calcite (bright CL), the initial stage of fracturing pre-dates stylolites while the latter post-dates stylolites. The latter phase of fracturing is associated with sphalerite mineralisation.

Core 5: In this core only minor fracturing is present and thus was not further studied.

Core 6: This core shows severe fracturing and brecciation with multiple episodes of cementation by ferroan and non-ferroan calcite and dolomite. Early phases of cementation are interpreted to have formed by low temperature from $\delta^{18}O$ depleted fluids. Later phases were precipitated from fluids of higher temperatures (greater than 100 ^{o}C). The fractures also contain degraded hydrocarbons.

Core 7: In this core, fracturing occurs in some intervals; most fractures have been infilled by milky quartz but some fractures have a late stage infill by rose quartz.

11.7.1 Cathodoluminescence (SCAN project)

Locally early, zoned calcite cements can be observed in the matrix of the limestone (Figure 11-11). The calcite vein cross cutting the limestone host rock is characterised by a non-luminescent core and finely zoned bright and dull luminescent rim (Figure 11-12).

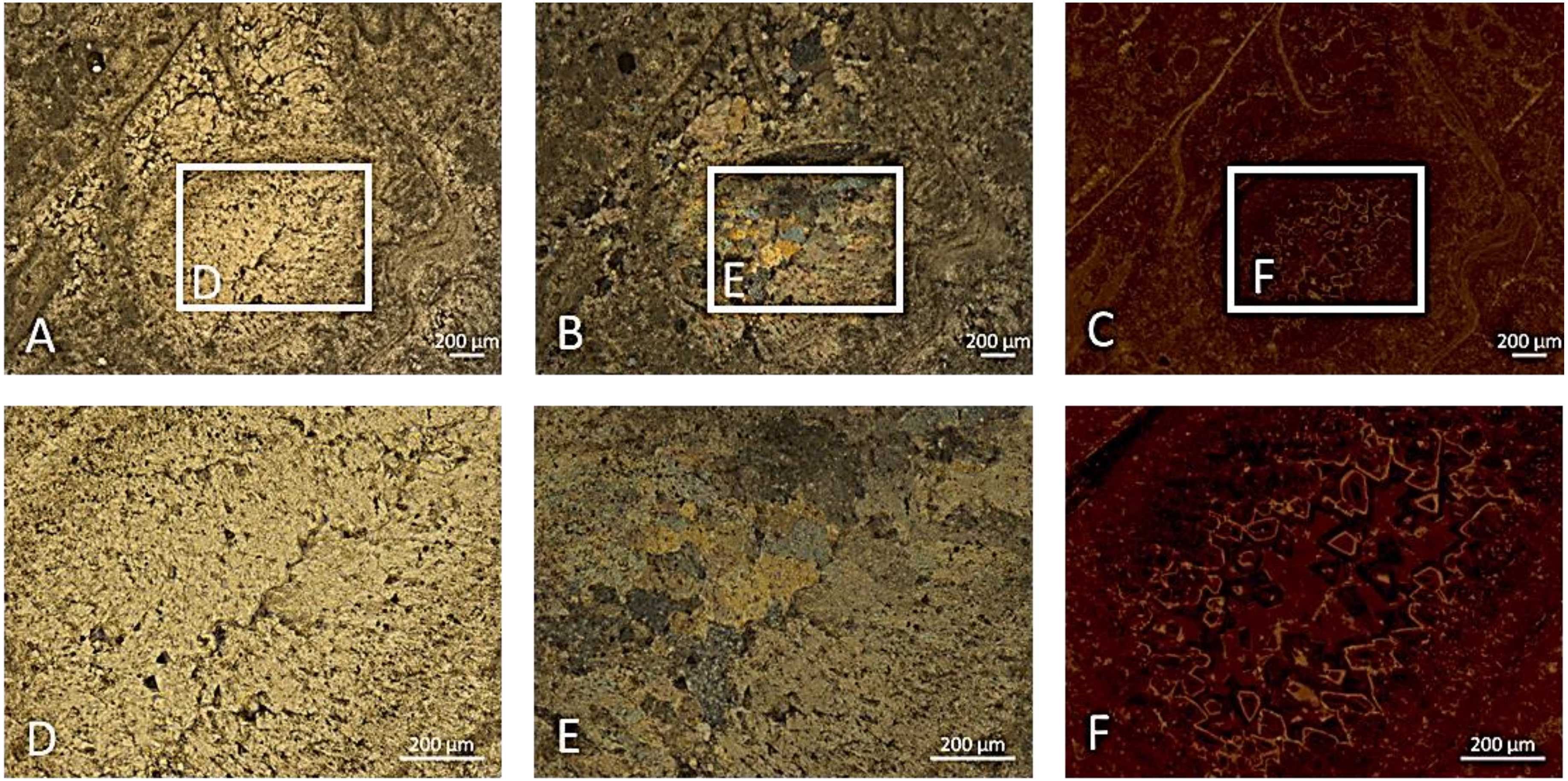

Figure 11-11: Equivalent PPL (plane polarised light), XPL (cross polarised light) and CL (cathodoluminescence) microphotographs. Early calcite cements zoned luminescence (5266 ft).

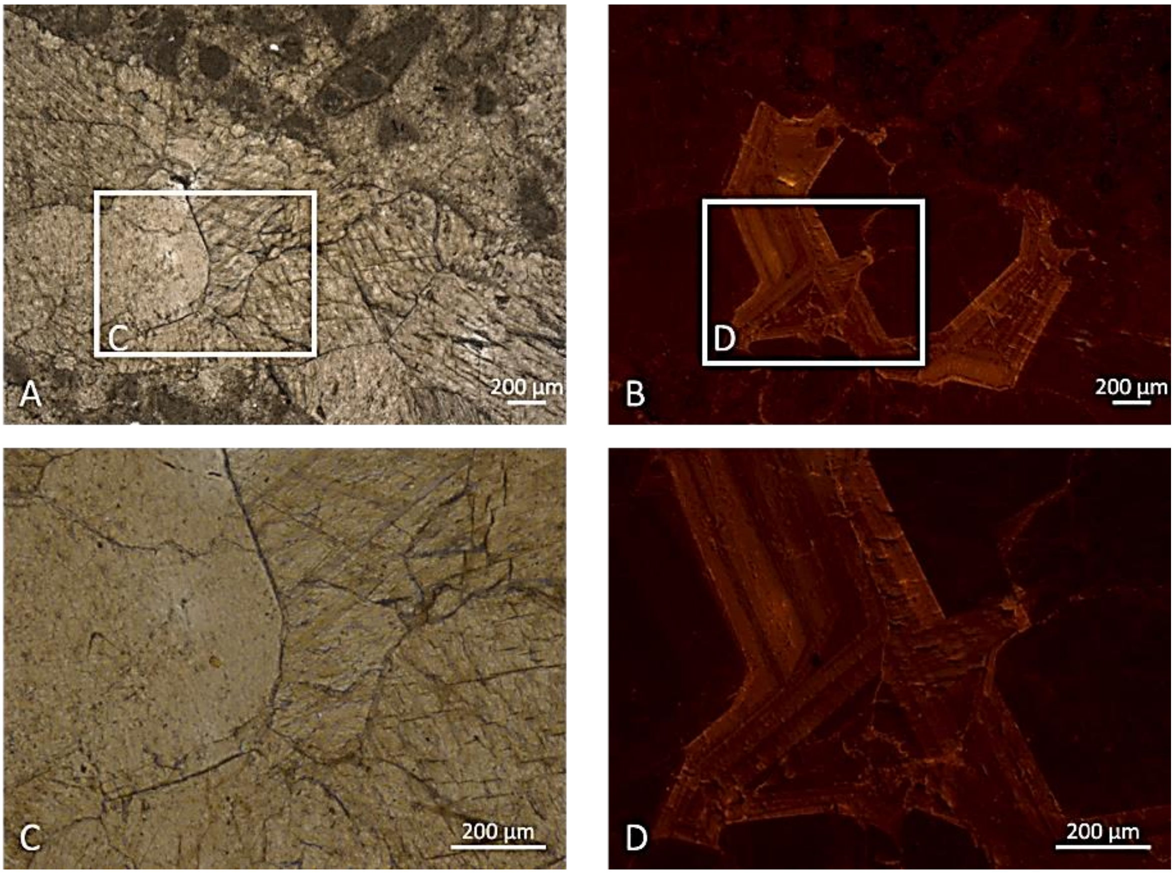

Figure 11-12: Equivalent PPL and CL microphotographs. The calcite vein cross cutting the Namurian karst infill has a dull luminescent core and finely zoned bright and dull rim (5266 ft).

