ZEPHYR PROJECT

Hauptdolomit petrography and diagenesis overview

By Jo Garland, Cambridge Carbonates

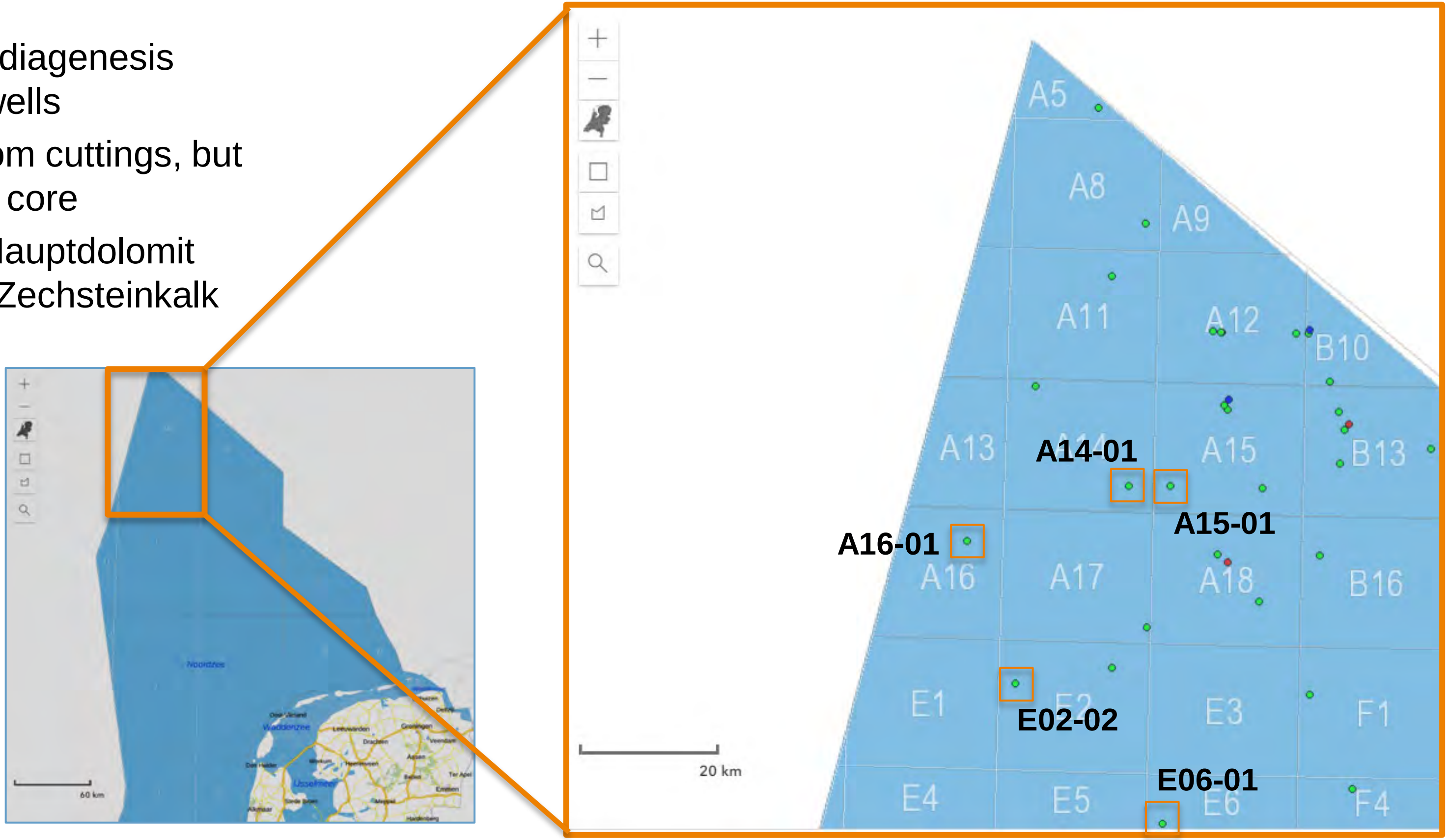
TNO innovation for life

OBJECTIVES

- Provide an overview of the Hauptdolomit microfacies, environment of deposition and reservoir porosities from cuttings and core in 5 wells.
- Gain a better understanding of the diagenesis, by evaluating samples using CL and O&C stable isotopes, drawing comparison to published examples.

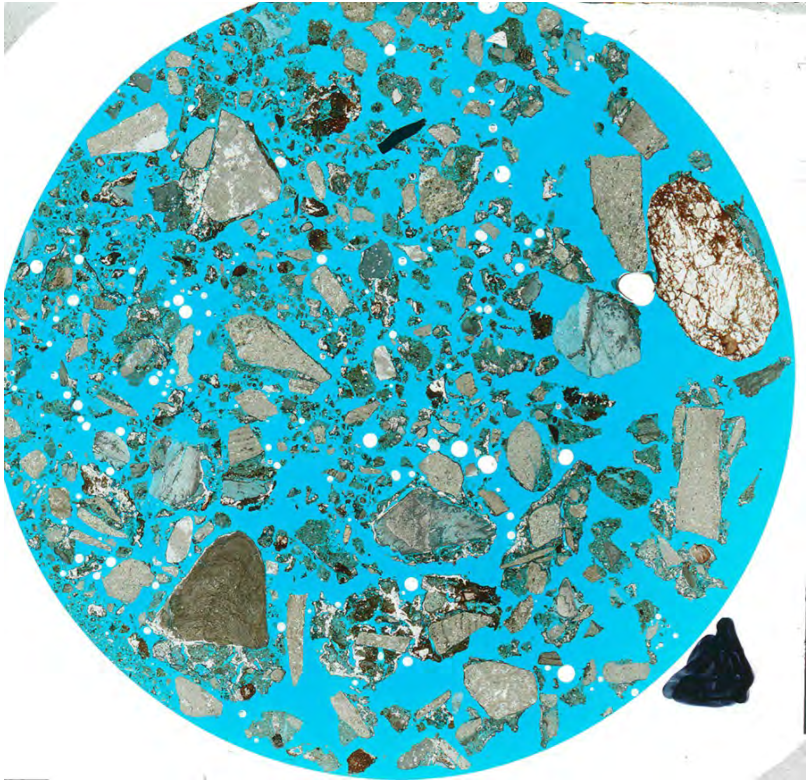
DATABASE

- Petrography and diagenesis undertaken in 5 wells
- Predominantly from cuttings, but A16-01 has short core
- All intervals are Hauptdolomit except E06-01 – Zechsteinkalk



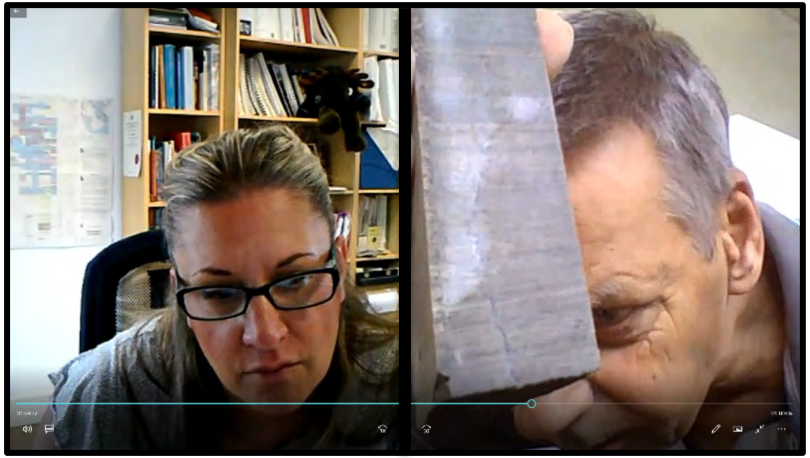
CUTTINGS METHODOLOGY

- Washed and dried cuttings subsampled by TNO over the Hauptdolomit interval of each well.
- Cuttings were resin impregnated and prepared into polished thin sections so that petrography and CL could be undertaken on the same sample. Note that some thin sections were later stained with a carbonate stain to confirm mineralogy.
- For each thin section, cuttings microfacies were described, and the abundance noted (dominant, common, trace). Any matrix or macroporosity was also noted.
- Data tabulated in excel.
- Multiple photomicrographs taken of each microfacies/sample.



CORE LOGGING METHODOLOGY

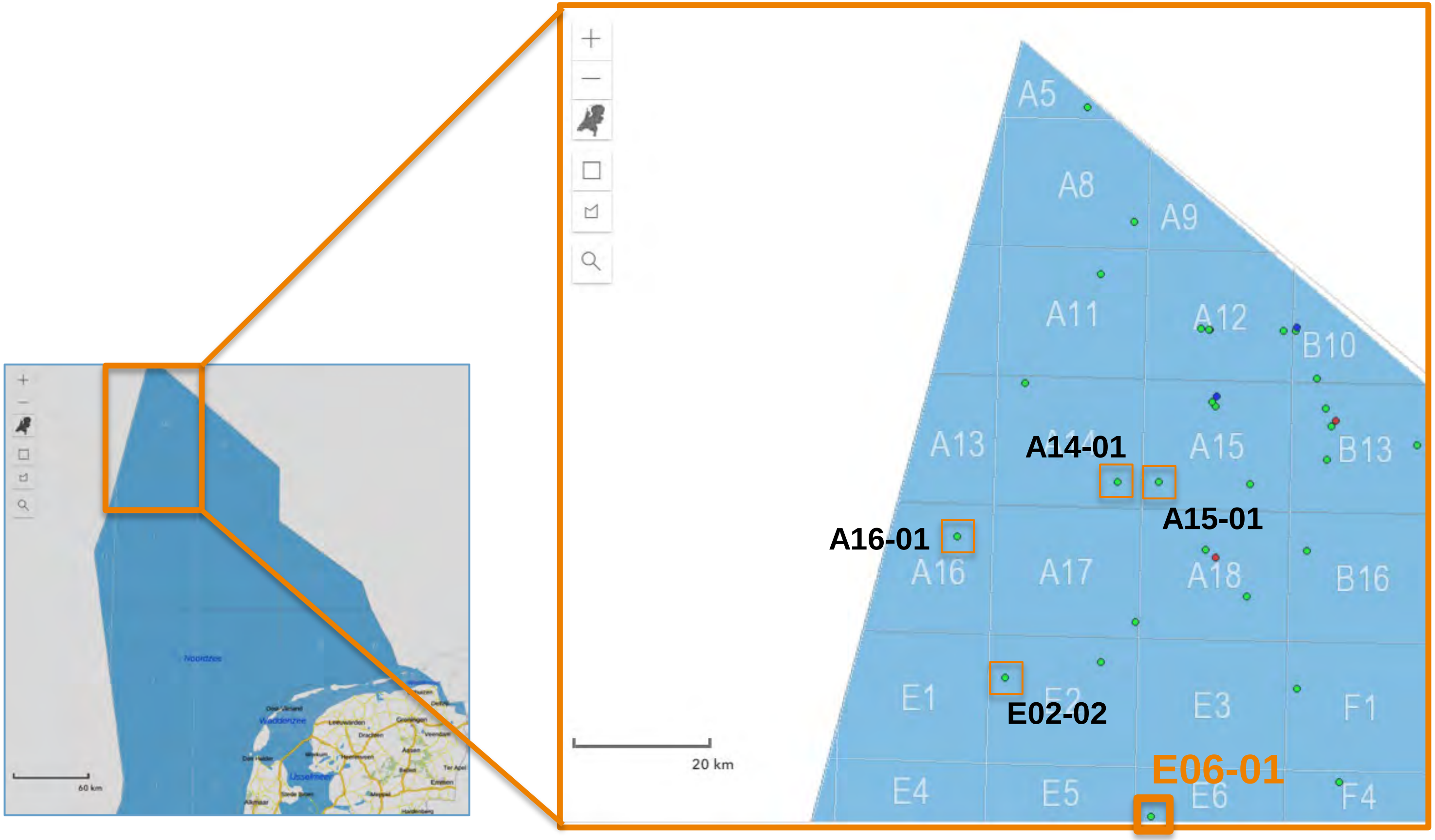
- A16-01 has short core over the Hauptdolomit.
- Due to COVID-19 travel restrictions, core logging was undertaken remotely
- Arranged a virtual conference call between CCL (in UK) and TNO (at core store) to log the core.
- Core pieces were viewed through video conference, and by live streaming using a digital microscope.
- 3 hour session was recorded, so that it could be cross-checked later if necessary.
- Core log drawn by hand, and then converted to a digital format using CORECAD software.



DELIVERABLES

- PowerPoint report for each well, detailing petrography, microfacies, depositional setting and reservoir porosities through the Hauptdolomit.
- Cuttings and core photomicrographs (297)
- Core log for A16-01
- PowerPoint report for diagenesis detailing CL character, O&C stable isotopes, and comparison to published analogues.
- CL photomicrographs (96)

E06-01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A14-01
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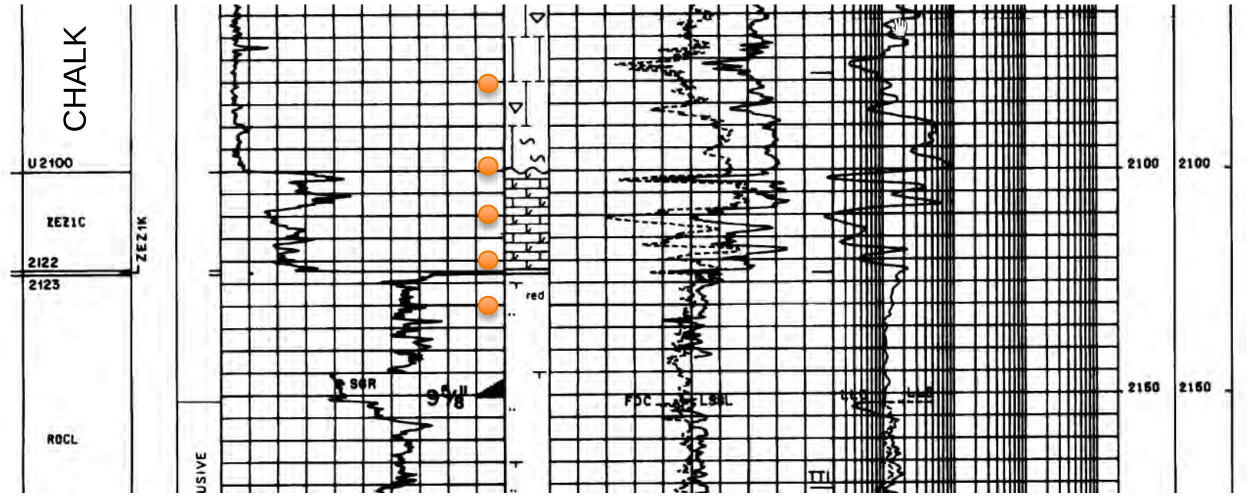
A15-01
A16-01
A16
A17
A18
B16
E1
E02-02
E3
F1
20 km
E06-01
E4
E5
E6
F4

E06-01 SAMPLES

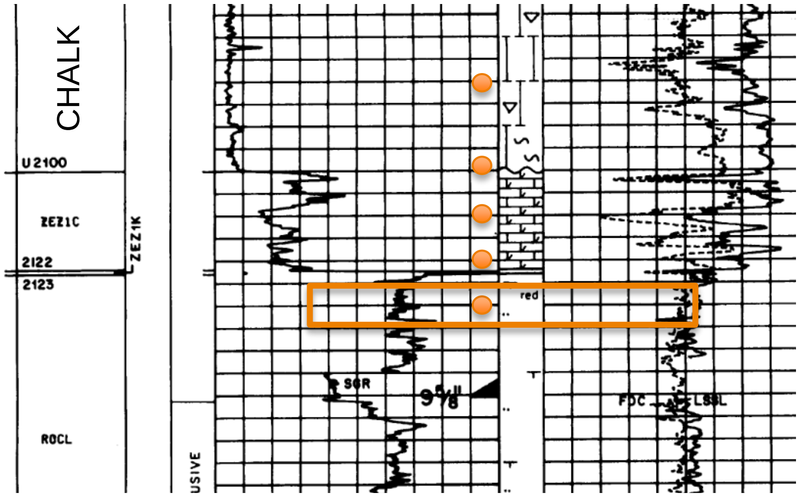
- NOT Hauptdolomit, but Zechsteinkalk. ~21m thick.
- Significant unconformity – chalk sitting on top of Zechteinkalk
- 5 cuttings samples collected by TNO