11.7.2 Stable isotopes

Four stable isotope samples were collected from the O18-01 well at 5266 ft and 5266.11 ft of depth (SCAN project). These samples consist of the limestone host rock and the calcite vein cross cutting the Namurian karst infill (Figure 11-13 and Table 11-4).

The $\delta^{18}O$ signature of the O18-01 host rock is depleted compared to the marine reference reported by Muchez et al. (1991) and Nielsen (1994). They are similar to the host rock signature of the other wells studied. The $\delta^{13}C$ signature falls within the range of the marine reference value.

The studied calcite cement is characterised by slightly more depleted $\delta^{18}O$ values than the limestone matrix.

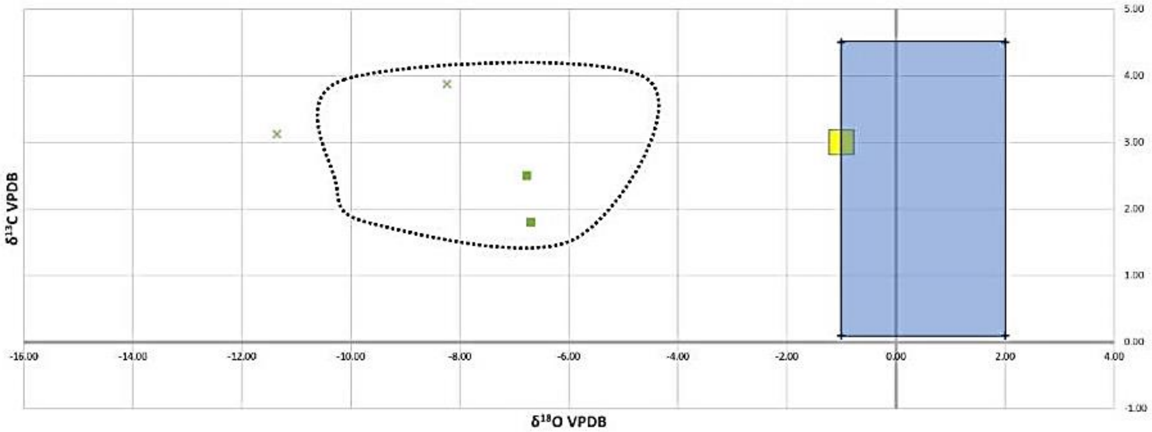

Figure 11-13: Stable isotope cross plot of the O18-01 limestone host rock (green squares) and calcite vein (green cross) cross cutting the Namurian karst infill. The dotted line represents the limestone host rock/matrix signature obtained from the other studied wells with the exception of UHM-01.

Table 11-4: Overview of the stable isotope results of the selected O18-01 samples expressed in per mill VPDB.

Depth (ft)	Mineralogy	matrix/vein	$\delta^{13}C$	$\delta^{18}O$
5266	Calcite	Matrix	1.80	-6.71
5266.11	Calcite	Matrix	2.50	-6.78
5266	Calcite	Vein	3.12	-11.36
5266.11	Calcite	Vein	3.88	-8.23

11.7.3 Fluid inclusion microthermometry (SCAN project)

The sample containing the calcite vein cross cutting the Namurian karst infill (5266 ft) was analysed for the of fluid inclusion microthermometry (Figure 11-14 and Table 11-5). The calcite precipitated from a hot fluid with most homogenisation temperatures (Th) between 92.7 °C and 125.0 °C (average 110 °C). One outlier has a Th of 67.0 °C. The salinity varies from fresh water (0 wt. % eq. NaCl) to moderately saline brine (3X sea water salinity, i.e. 11.2 wt. % eq. NaCl).