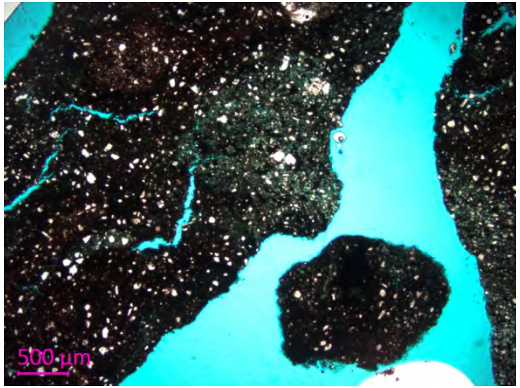
Cuttings sample

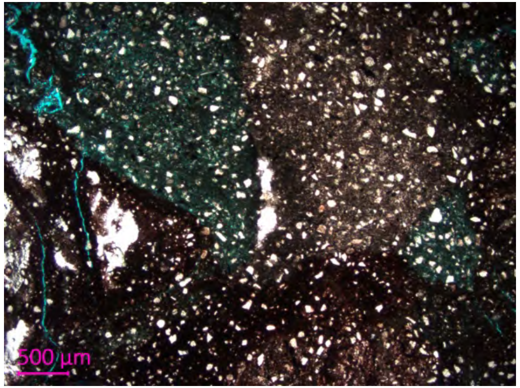
E06-01 PETROGRAPHY

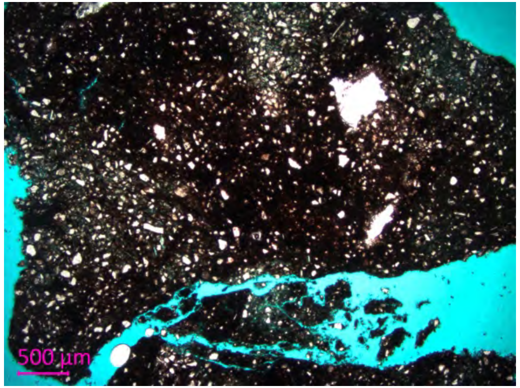
Rotliegendes – silty claystones



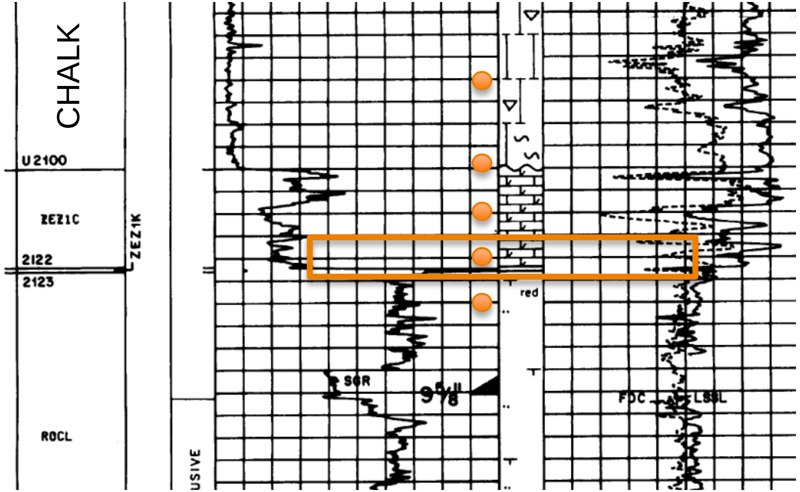
Cuttings sample





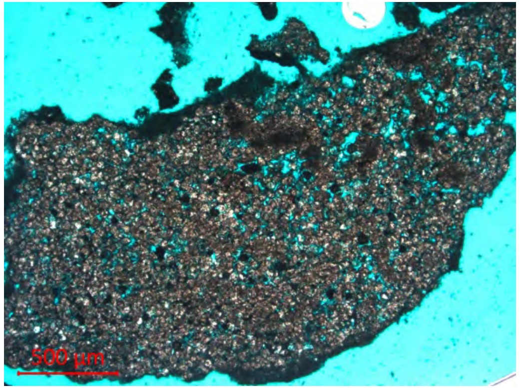


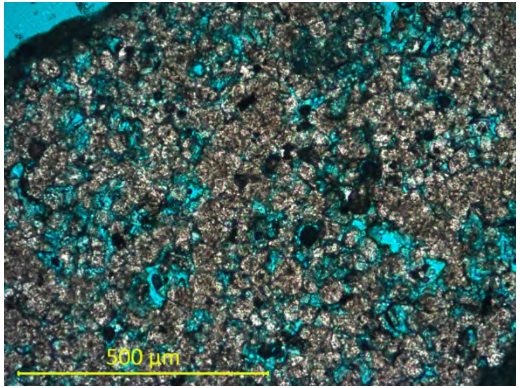
E06-01 PETROGRAPHY

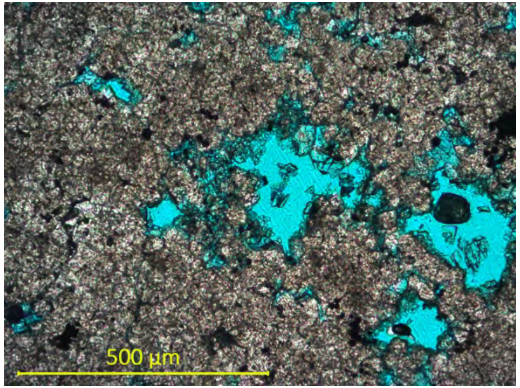


Cuttings sample

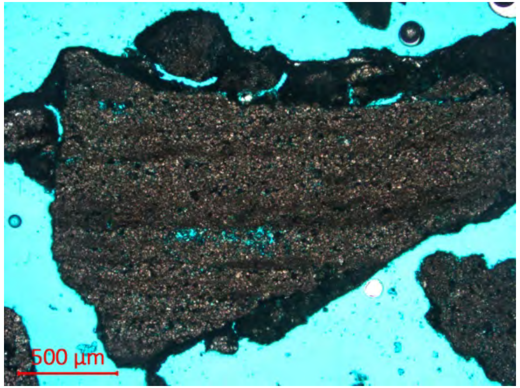
Dominant fine crystalline dolomite



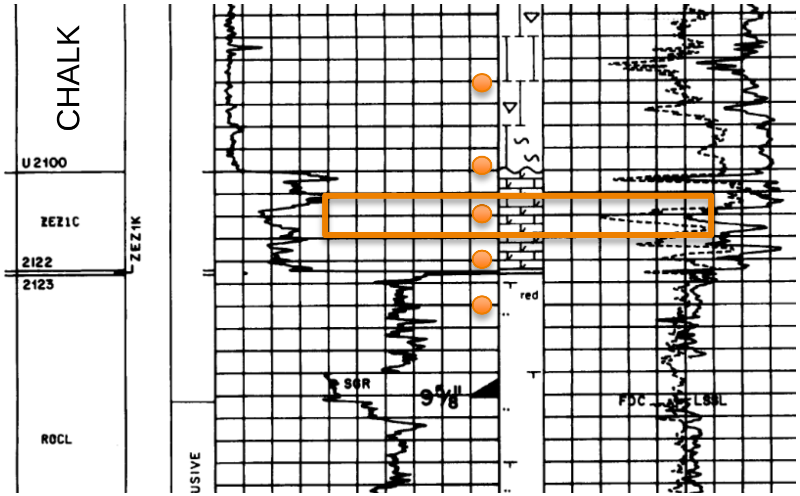




Common dolomicrite (laminated)

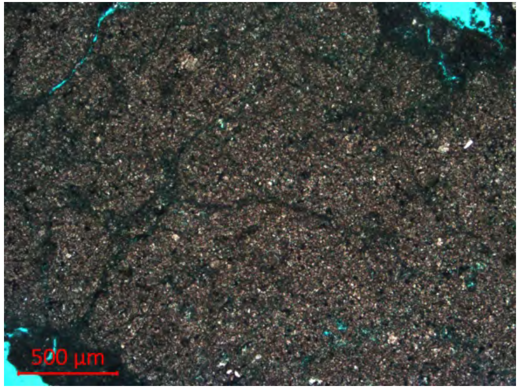


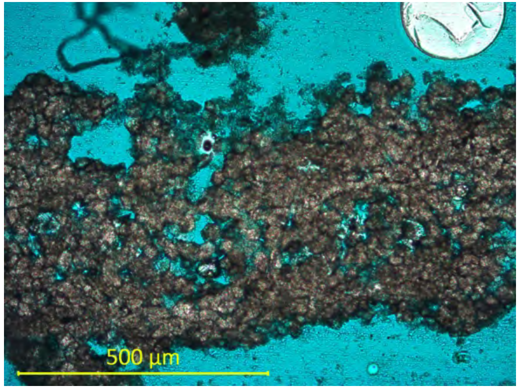
E06-01 PETROGRAPHY



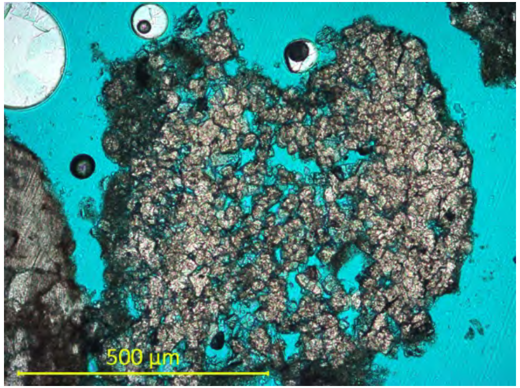
Cuttings sample

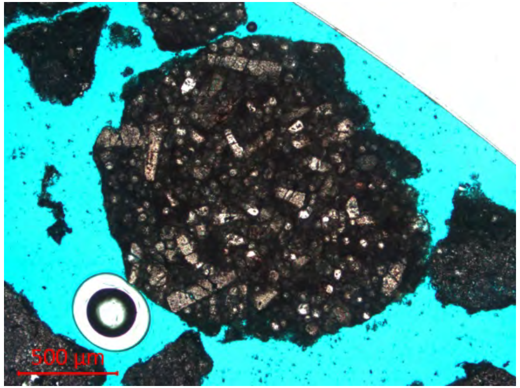
Dominant fine crystalline dolomite





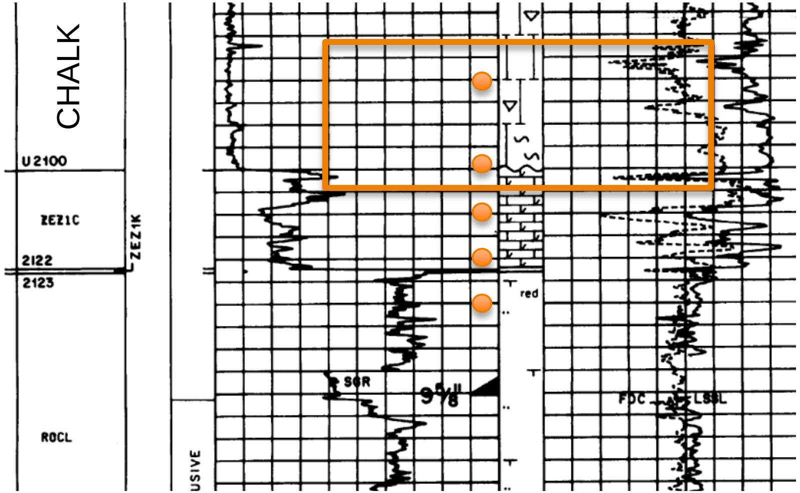
Common chalk





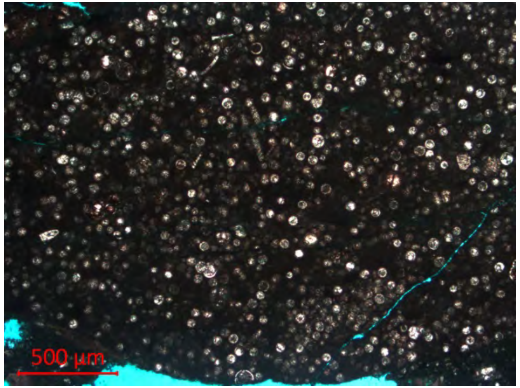
E06-01 PETROGRAPHY

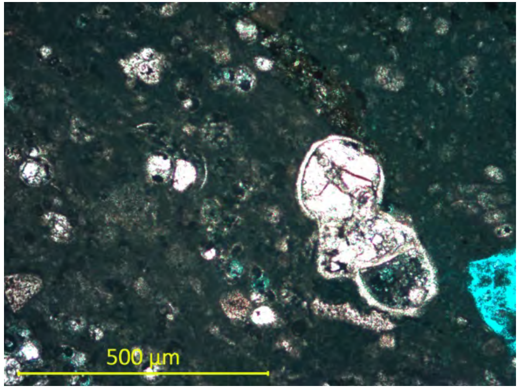
NB – samples from the chalk and chalk/ Zechstein boundary



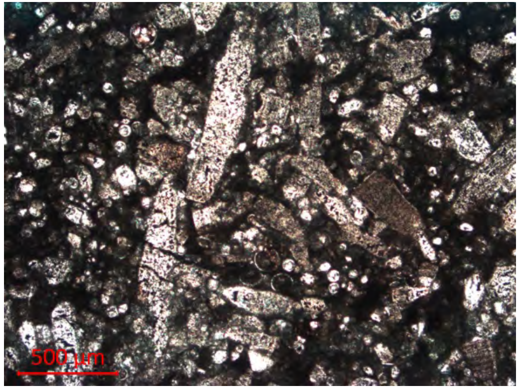
Cuttings sample

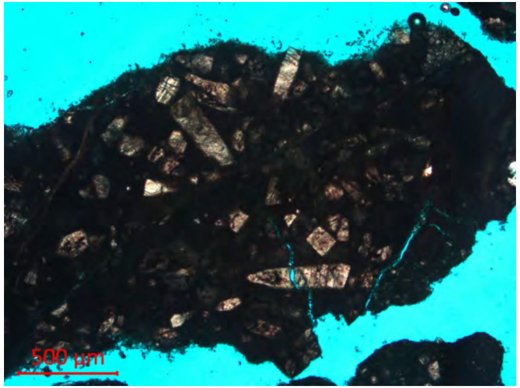
Dominant foraminiferal-calcisphere mud-packstone





Common Inoceramid wackestone to packstone

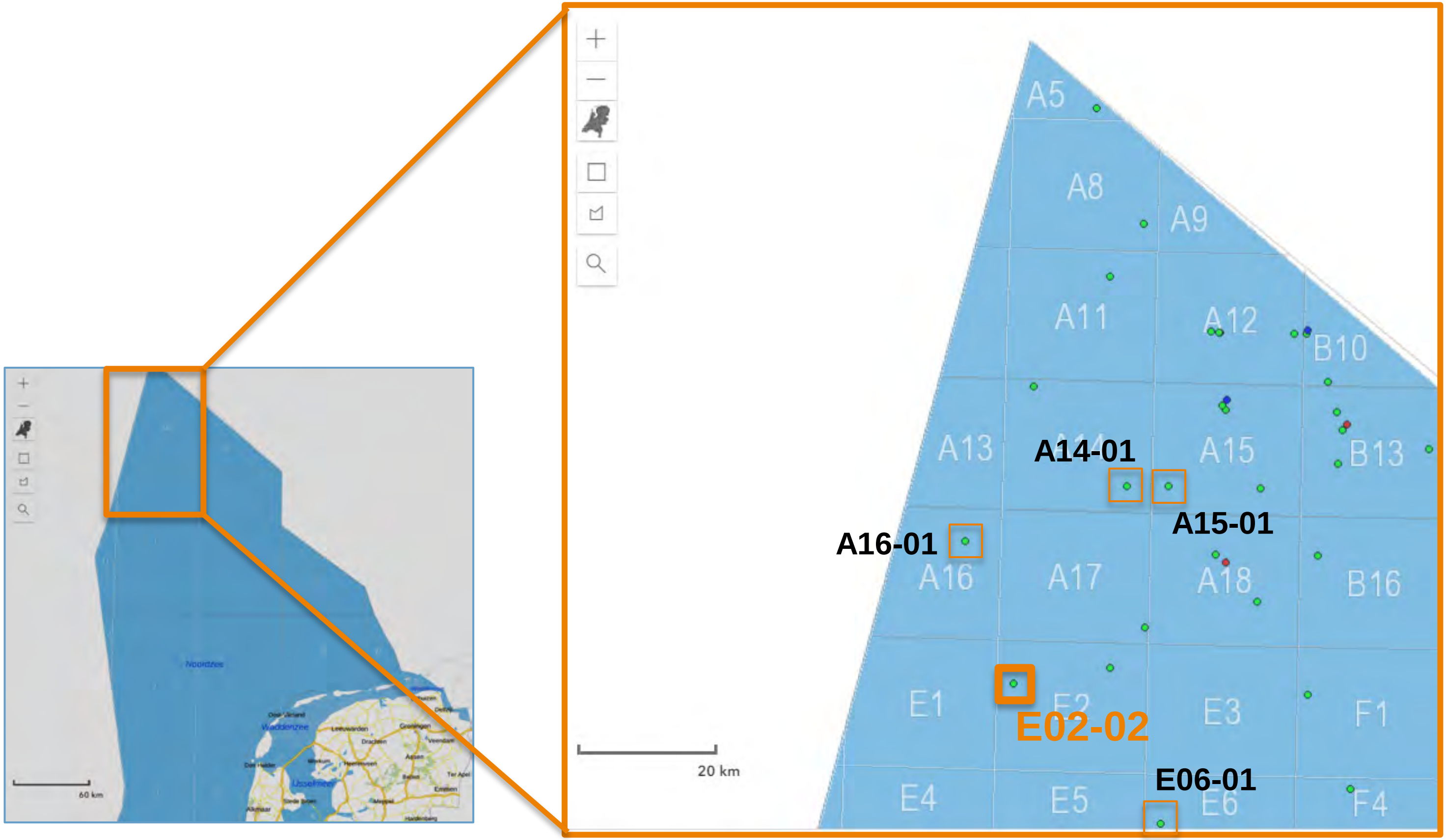




E06-01 SEDIMENTOLOGICAL INTERPRETATION

- The Chalk sits unconformably over the Zechsteinkalk interval, which has undergone dissolution.
- The Zechsteinkalk facies are predominantly dolomicrites, laminated dolomicrites and fine crystalline dolomites, suggesting the dolomites replaced matrix-supported textures.
- Matrix-supported facies were deposited in low-energy depositional settings, either in protected lagoons or in a deeper water, open marine setting below wave base.

E02-02



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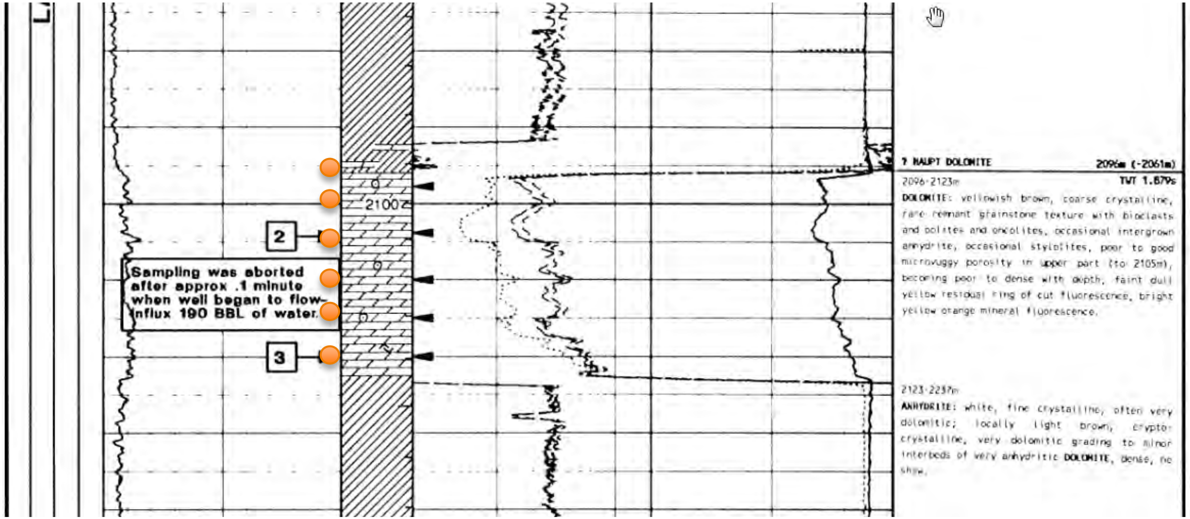
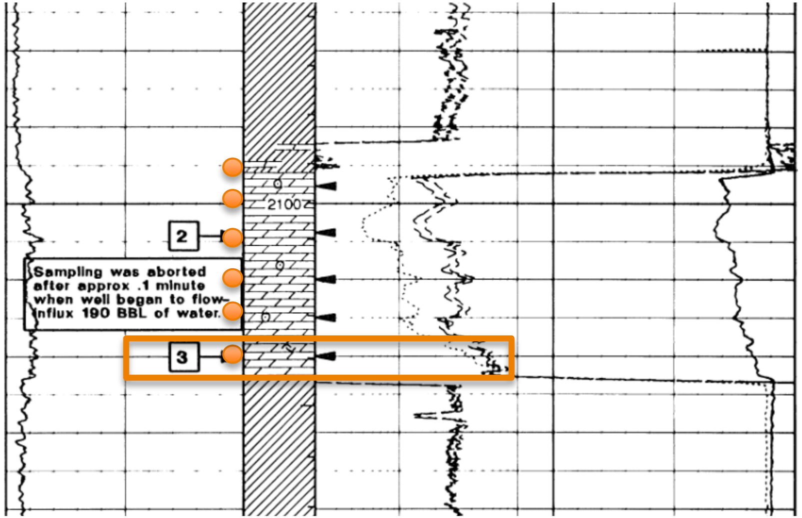
B16
E1
E2
E02-02
E3
F1
20 km
E06-01
E4
E5
E6
F4
60 km

E02-02 SAMPLES

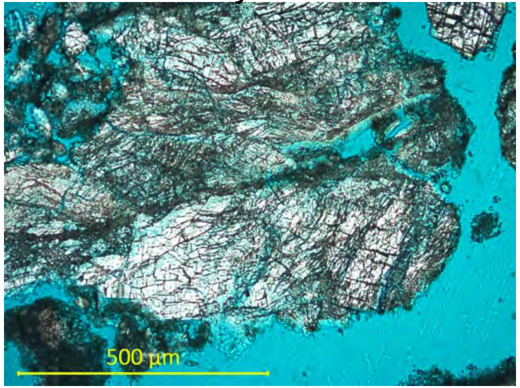
- Hauptdolomit ~27m thick
- 6 cuttings samples collected by TNO
- Cuttings samples are of poor quality