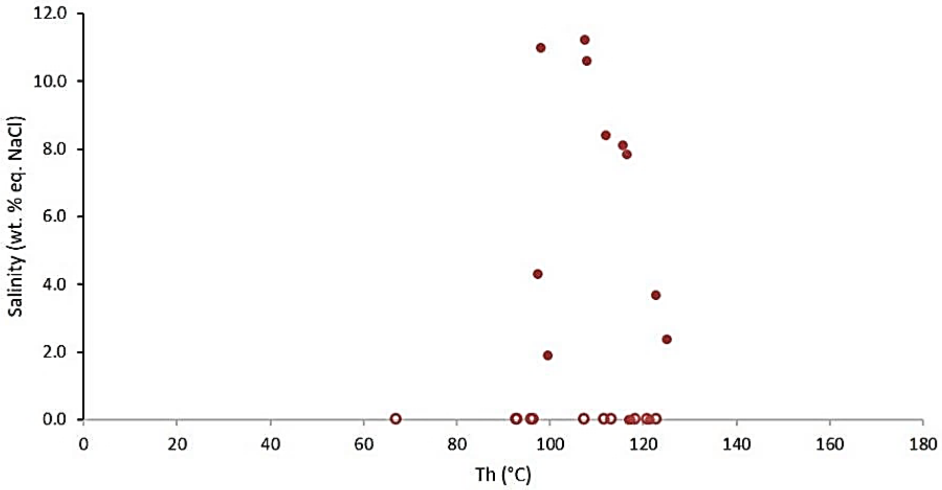

Figure 11-14: Temperature - salinity cross plot of the calcite vein cross cutting the Namurian karst infill (5266 ft). Inclusions for which Tm ice could not be observed have been were attributed an arbitrary salinity of 0 wt. % eq. NaCl. These data points are marked by symbols without fill and should only be considered as temperature indicators.

Table 11-5: Overview of the fluid inclusion microthermometry results of the calcite vein cross cutting Namurian karst in O18-01 5266 ft.

F. i. Number	F. i. Type	F. i. Host mineral	F. i. Host type	$T_{m\,ice}$ (°C)	Salinity (wt. % NaCl eq)	T_h (°C)
1	aq	calcite	primary	-2.2	3.7	122.7
2	aq	calcite	primary	n.o.		120.9
3	aq	calcite	primary	-1.4	2.4	125.0
4	aq	calcite	primary	-5.2	8.1	115.6
5	aq	calcite	primary	0.0	0.0	121.5
6	aq	calcite	primary	0.0	0.0	117.3
7	aq	calcite	primary	-1.1	1.9	99.5
8	aq	calcite	primary	0.0	0.0	116.9
9	aq	calcite	primary	n.o.		107.3
10	aq	calcite	primary	-7.4	11.0	98.1
11	aq	calcite	primary	-5.0	7.8	116.5
12	aq	calcite	primary	-2.6	4.3	97.3
13	aq	calcite	primary	n.o.		122.8
14	aq	calcite	primary	n.o.		113.2
15	aq	calcite	primary	n.o.		111.7
16	aq	calcite	primary	-7.6	11.2	107.4
17	aq	calcite	primary	-7.1	10.6	108.0
18	aq	calcite	primary	n.o.		67.0
19	aq	calcite	primary	n.o.		92.7
20	aq	calcite	primary	n.o.		93.0
21	aq	calcite	primary	-5.4	8.4	112.0
22	aq	calcite	primary	n.o.		95.9
23	aq	calcite	primary	n.o.		96.4
24	aq	calcite	primary	n.o.		118.4

11.7.4 Diagenetic sequence in the context of burial/thermal history

The burial/thermal history of the O18-01 well as been constructed (Figure 11-15) based on the following assumptions. A study by Mann et al. (1991) concluded that at 3777-8600 ft the vitrinite reflectance values were 0.60 to 1.15 % with a gradient of 0.3% per km. Values of 3.0% below 10,000 ft are from the Silurian. The Visean has no source rock potential with a max. TOC of 0.2%. A study by Wygrala (1991) used vitrinite reflectance to calibrate the thermal history of the well as follows:

- A significant thermal event indicated at the Upper Silurian suggests that ~ 3 km of Silurian sediments are missing, and post-Silurian erosion of ~ 4 km is required to match the modelled thermal history.
- Early lithification of Tournaisian and Visean carbonates may have increased thermal conductivity.
- Thickness of the Westphalian sediments is significantly unknown, requiring between 1300 m (high heat flow model) and 1800 m (low heat flow model) of erosion.
- Cretaceous erosion was also incorporated into the model but is not considered to be a critical factor in basin modelling.