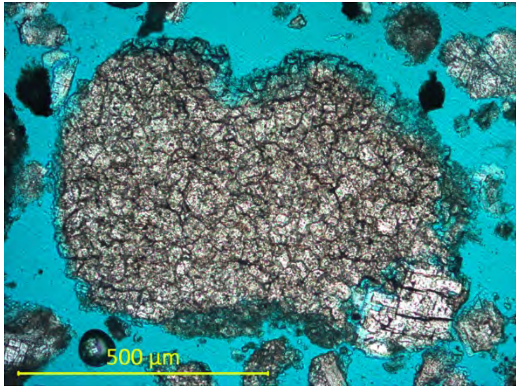
E02-02 PETROGRAPHY

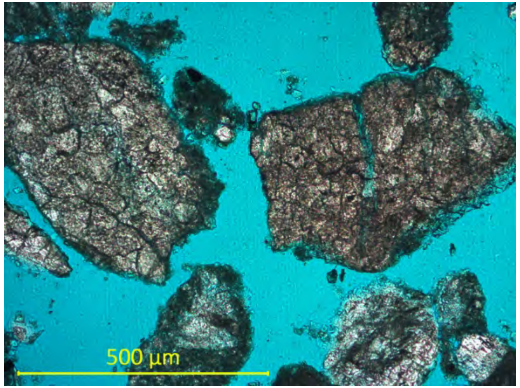


Dominant anhydrite

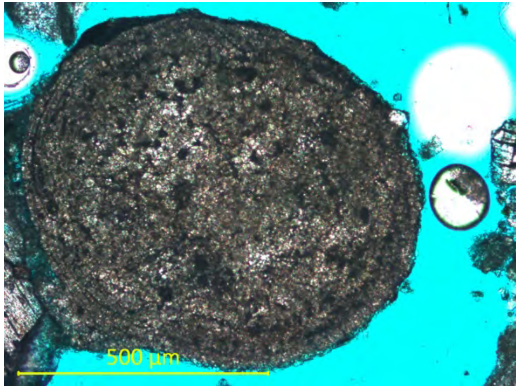


Common fine crystalline dolomite

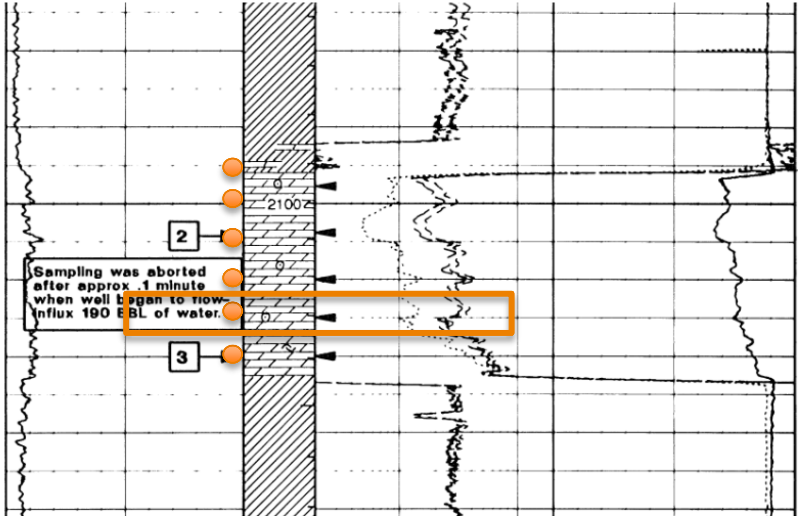




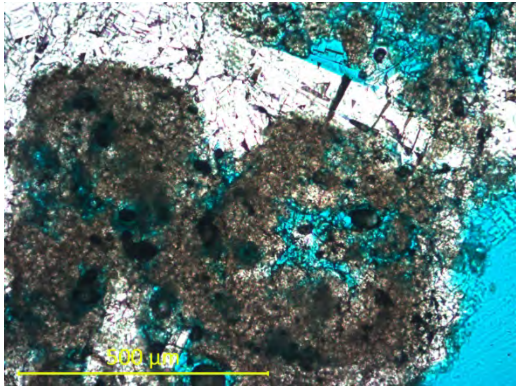
Rare ooid grainstone



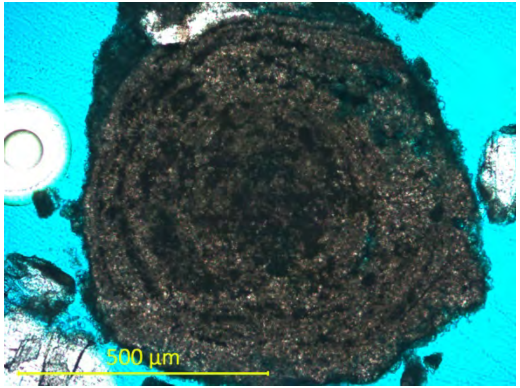
E02-02 PETROGRAPHY

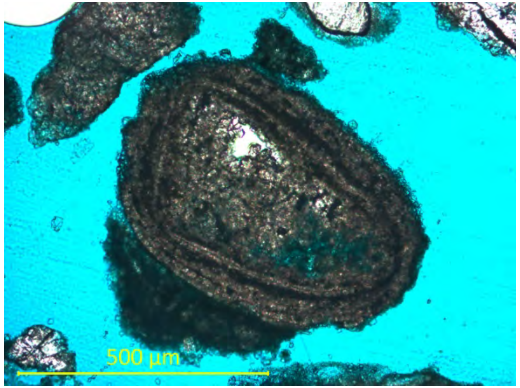


Dominant anhydrite
(poorly preserved)

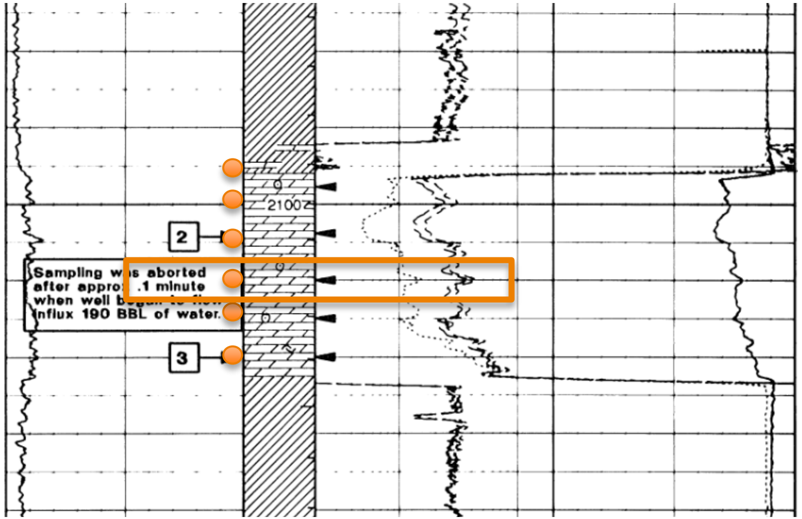


Common ooid grainstone

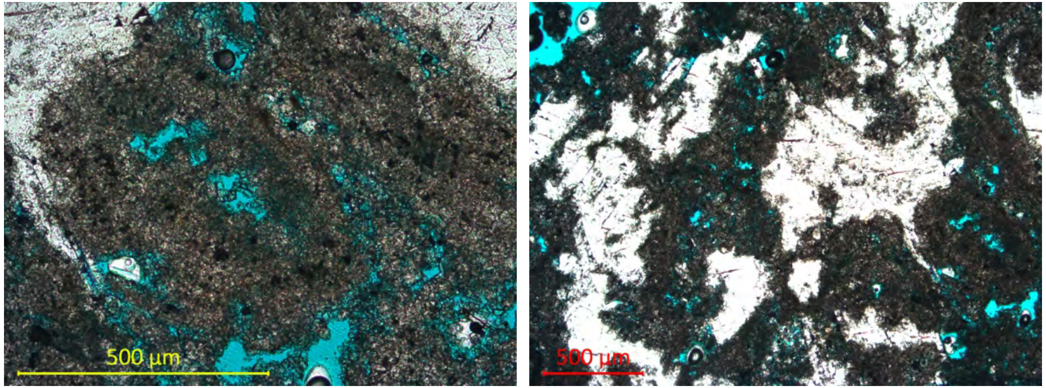




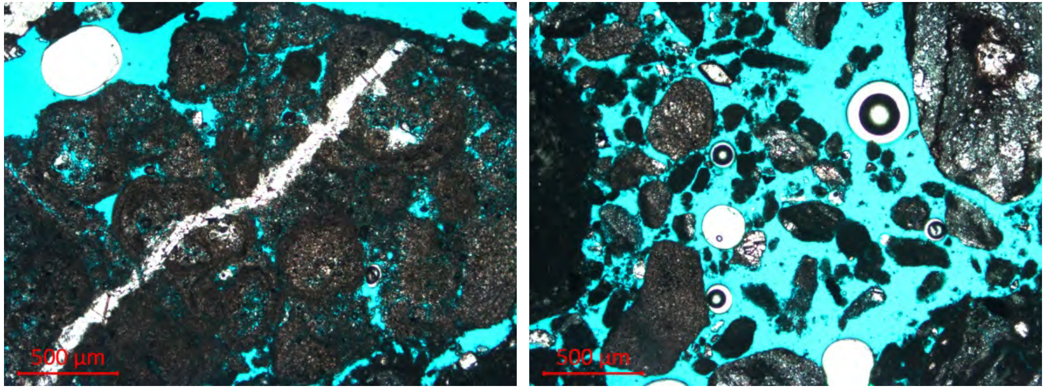
E02-02 PETROGRAPHY



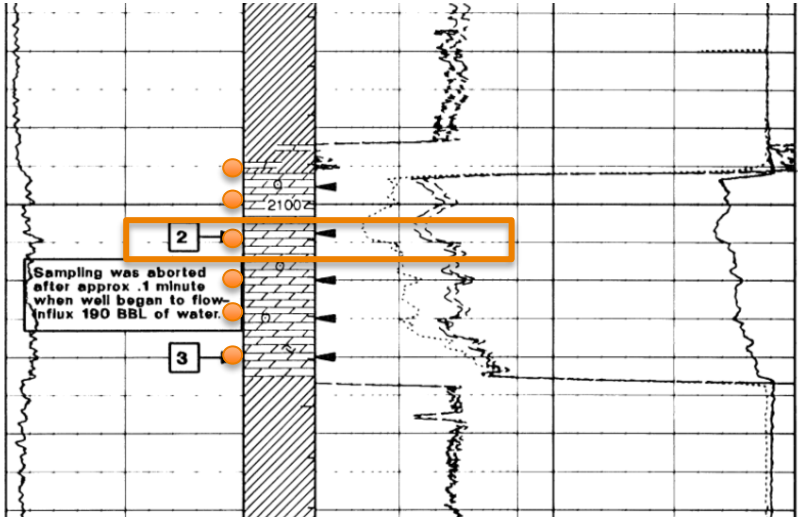
Dominant ooid/coated-grain grainstone



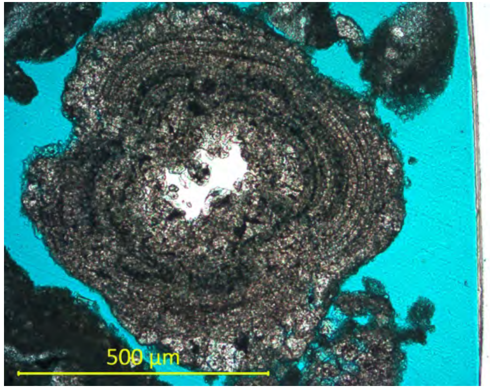
Common dolomicrite

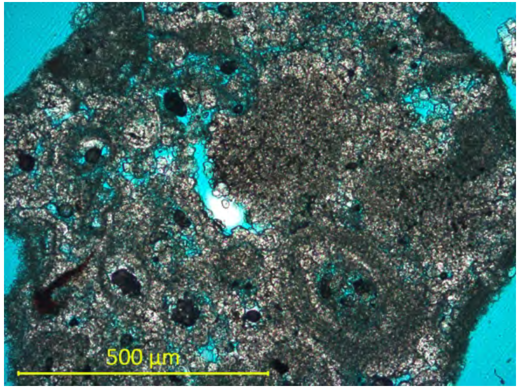


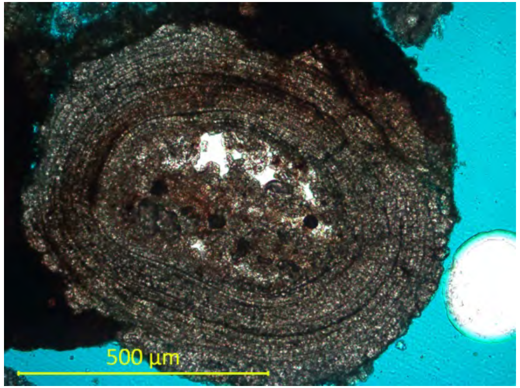
E02-02 PETROGRAPHY



Dominant ooid/coated-grain grainstone

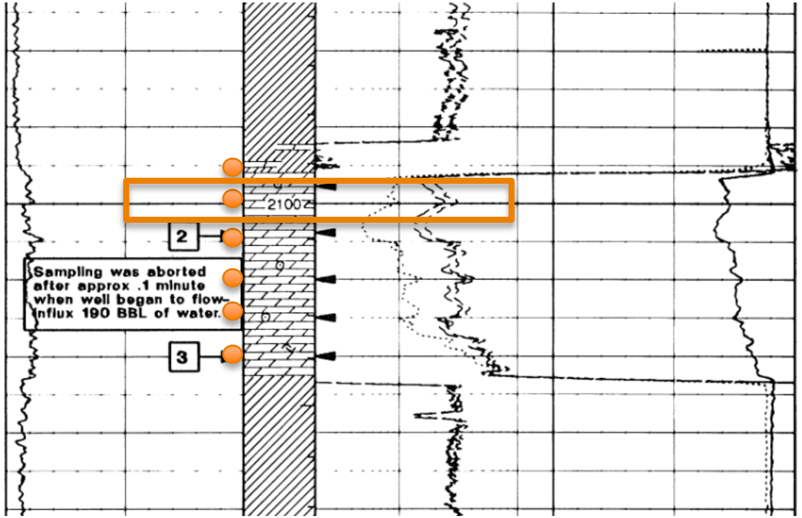




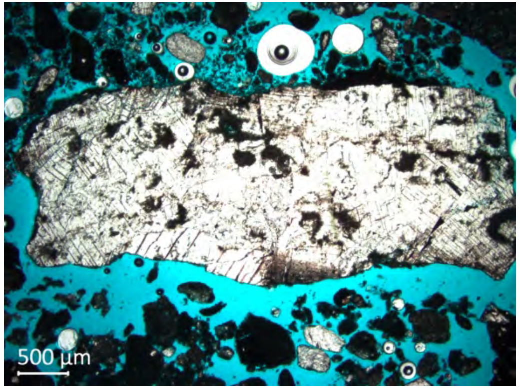


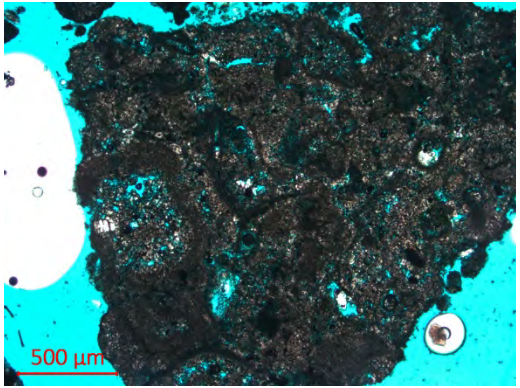
Common anhydrite

E02-02 PETROGRAPHY

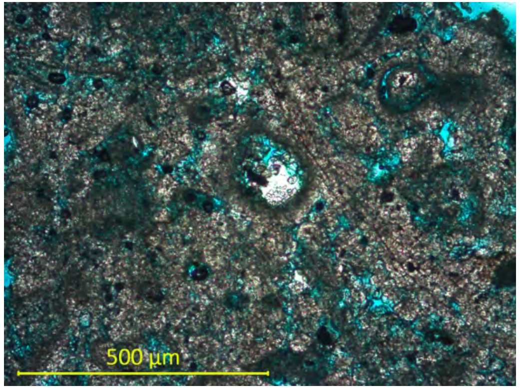


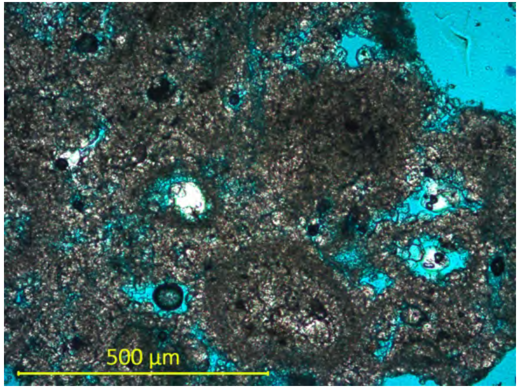
Dominant anhydrite



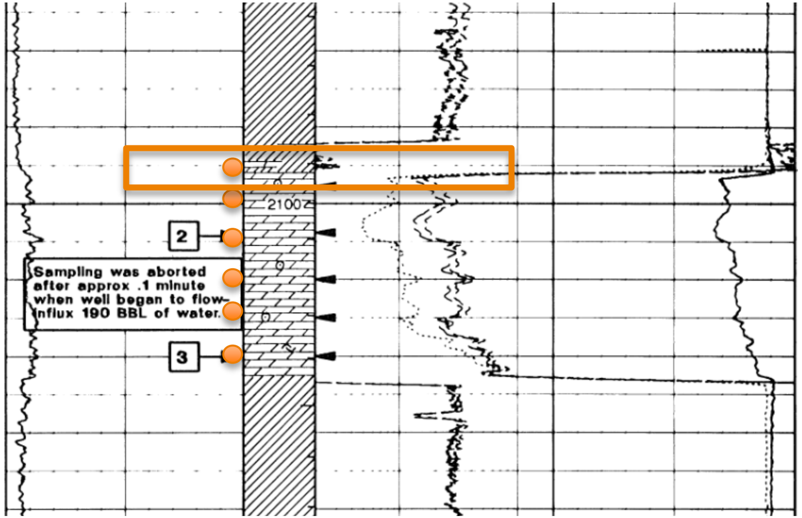


Common ooid/coated-grain grainstone

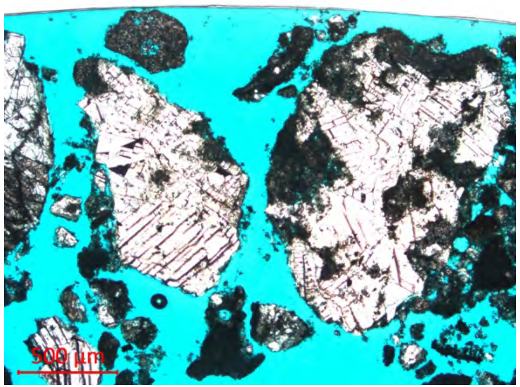


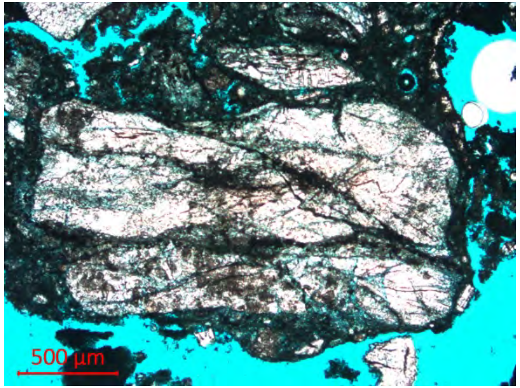


E02-02 PETROGRAPHY

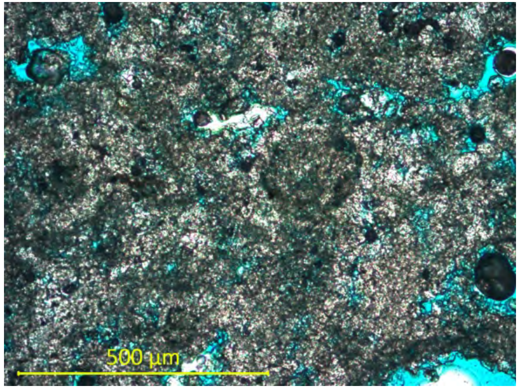


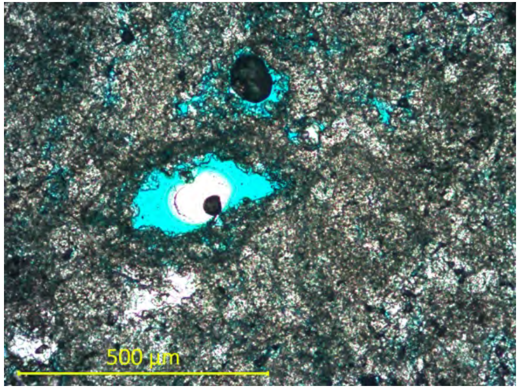
Dominant anhydrite





Common peloid/ooid grainstone





E02-02 SEDIMENTOLOGICAL INTERPRETATION

- The Hauptdolomit characterised predominantly by ooid and coated grain grainstones, deposited in a high energy, shallow marine depositional setting.

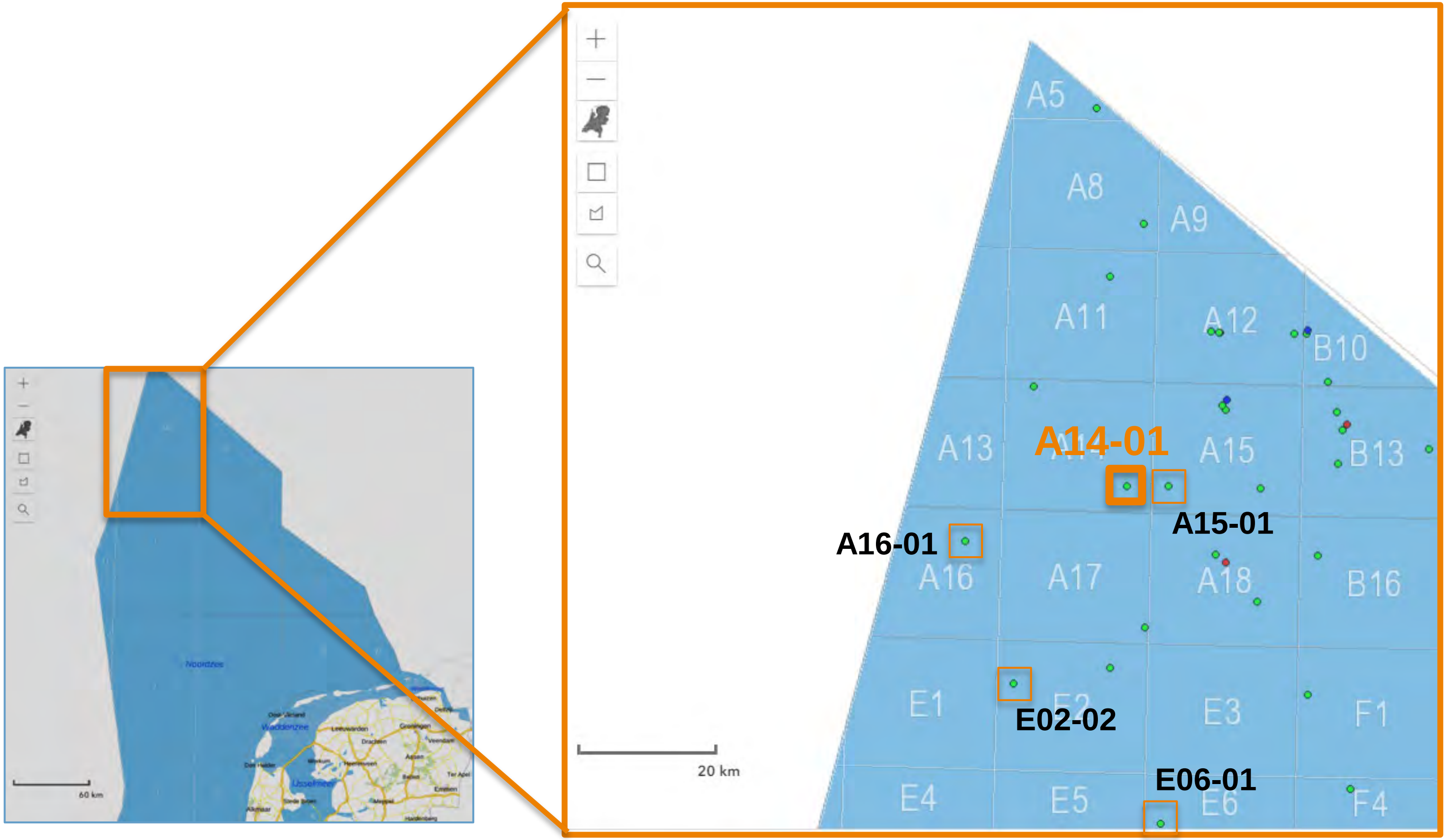
- The presence of a mix of coated grains (ooids, composite grains), suggests that this was not a consistently high energy shoal setting, and may represent a slightly protected, but still high energy, back-shoal setting.

- These high energy facies are dominant between 2110m to 2105m, but extend from 2115m to 2095m (20m thickness).

- Fine crystalline dolomites are common towards the top and base of the Hauptdolomit, as are anhydrites.

- The platformal facies of the Hauptdolomit sit above a thick (>200m) Werraanhydrit sulphate platform.

A14-01



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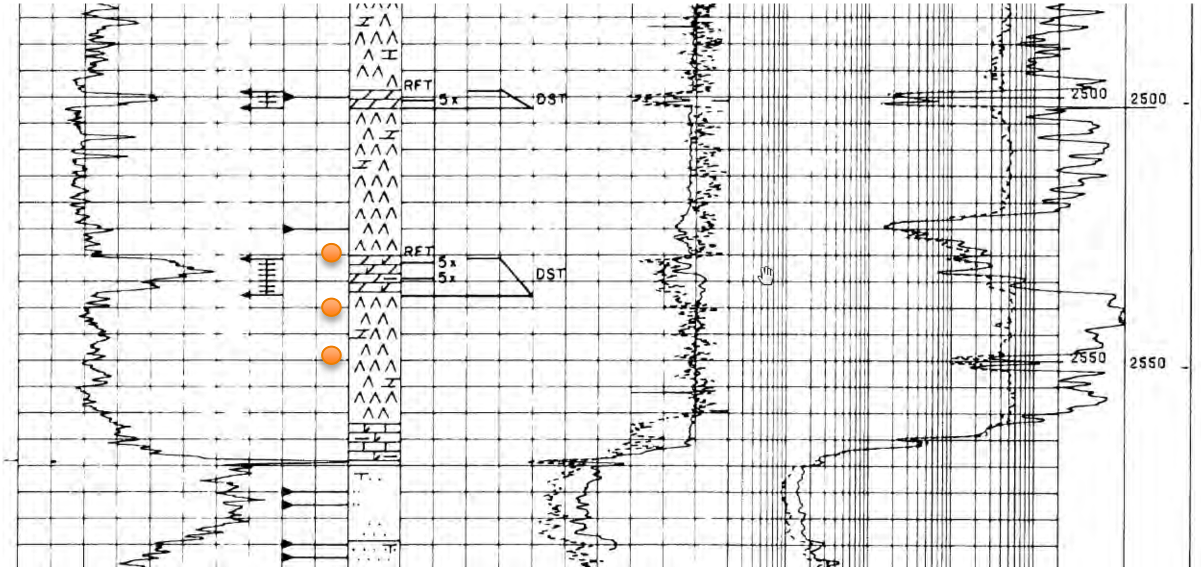
A15-01
A16-01
A16
A17
A18
B16
E1
E02-02
E3
F1
E06-01
E4
E5
E6
F4
20 km
60 km
Noordzee

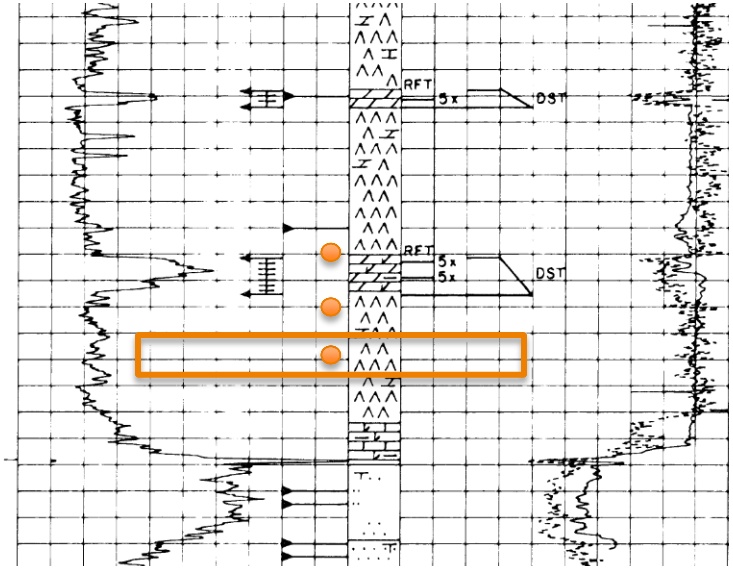
A14-01 SAMPLES

- Hauptdolomit ~6.5m thick
- 3 cuttings samples collected by TNO
- Cuttings samples are of good quality