Therefore, the maximum burial temperatures are assessed as:

- Caledonian basement reached 220 ºC during Silurian burial (such high temperatures have not been reached since).
- Tournaisian and Visean carbonates reached 160-165 ºC during Westphalian, these were reduced to 60-70 ºC and then reached 100 ºC during Tertiary burial.
- Carboniferous clastics reached 125-130 ºC during Westphalian burial, these were reduced to 30-40 ºC and then reached 65 ºC during the mid-Tertiary.

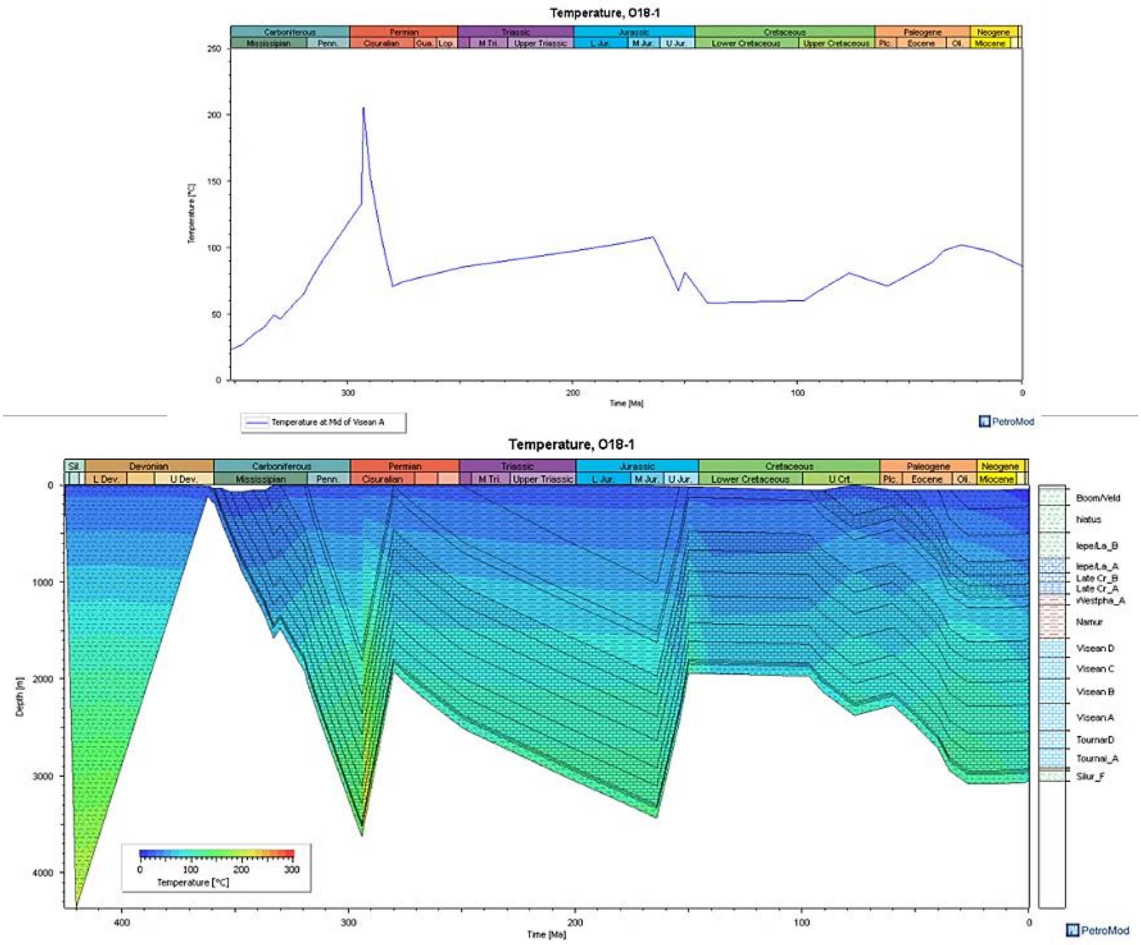

Figure 11-15: Temperature history and burial history for O18-01 based on in-house models.

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Onderzoek in de ondergrond voor aardwarmte

www.scanaardwarmte.nl