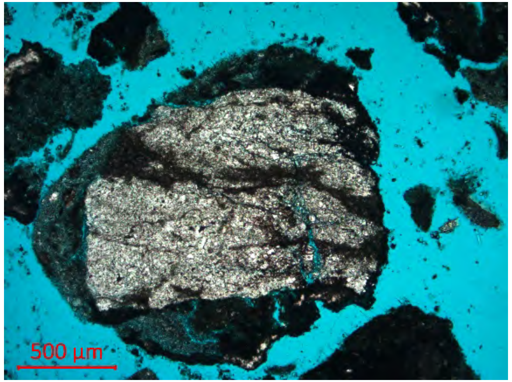
Cuttings sample

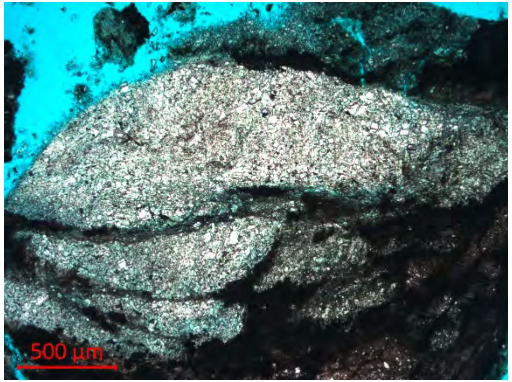
A14-01 PETROGRAPHY



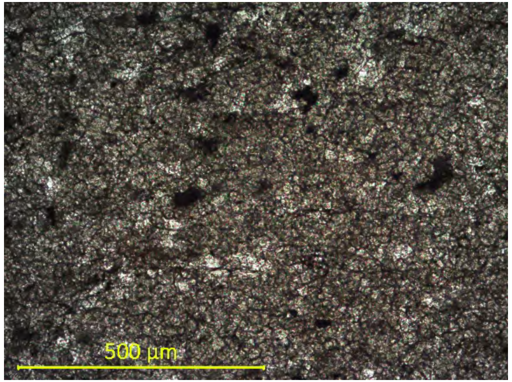
Cuttings sample

Dominant anhydrite

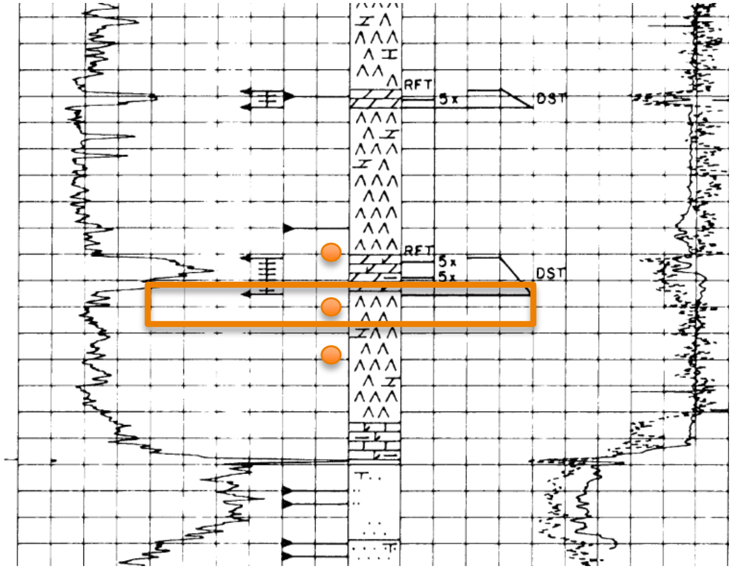




Common fine crystalline dolomite

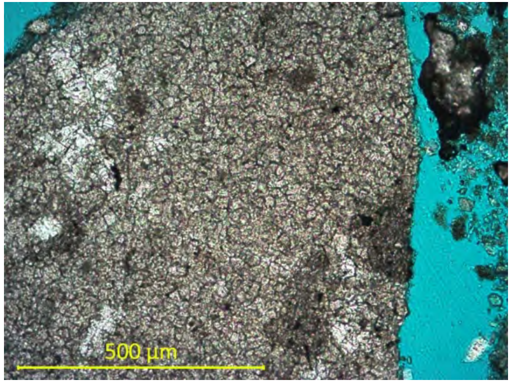


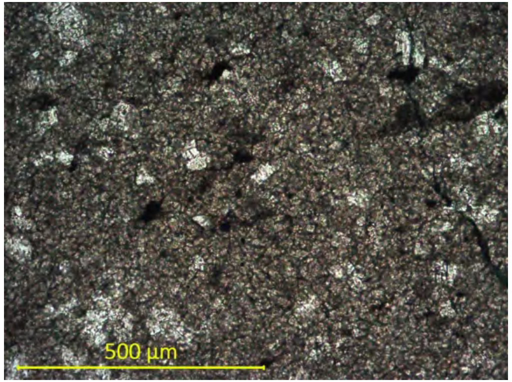
A14-01 PETROGRAPHY



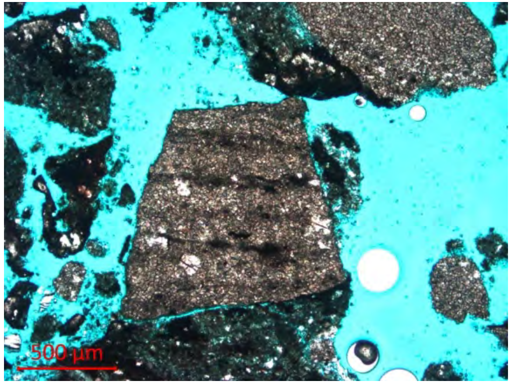
Cuttings sample

Dominant fine crystalline dolomite

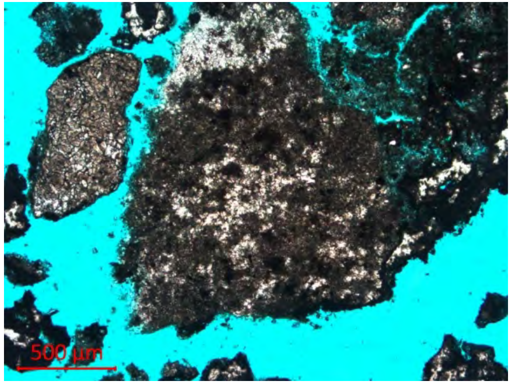




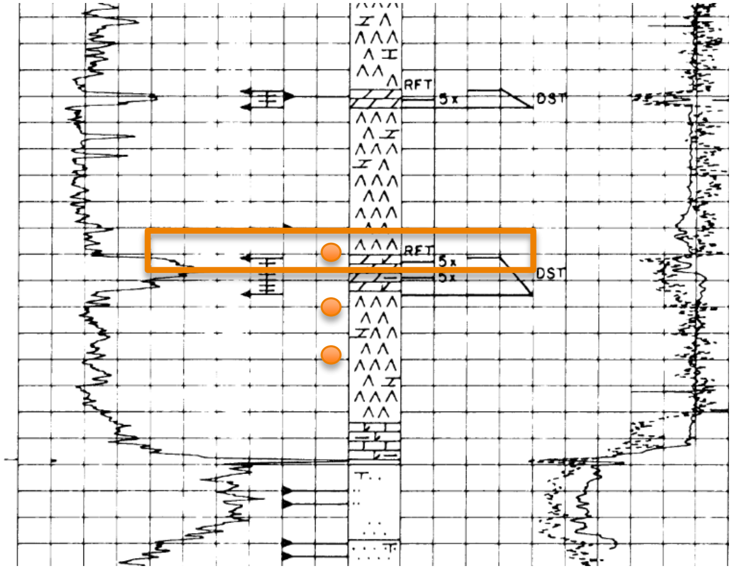
Common laminate dolomicrite



Common dol micropeloidal gst

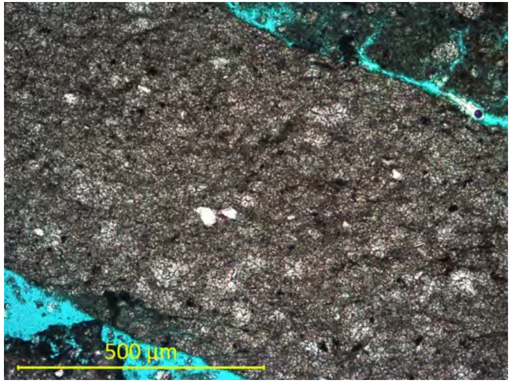


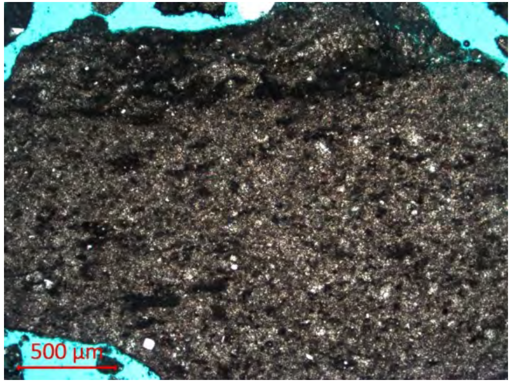
A14-01 PETROGRAPHY



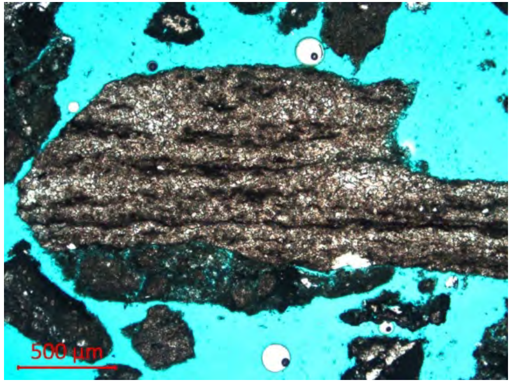
Cuttings sample

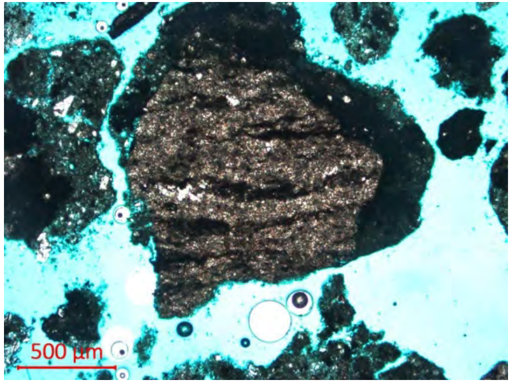
Dominant dolomicrite





Common laminated dolomicrite

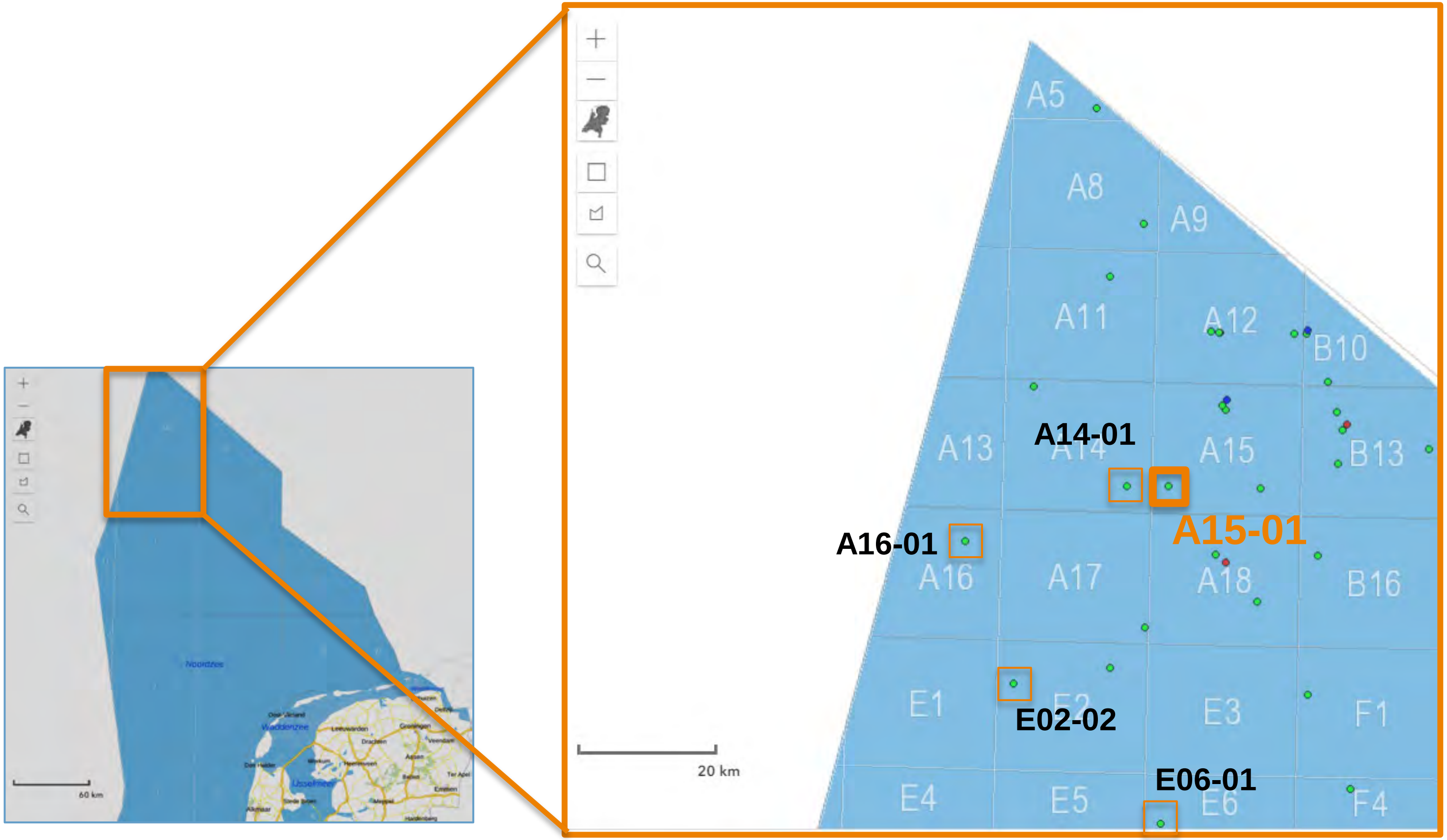




A14-01 SEDIMENTOLOGICAL INTERPRETATION

- Dominated by matrix-supported facies, in particular dolomicrite, fine crystalline dolomite and rarer fine micropeloidal grainstones.
- Indicative of low energy depositional settings below wave base
- Petrographically, this could represent either a protected lagoonal setting or a low energy, open marine, depositional environment.
- Since the underlying Werraanhydrit is relatively thin (~20m), it is probable that this well did not penetrate a sulphate platform, and therefore a open marine, slope/basinal setting is more likely.

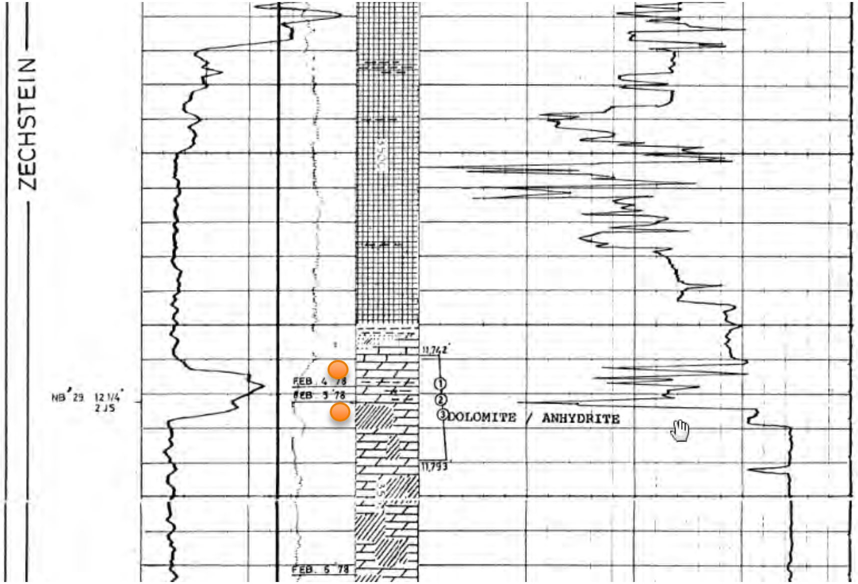
A15-01



A5
A8
A9
A11
A12
B10
A13
A14
A14-01
A15
B13
A15-01
A16-01
A16
A17
A18
B16
E1
E2
E02-02
E3
F1
E06-01
E4
E5
E6
F4
20 km
60 km
Noordzee
Waddenzee
IJsselmeer

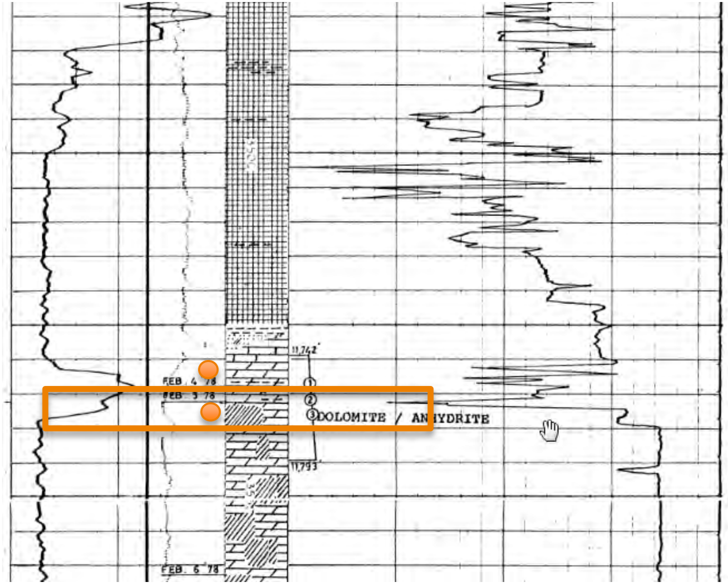
A15-01 SAMPLES

- Hauptdolomit ~7m thick
- 2 cuttings samples collected by TNO
- Cuttings samples are of moderate quality



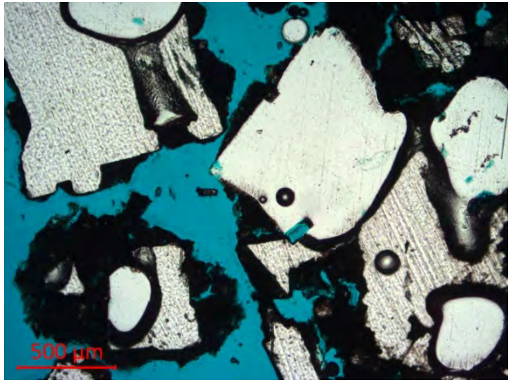
Cuttings sample

A15-01 PETROGRAPHY

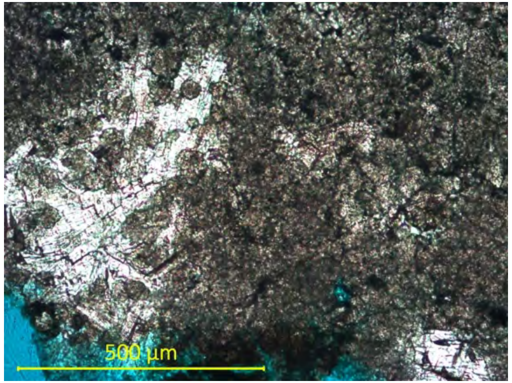


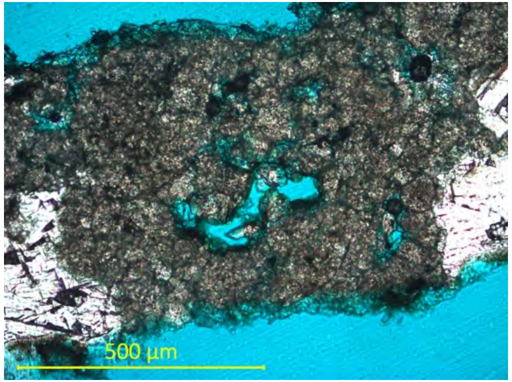
Cuttings sample

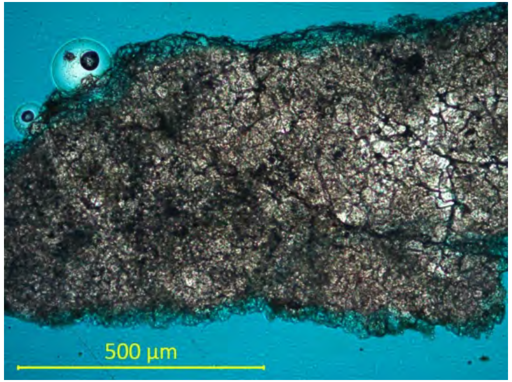
Dominant halite



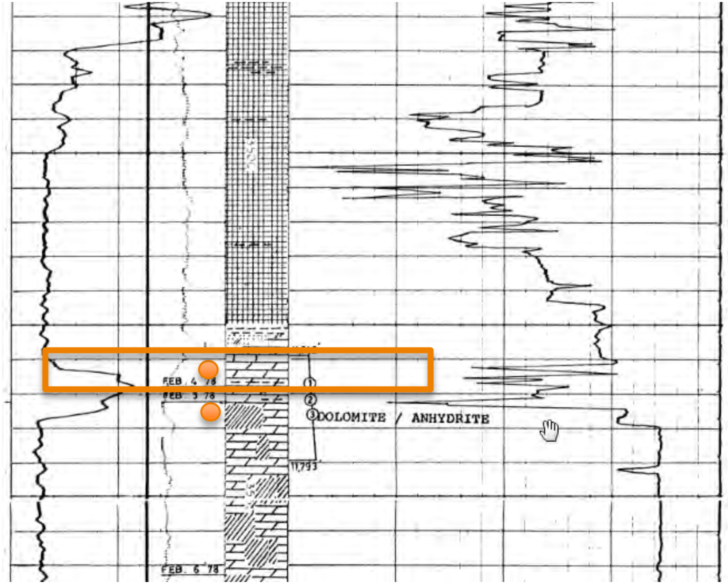
Common fine crystalline dolomite





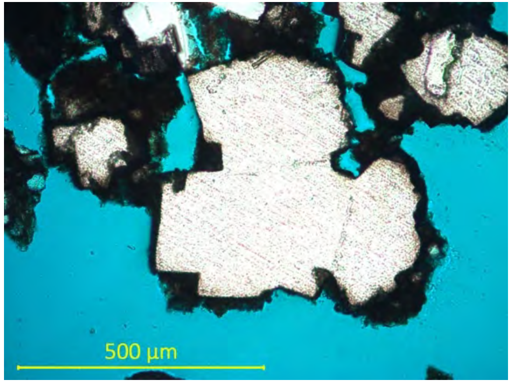


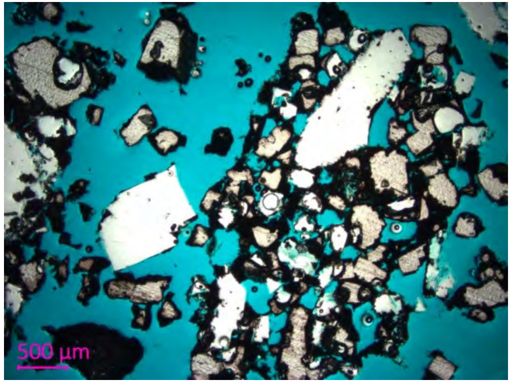
A15-01 PETROGRAPHY



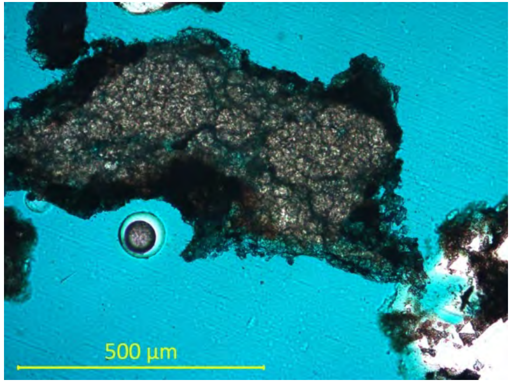
Cuttings sample

Dominant halite





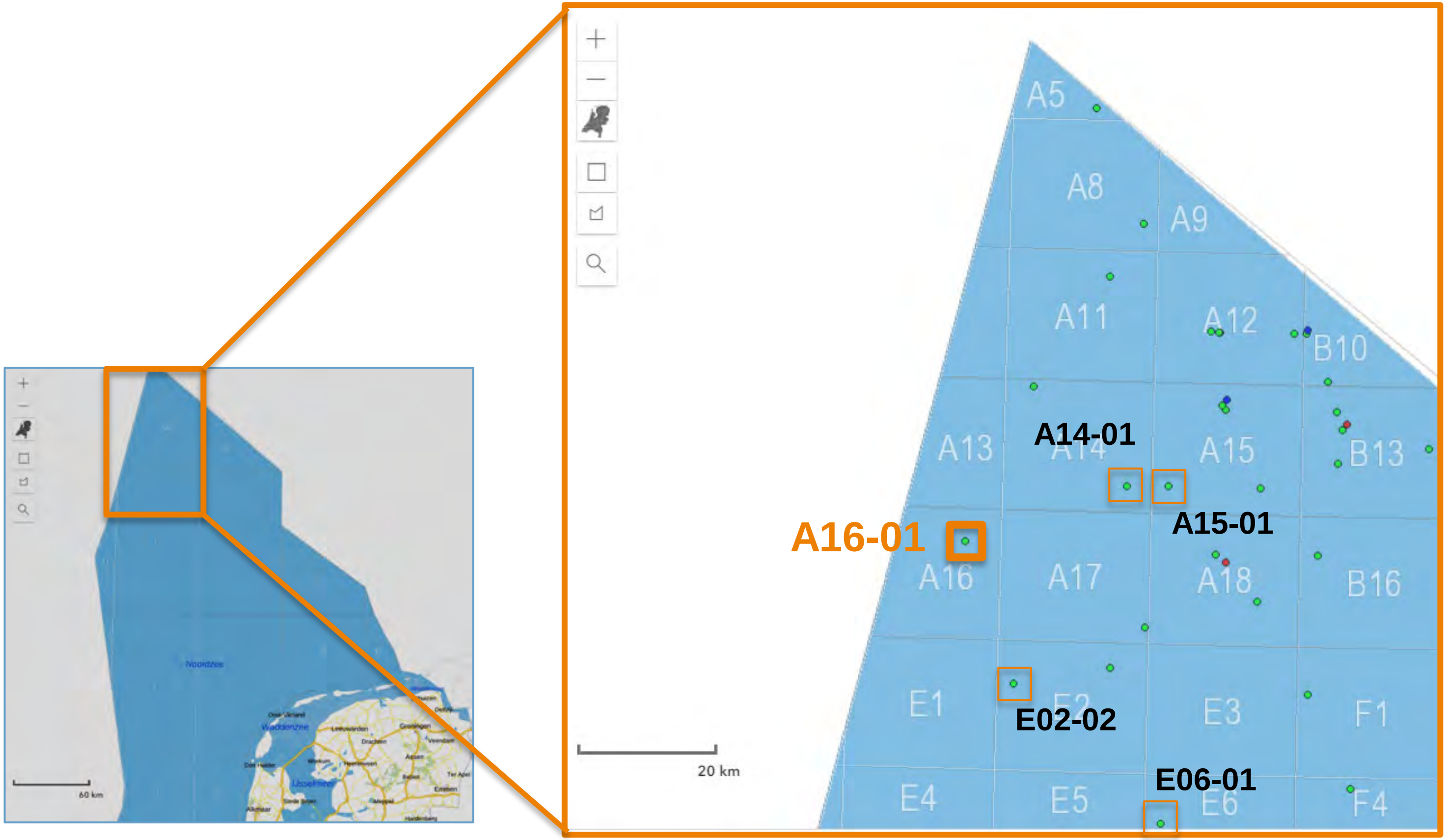
Rare dolomicrite



A15-01 SEDIMENTOLOGICAL INTERPRETATION

- Very thin Hauptdolomit interval.
- Fine crystalline dolomite most likely replaces mud-support facies, although the size of the cuttings makes this difficult to determine with certainty.
- Deposition in a low energy depositional setting, below wave base.
- Petrographically, this could represent either a protected lagoonal setting or a low energy, open marine, depositional environment.
- Thick halite above – most likely basinal setting

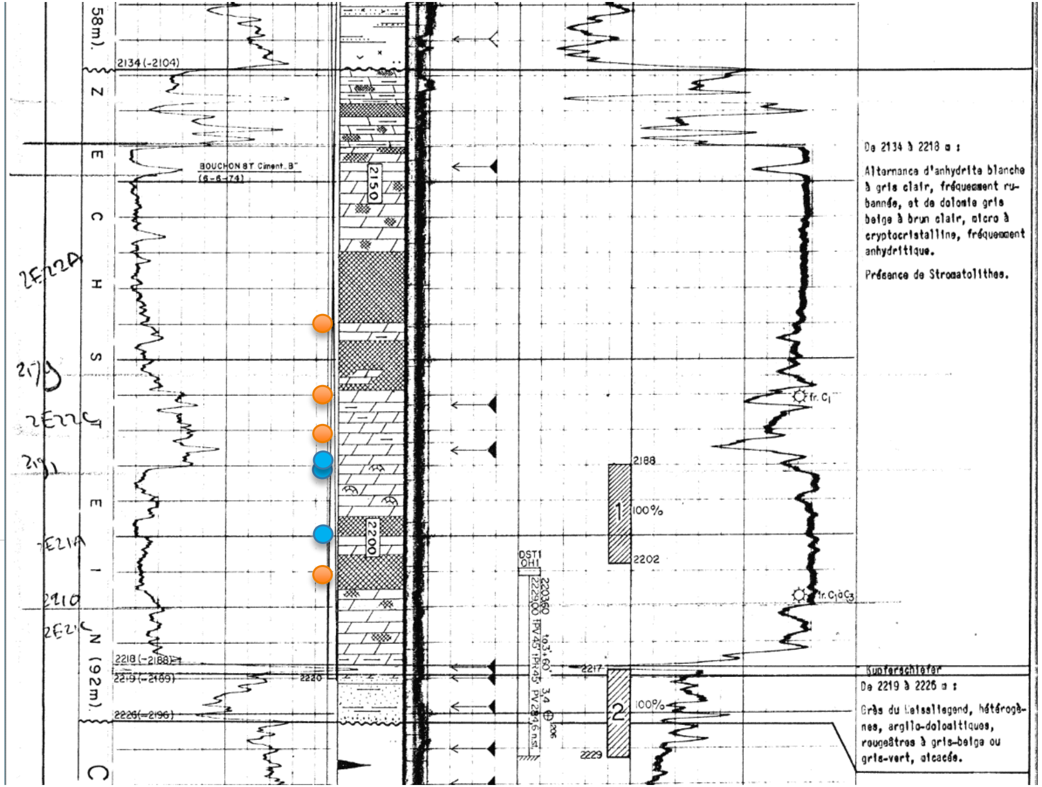
A16-01



A5
A8
A9
A11
A12
B10
A13
A14-01
A14
A15
B13
A15-01
A16-01
A16
A17
A18
B16
E1
E2
E3
F1
E02-02
20 km
E4
E5
E06-01
E6
F4

A16-01 OVERVIEW

- Hauptdolomit ~12m thick
- Core 1 taken at the transition from the underlying Werraanhydrit and overlying Hauptdolomit.
- 4 cuttings samples collected by TNO
- 3 core samples collected by TNO – one from Werraanhydrit



Cuttings sample   Core sample

CORE 1: WERRAANHYDRIT

Nodular anhydrites and laminated dolomites. 2198m (top left) – 2200m (bottom right)

Nodular anhydrites. 2200.75m

Exposure surface at top of Werraanhydrit. 2196.6m

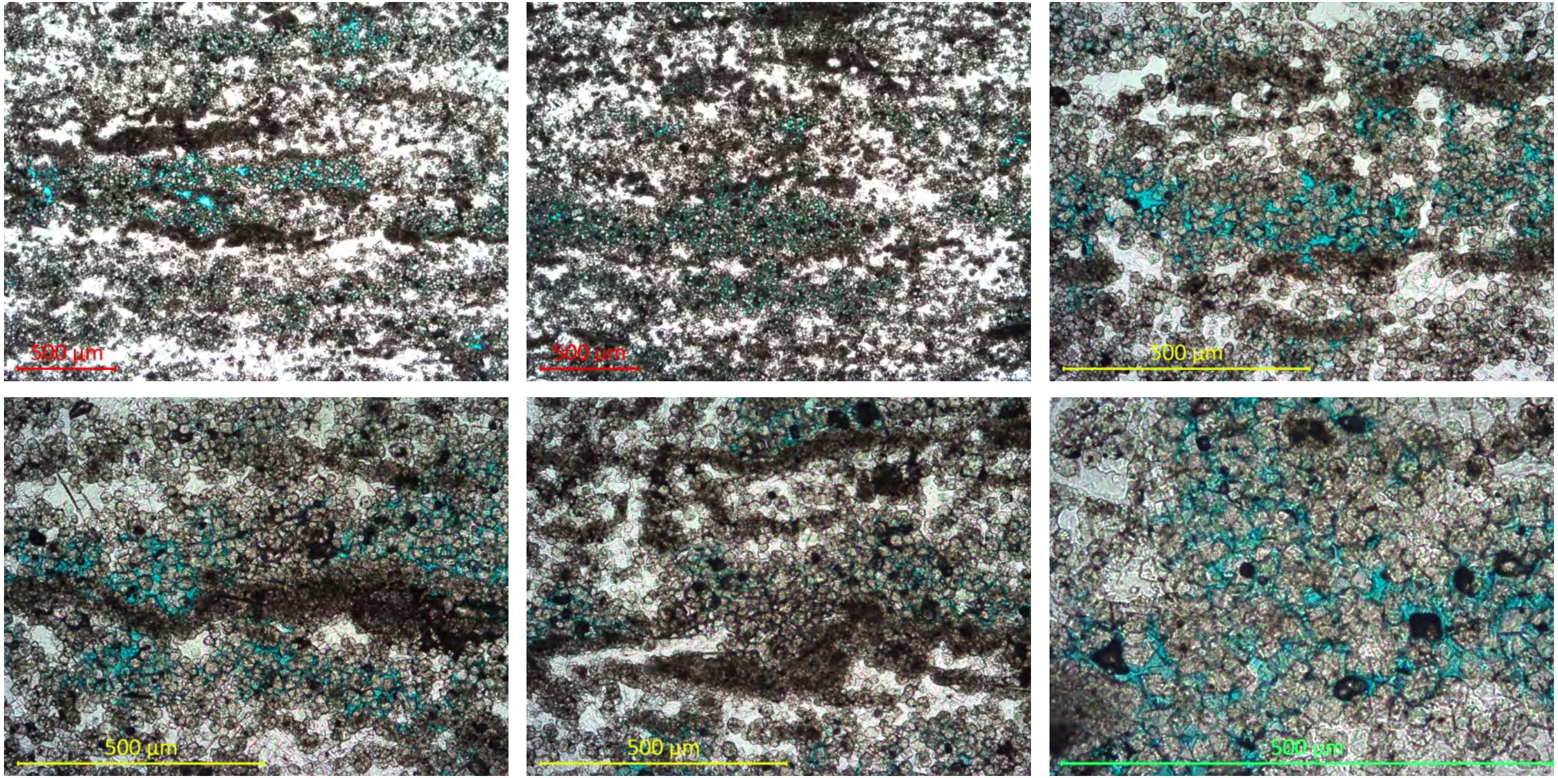
CORE 1: HAUPTDOLOMIT

Laminated/varved nature of the Hauptdolomit. 2192m (top left) – 2194m (bottom right)

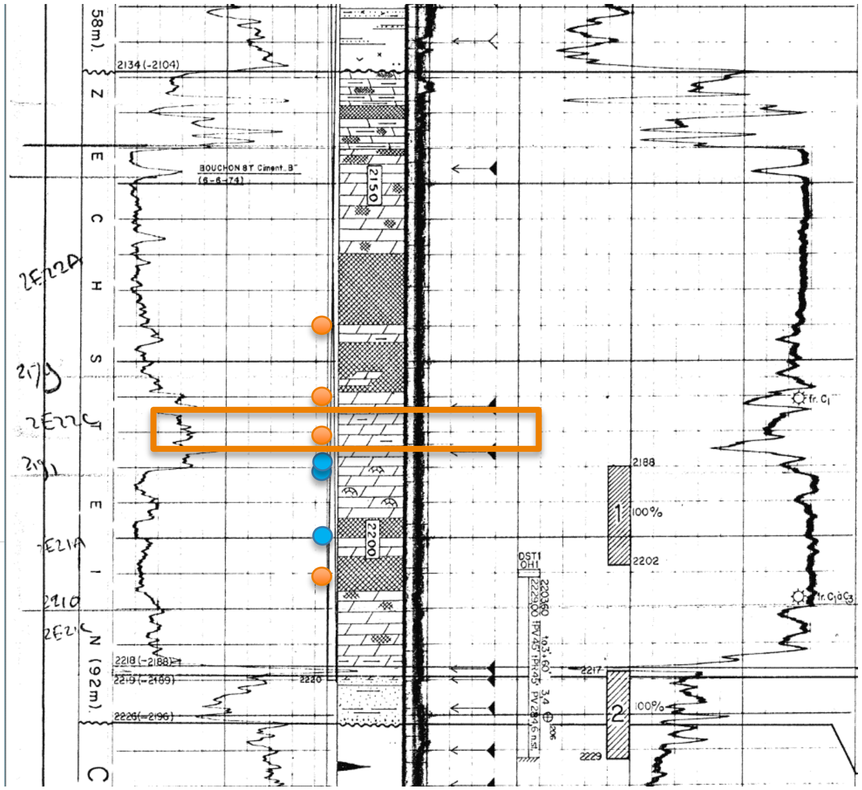
Interval with laminated anhydrites/ dolomitic limestones. 2190.35m

Laminated/varved nature of the Hauptdolomit at the top of the core. 2188m (top left) – 2190m (bottom right)

A16-01 2188M CORE SAMPLE PETROGRAPHY

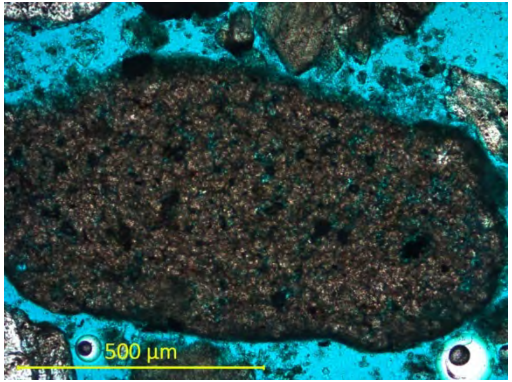


A16-01 CUTTINGS PETROGRAPHY

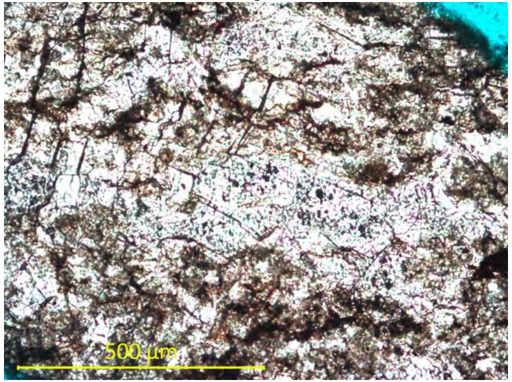


Cuttings sample Core sample

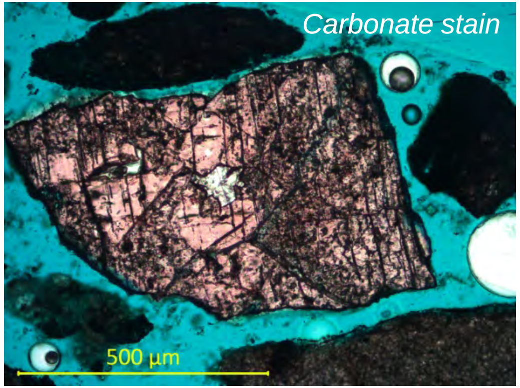
Dominant dolomicrite

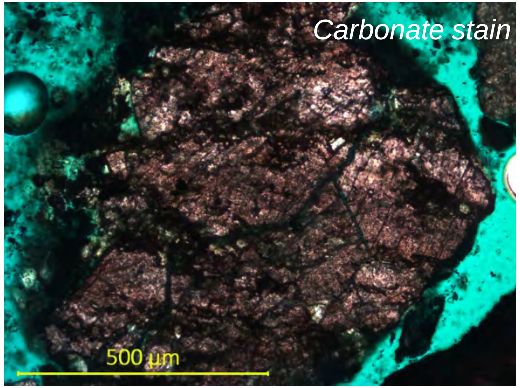


Common anhydrite

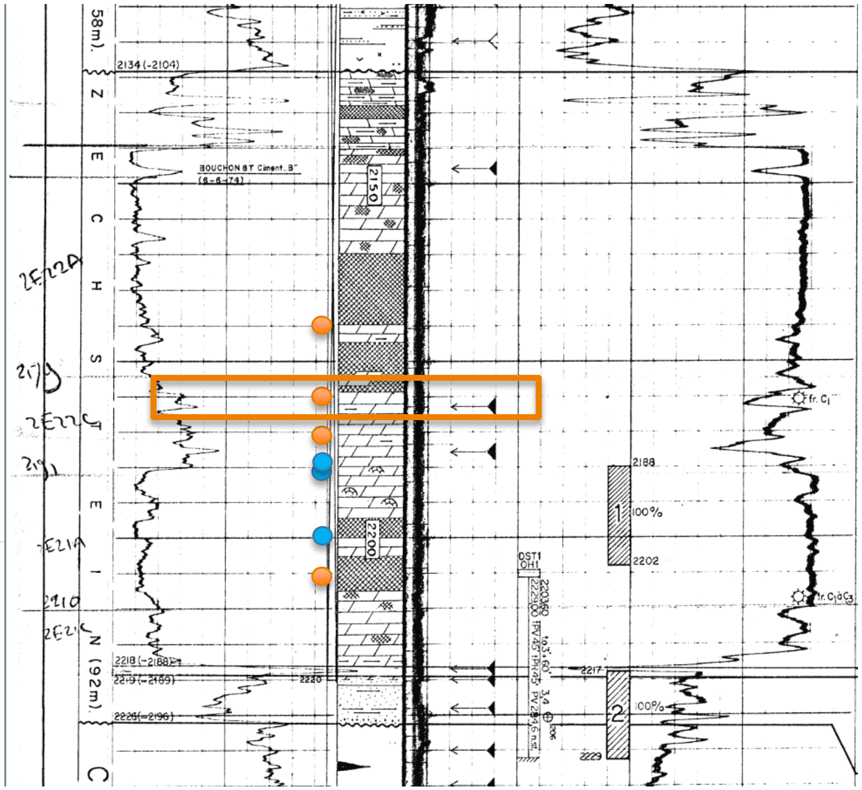


Common calcite spar/cement



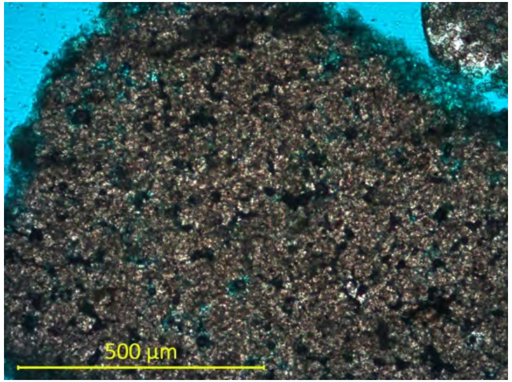


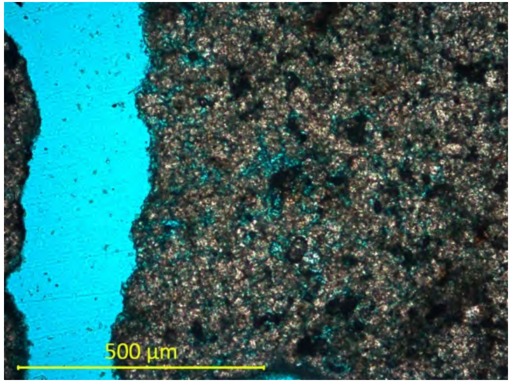
A16-01 CUTTINGS PETROGRAPHY



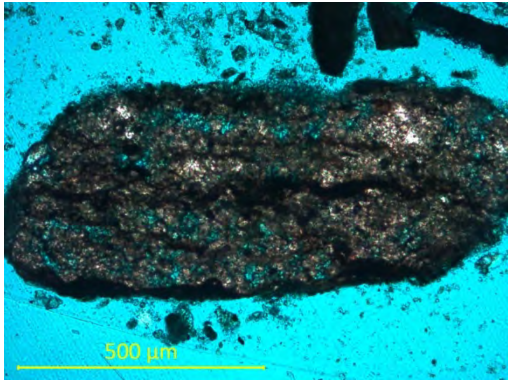
Cuttings sample Core sample

Dominant dolomicrite

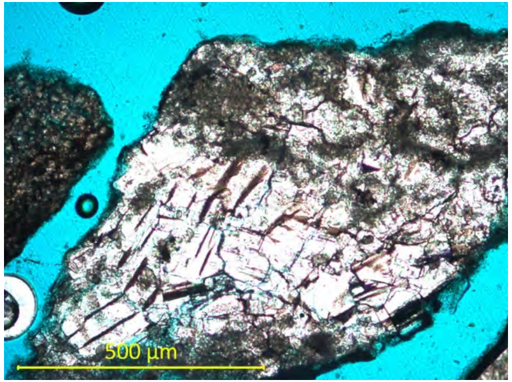




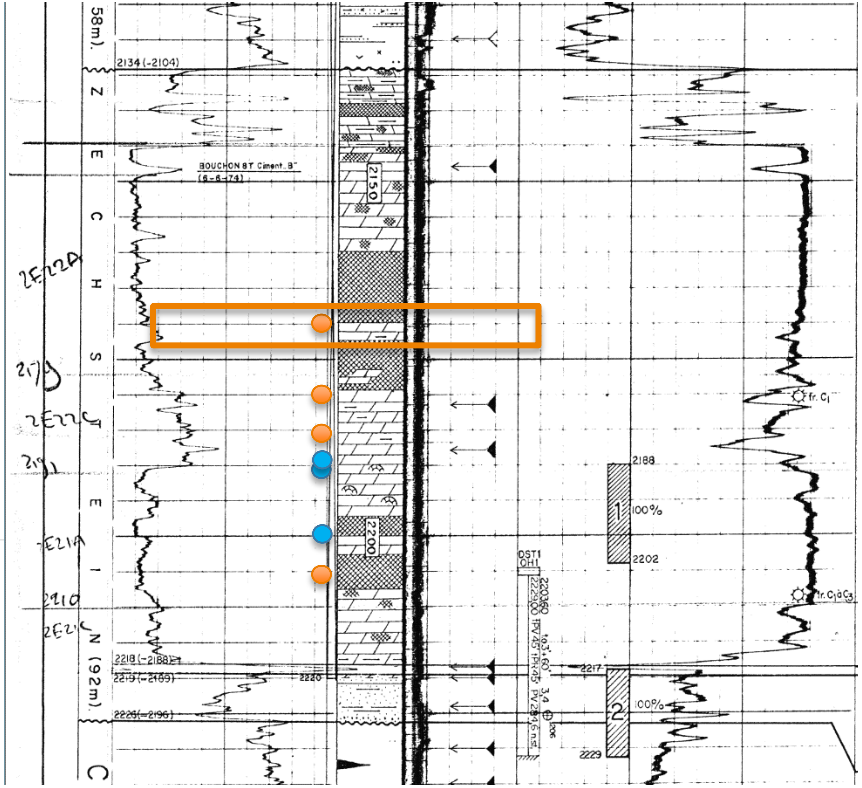
Common laminated dolomic



Common anhydrite

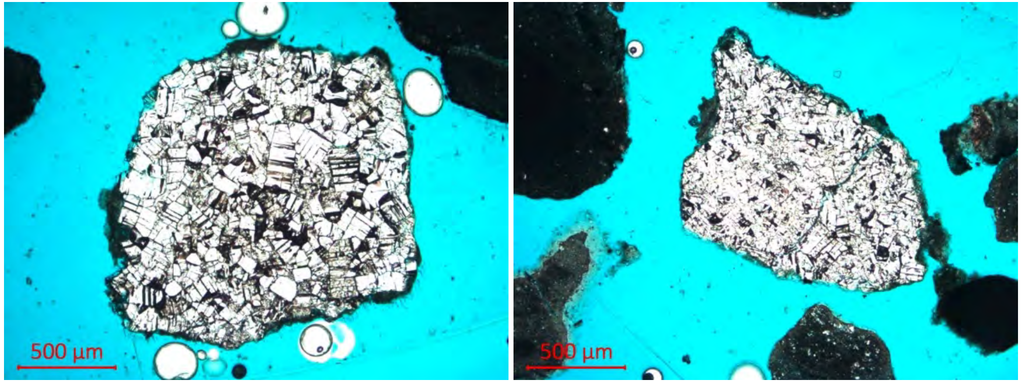


A16-01 CUTTINGS PETROGRAPHY

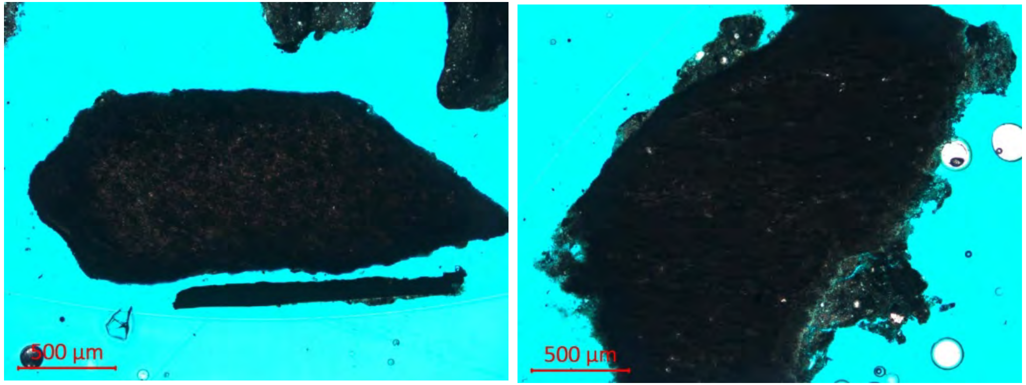


Cuttings sample
Core sample

Dominant anhydrite



Common ?carbonate mudstone



A16-01 SEDIMENTOLOGICAL INTERPRETATION

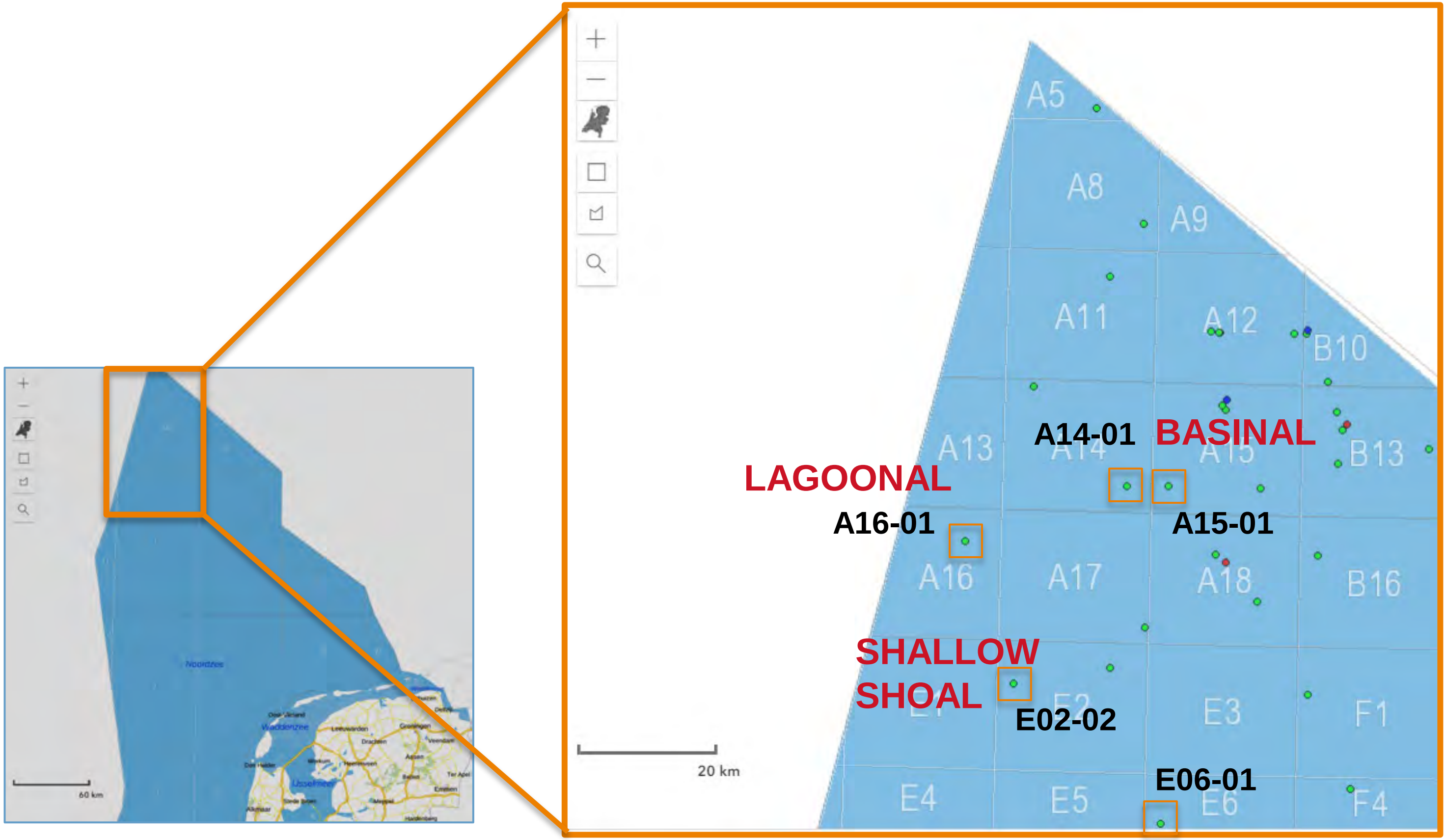
- Cored interval characterised by laminated (?varved) very fine dolomite/anhydrite. Possible microbial character – stromatolitic?. Core logging suggests more calcitic upwards.

- The cuttings in the Hauptdolomit are dominated by matrix-supported facies, in particular dolomicrite, fine crystalline dolomite and rarer fine micropeloidal grainstones.

- The sediments were deposited in a low-energy depositional setting. The very regular nature of the laminations/varves draws comparison to the Castile Formation in the US Permian Basin, which is interpreted as basinal deposits (i.e. Kirkland, 2003).
- However, these appear more stromatolitic/microbial in nature, and integration with seismic data suggests that a restricted, lagoonal setting is more appropriate.

*Kirkland, D.W. 2003. An explanation for the varves of the Castile evaporites (Upper Permian), Texas and New Mexico, USA. Sedimentology (2003) 50, 899–920

DEPOSITIONAL SETTINGS



DIAGENESIS

TNO innovation for life

- AIMS: to better understanding diagenesis, in particular paragenesis. Compare CL and isotope signatures to published datasets.
- CL undertaken on 12 samples (in-house analysis)
- C&O stable isotope analysis undertaken on 14 samples – bulk analysis taken from selected cuttings (picked) and core samples (subsampled with dentist drill). Analysis undertaken at University of Liverpool.

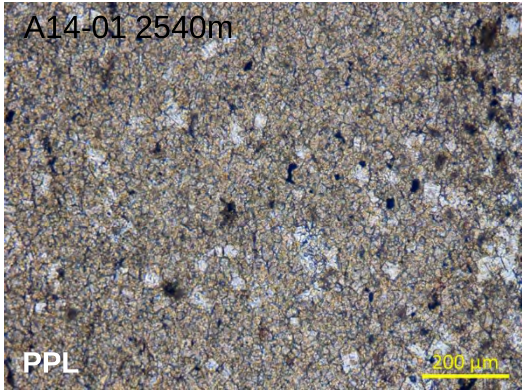
	Well	depth (m)	Cuttings/core	Polished TS	C&O	CL
1	A14-01	2530	cuttings	Yes	Yes	No
2	A14-01	2540	cuttings	Yes	Yes	Yes
3	A14-01	2550	cuttings	Yes	No	No
4	A15-01	3532	cuttings	Yes	No	No
5	A15-01	3538	cuttings	Yes	Yes	Yes
6	A16-01	2170	cuttings	Yes	No	No
7	A16-01	2180	cuttings	Yes	Yes	Yes
8	A16-01	2185	cuttings	Yes	Yes	Yes
9	A16-01	2205	cuttings	Yes	No	No
10	A16-01	2188	core	Yes	Yes	Yes
11	A16-01	2190	core	Yes	Yes	Yes
12	A16-01	2200	core	Yes	No	No
13	E02-02	2095	cuttings	Yes	No	No
14	E02-02	2100	cuttings	Yes	Yes	Yes
15	E02-02	2105	cuttings	Yes	Yes	Yes
16	E02-02	2110	cuttings	Yes	Yes	Yes
17	E02-02	2115	cuttings	Yes	No	Yes
18	E02-02	2120	cuttings	Yes	No	No
19	E06-01	2090	cuttings	Yes	Yes	No
20	E06-01	2100	cuttings	Yes	Yes	No
21	E06-01	2110	cuttings	Yes	Yes	Yes
22	E06-01	2120	cuttings	Yes	Yes	Yes
23	E06-01	2130	cuttings	Yes	No	No

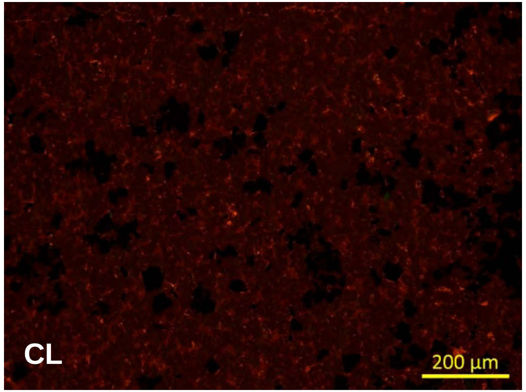
PARAGENESIS – KEY PHASES

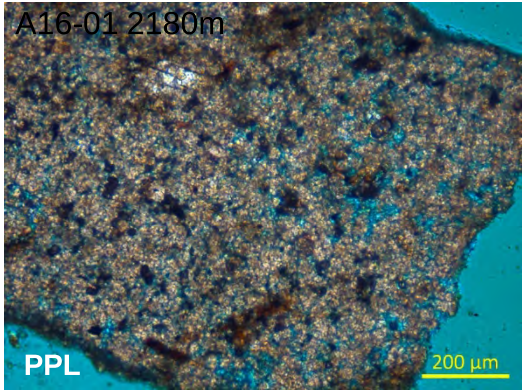
EARLY	Replacement dolomitisation
	↓
	Dolomite cements
	↓
	Dissolution
	↓
	Fractures
	↓
LATE	Anhydrite cementation

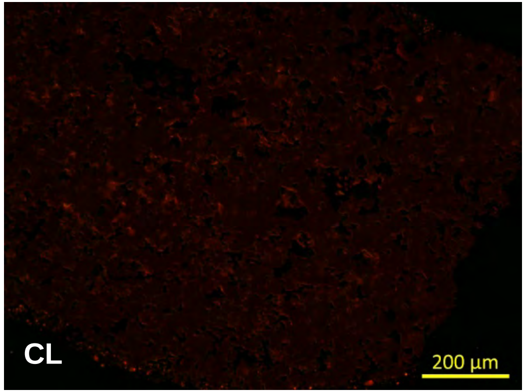
REPLACEMENT DOLOMITE

- Noted in all wells
- Typically the dolomites have a dull to moderate orange-brown CL character, which is comparable to other known Hauptdolomit dolomites (CCL experience).

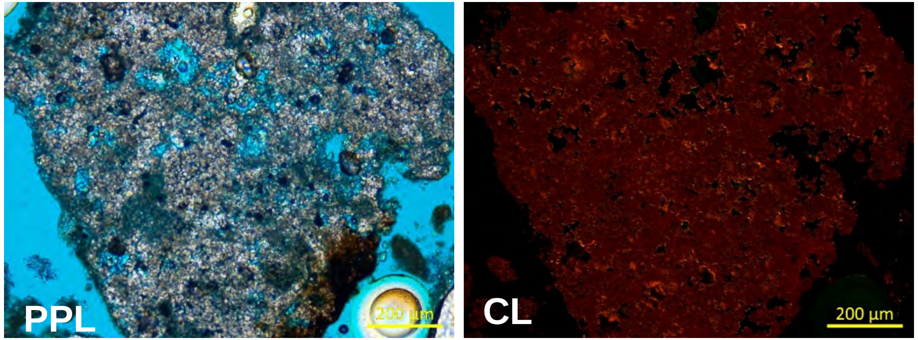




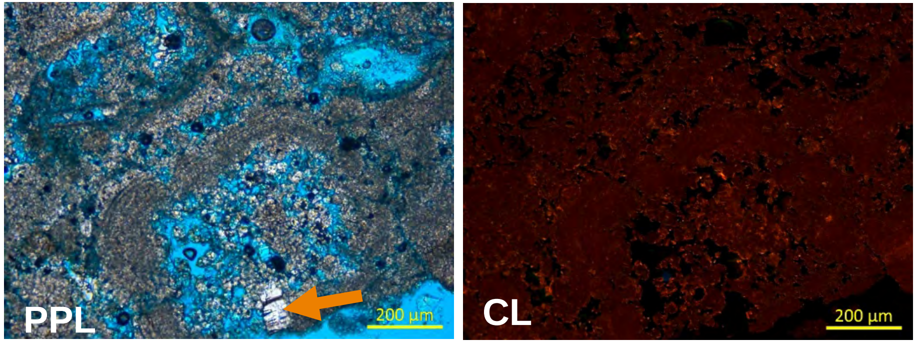




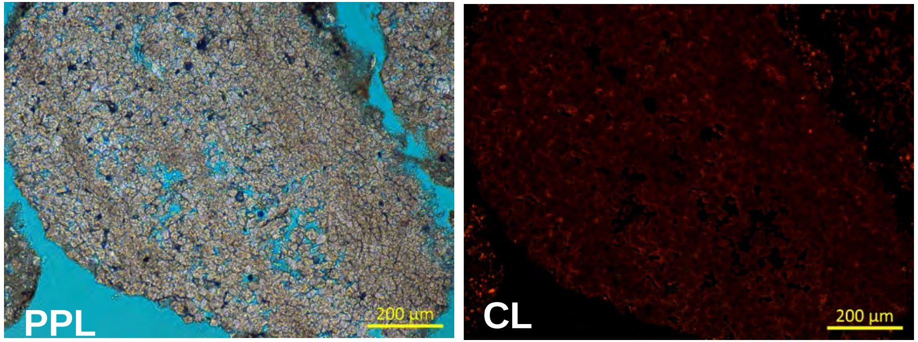
REPLACEMENT DOLOMITE



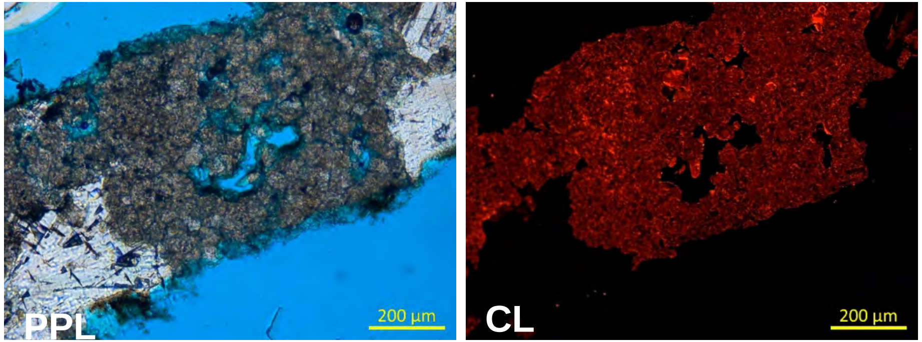
E02-02 2100m



E02-02 2100m



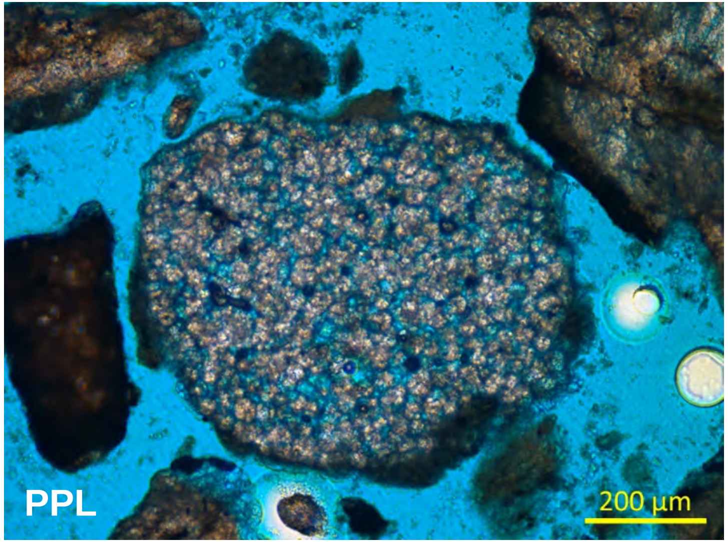
E06-01 2110m

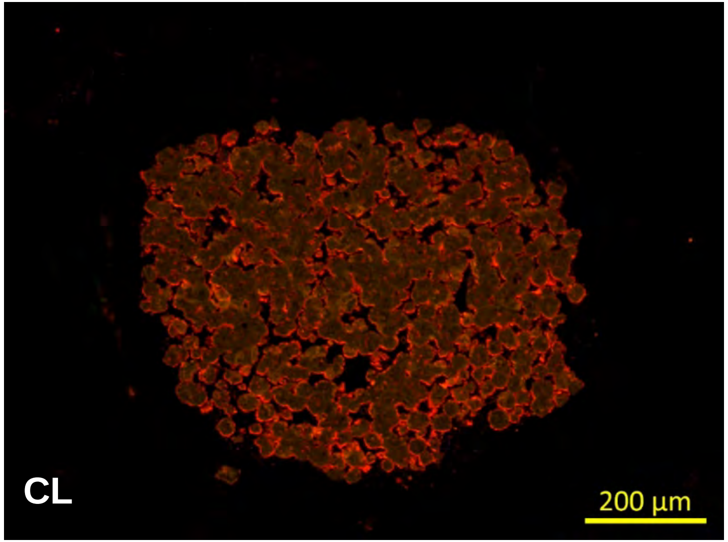


A15-01 3538m

REPLACEMENT DOLOMITE

- Locally the dolomites take on a greenish CL colour. This is relatively unusual, but most likely reflects a different chemistry/crystallography. It is probable these dolomites are calcium-rich – dolomite formed from seawater and evaporated seawater is Ca-rich and poorly ordered.

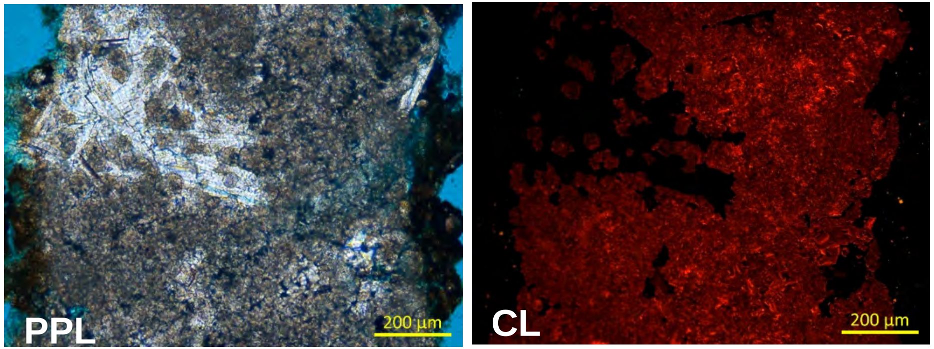




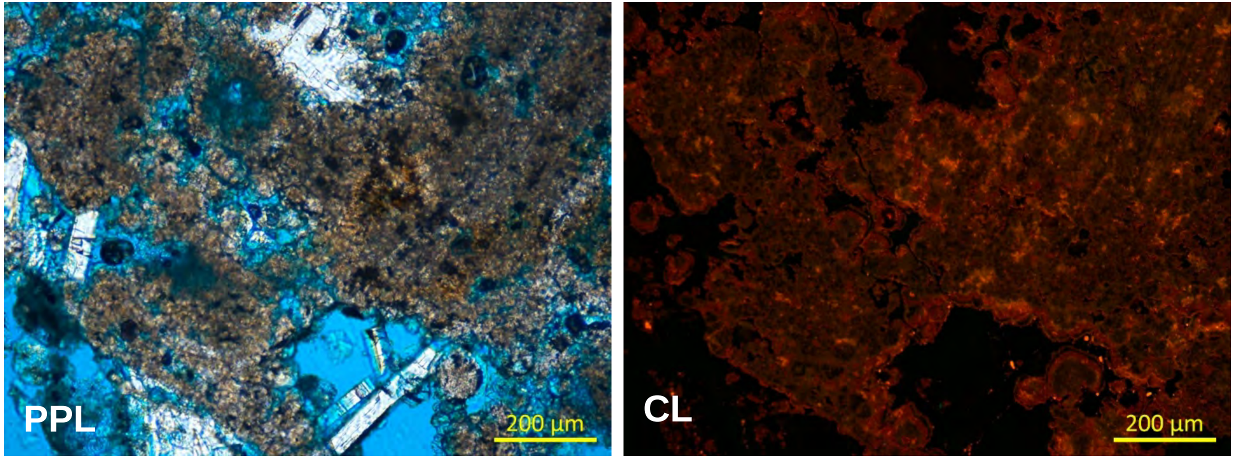
A16-01 2185m

DOLOMITE CEMENT

- Often, but not always, the replacement dolomites have developed fine cements around the cores. These are a brighter orange, and are locally multi-zoned oranges-reds-non CL.



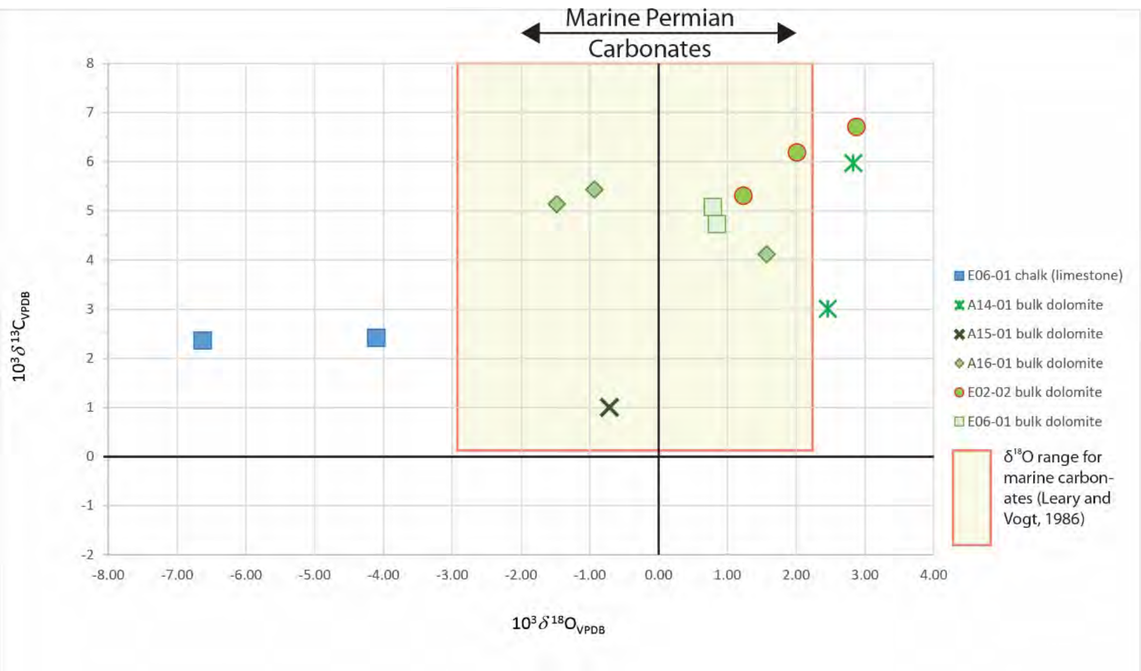
A15-01 3538m



E02-02 2115m

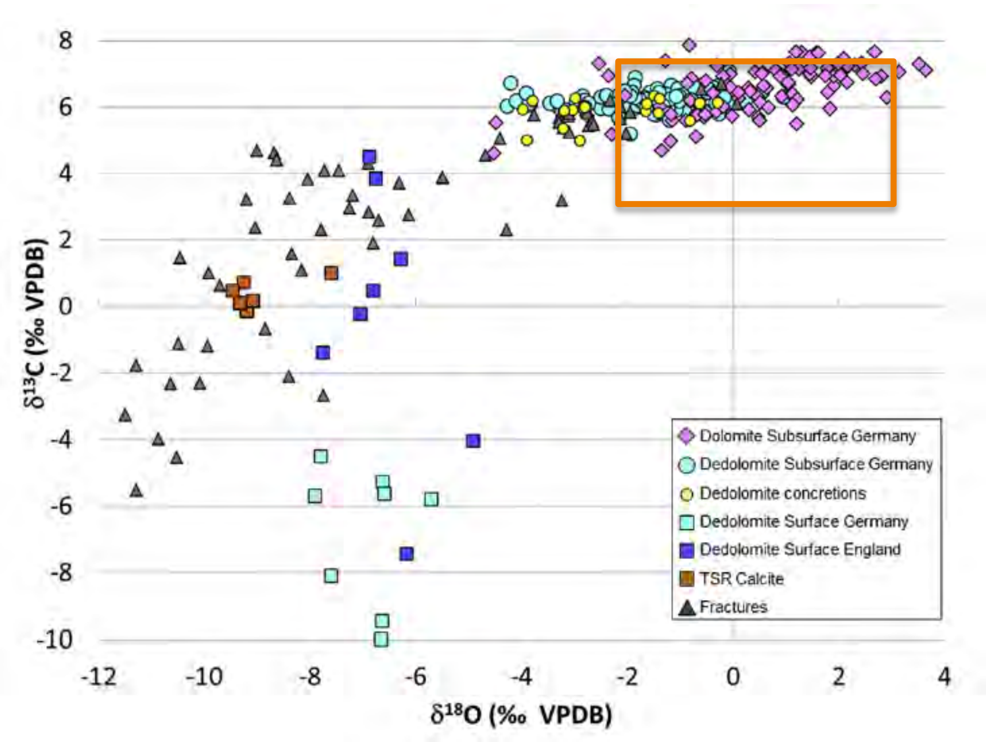
DOLOMITE C&O ISOTOPE DATA

- Bulk dolomite samples mostly sit within the expected $\delta^{18}O$ Marine Permian Carbonate realm.
- Some samples (i.e. A14-01) have an elevated $\delta^{18}O$, which indicate slightly increased salinities (evaporation-concentrated marine brines).
- Two samples were also taken from the overlying chalk to highlight the clear difference in C&O isotope signature



- The $\delta^{13}C$ on the whole displays heavy values which are typical of Late Permian limestones worldwide, indicating the dolomites have inherited their $\delta^{13}C$ from precursor limestones.

C&O ISOTOPE DATA – COMPARISON TO ANALOGUES

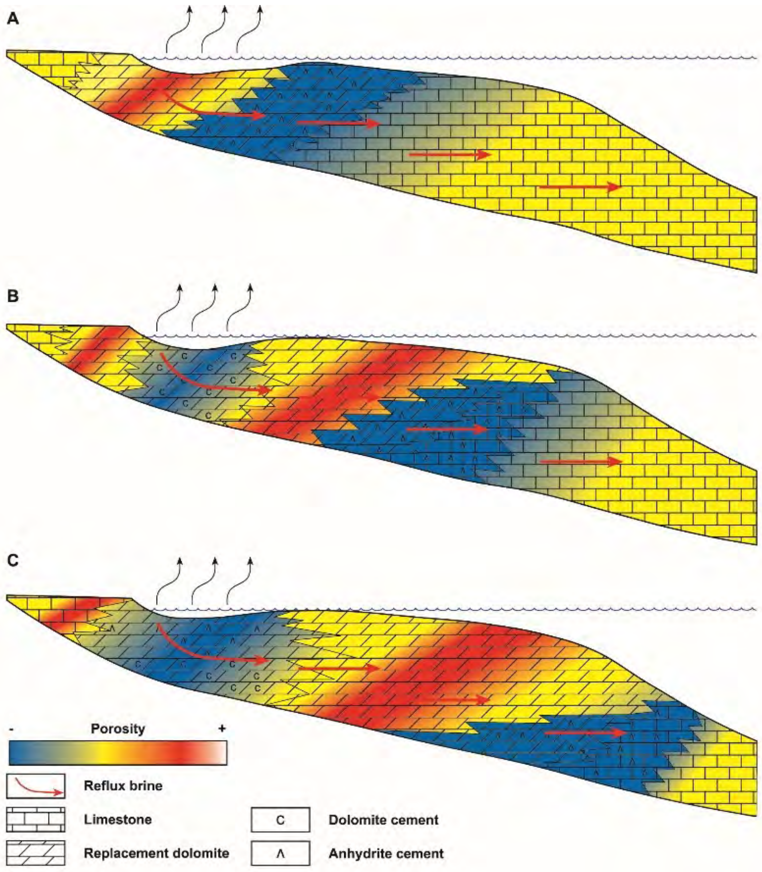


- This plot is from Schoenherr et al (2018). It plots the isotope signature of Zechstein dolomites and dedolomites from Germany and England.
- The dolomite data from the Dutch offshore (orange box) is comparable to dolomites seen in the subsurface in Germany (pink diamonds), which are interpreted as early dolomites.

Data from this study

DOLOMITISATION MODEL

- The replacement dolomites are most likely an early dolomitisation phase (seepage reflux). Dolomites are generally very fine crystalline and often mimetic. Stable isotope data also supports this interpretation, as well as comparisons to analogue Zechstein data.

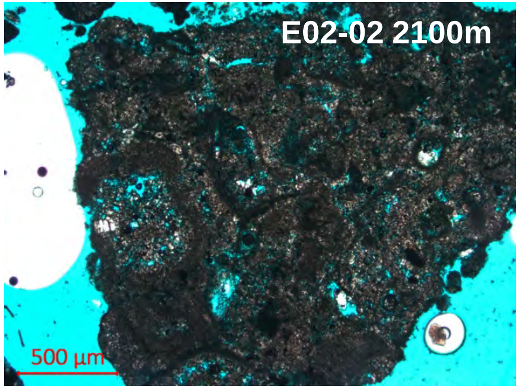


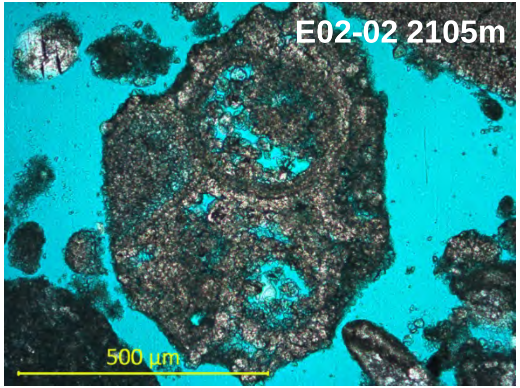
Redrafted from Labourdette et al (2007).

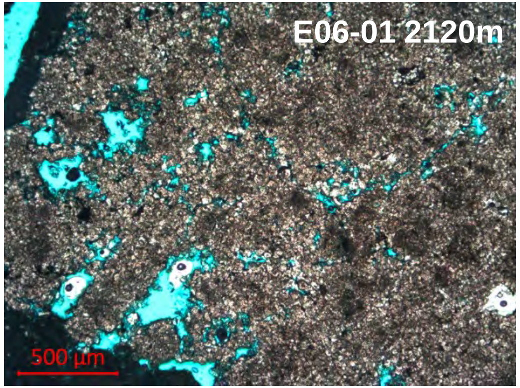
DISSOLUTION

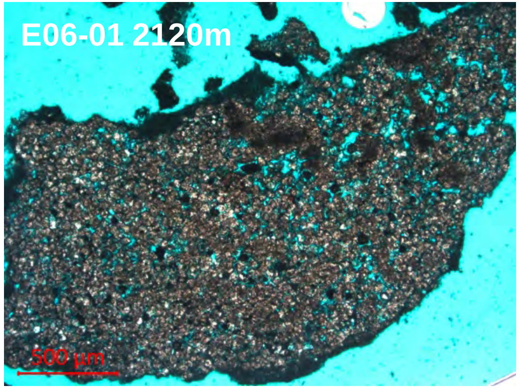
- Dissolution is common in several of the samples, in particular in wells E06-01 and E02-02. It is possible that this dissolution relates to the significant Mid-Cimmerian unconformity that is notable in these two wells.

- For example, in E06-01, the Chalk sits directly on top of the Zechsteinkalk, reflecting a significant phase of exposure, probable meteoric diagenesis, and dissolution.



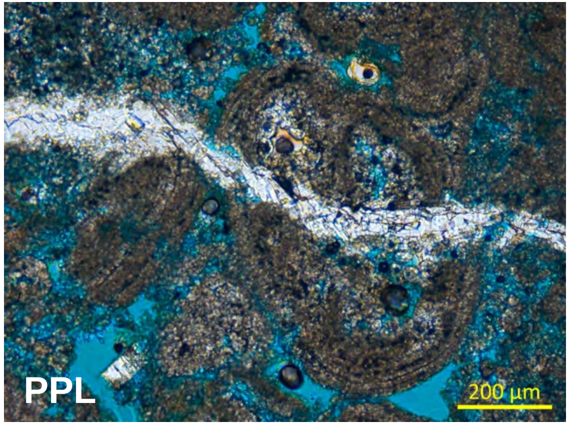


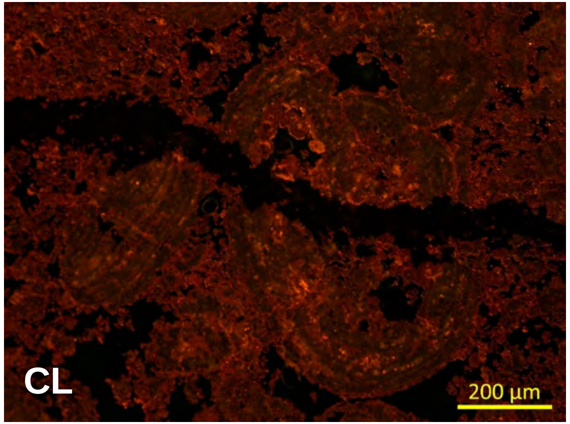


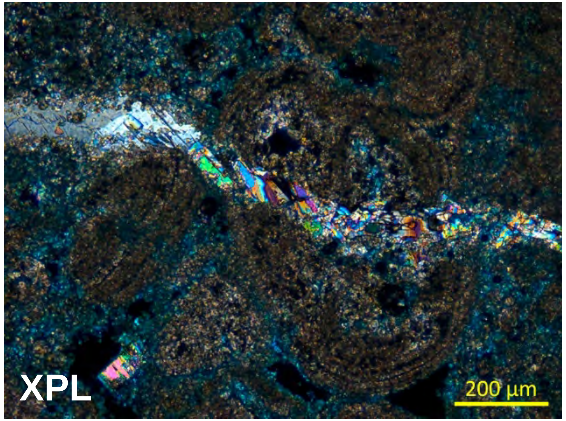


FRACTURING

- Rare examples of anhydrite cemented fractures. Preferential cementation of fracture by anhydrite, because of pore-size controlled solubility.

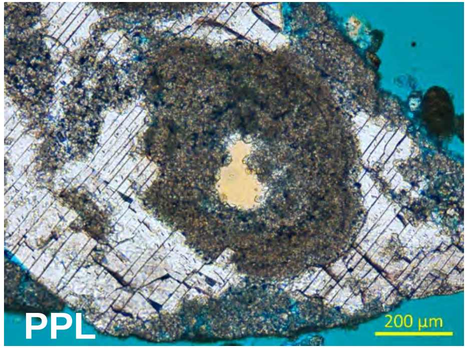


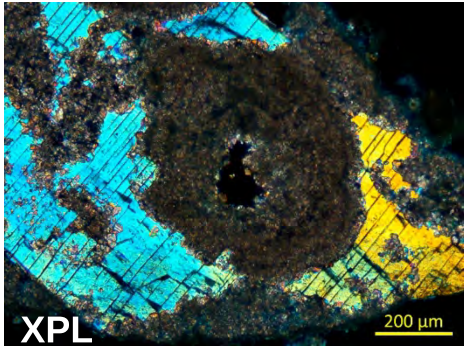




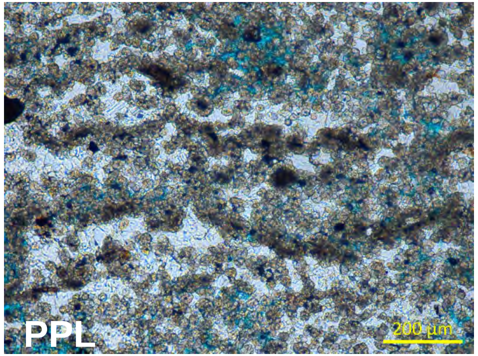
ANHYDRITE CEMENTATION

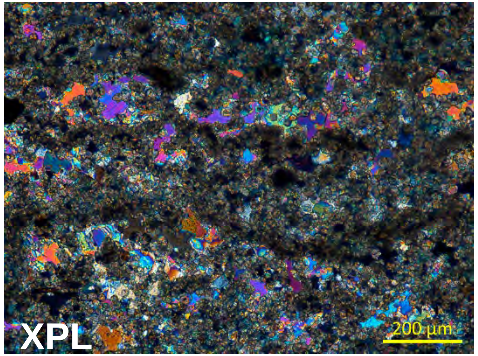
- Anhydrite cements are relatively coarse, and interpreted as burial in origin.
- Their distribution is relatively patchy.
- Anhydrite cementation mostly post-dates dissolution.



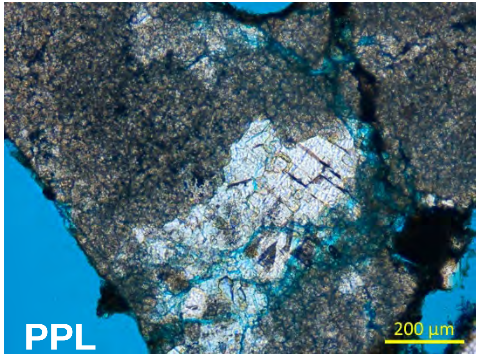


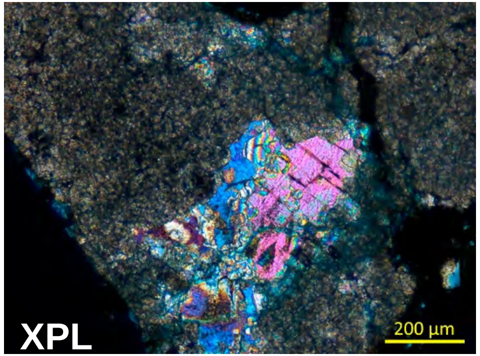
E02-02 2105m





A16-01 2190m

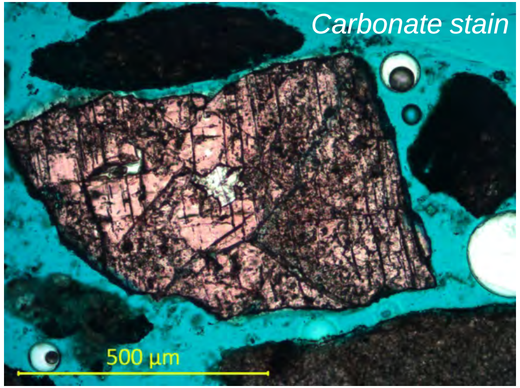


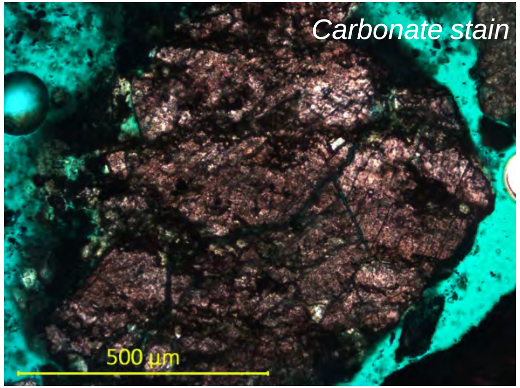


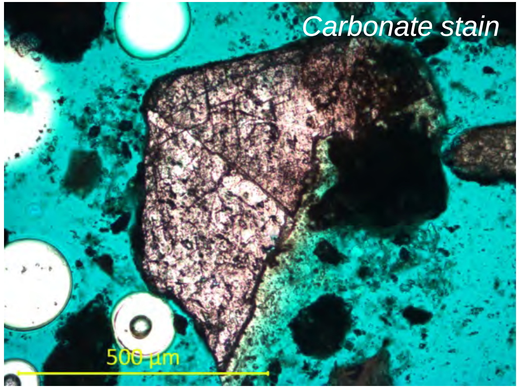
A15-01 3538m

?DEDOLOMITISATION

- In well A16-01, a number of cuttings are calcitic in nature (coarse calcites) – associated with distinct drop in density log.
- It cannot be said with certainty if these are calcites that are cementing fractures, or it is possible that they are coarse dedolomites.
- Dedolomites well-documented (*) onshore Netherlands, Germany, and Poland, and are noted in these examples to have a burial origin.







A16-01 2185m

*Reijers (2012); Clark (1986); Clark (1980); Van der Baan et al. (1990); Schoenherr et al. (2018); Peryt and Scholle (1996)

CONCLUSIONS AND DELIVERABLES

- 5 wells studied for petrography and diagenesis. Microfacies documented, and depositional settings interpreted. Paragenesis established and comparisons drawn to analogues.

- PowerPoint report for each well, detailing petrography, microfacies, depositional setting and reservoir porosities through the Hauptdolomit.
- Cuttings and core photomicrographs (297)
- Core log for A16-01
- PowerPoint report for diagenesis detailing CL character, O&C stable isotopes, and comparison to published analogues.
- CL photomicrographs (96)