Candidate:Jolien van der KrogtStudent No:5930871Email address:j.vanderkrogt@students.uu.nlTelephone:+31639054873No of credits:22,5 ETCS1st supervisor:Dr. Peter K. Bijl2nd supervisor:Prof. Dr. Appy Sluijs

Eocene-Oligocene transition iceberg discharge reconstruction for the Falkland Plateau, using process length of *Operculodinium centrocarpum* as a surface-water density proxy.

## Abstract

The cause of the onset of the Eocene-Oligocene transition is still disputed, as is the effect of the glaciation that happened right after. We use a process length *Operculodinium centrocarpum* as a salinity proxy to detect freshwater fluxes resulting from iceberg discharge. These icebergs originate from calving ice shelves, indicating a marine-terminating ice sheet on the Antarctic continent. Palynological slides from DSDP Leg 71 Site 511 are used for the reconstruction. This core is located at the North Scotia Ridge, south-west Atlantic, connected to the Scotia Sea and thus the iceberg alley. Optically, four *Operculodinium* morphotypes are distinguished, based on their process length. Average process lengths in the record that spans the EOT is compared to bulk and thermocline  $\delta$ 180 records from the same site, for stratigraphic purposes and to potentially detect salinity changes in the difference between bulk and thermocline d180. Beside that, the process length is compared to the abundance of *Phthanoperidinium* cysts that indicate freshwater conditions, and to a TEX<sub>86</sub> reconstruction of the sea surface temperature.

We found low density sea-water conditions immediately following the EOT, probably as a result of iceberg melting. Therefore, the Antarctic ice sheet was more likely to be 130% than 60% of today's ice volume during the early Oligocene. Combining morphology change with SST data showed that the changes in density have been mostly due to temperature until Oi1, and mostly due to salinity after Oi1, thus relating to ice volume on the Antarctic continent.

# Inhoudsopgave

Introduction1
Background3
Eocene Oligocene transition to icehouse earth
Topographic and oceanographic setting3
Palynology as paleosalinity proxy5
Stable oxygen Isotopes5
Methodology8
Collected and prepared material8
Counting cysts8
Categorizing Operculodinium
Measuring processes
Linking process length to sea water density
Results13
Randomly measured process length13
Operculodinium abundance over time15
Dinocyst comparison
Discussion and conclusion19
Reconstruction of iceberg discharge19
Comparison to local SST21
Morphology as proxy for salinity change
Conclusion23
Literature24

# Introduction

The Eocene Oligocene Transition (EOT; 33,6 million years ago) represents a time interval of global cooling and the onset of continental-scale Antarctic glaciation (Katz et al., 2008; Miller et al., 2009; Houben et al., 2018). Miller et al. states that the Antarctic ice sheet became a driver of the Oligocene climate change by adjusting oceanographic and atmospheric settings (2009). However, the exact volume, and with that the influence of the ice sheet is still unknown. According to Bohaty et al., the volume ranged from 60 to 130% of today's ice volume (2012). This large range of uncertainty underlines that the onset of the Antarctic glaciation is still not fully understood (Coxall and Wilson, 2011), and the influence of the ice sheet cannot be pinpointed yet.

A way to reconstruct the volume of past ice sheets is to check for marine terminations. When these termini are present, the ice sheet reaches at least until the margin of the continent in the shape of glaciers or ice shelves. At the termination, icebergs are discharged, releasing freshwater as they melt (Enderlin and Hamilton, 2014). The freshwater fluxes can be significant in density and salinity recordings, as it has a lower salinity and lower temperature than the ambient sea water (Silva et al., 2006; Voytenko et al., 2015). However, the recordings do not reach as far as the Eocene-Oligocene Transition and thus have to be reconstructed.

The options to do so are limited, but dinoflagellate cysts can shed a light on surface ocean conditions by looking into their biogeographic distributions. Dinocysts are fossil remains of unicellular plankton and are suitable to reconstruct high latitude environments (Sluijs et al., 2011). Moreover, they are one of the most important groups of plankton in the Southern Ocean (Pieńkowski et al., 2013) and prominent during the latest Eocene to lower Miocene (Brinkhuis et al., 2003).

Beside consulting dinocysts assemblages and their relative abundances to reconstruct general water mass characteristics, the morphology of specific dinocysts can be indicative for changes in certain ocean parameters. One of such dinocysts is the neritic *Operculodinium*. The species is found to reduce its process length in low sea water density condition in, for example, the Baltic Sea (e. g. Mertens et al., 2011) and throughout the Southern Ocean (Verleye et al., 2012). Since the density of sea water is determined by temperature and salinity, we can use the morphology of the *Operculodinium* cysts to track freshening of the subantarctic zone by icebergs, indicating a large ice sheet.

With the use of material from DSDP Leg 71 Site 511, the main question to be answered during this study is; does the morphology of *Operculodinium centrocarpum* cysts indicate a volume of 60 or 130% of the modern ice sheet? Th DSDP material is chosen because it is very well preserved, but more importantly, because of its location. The core was taken from the North Scotia Ridge, north of the Scotia Sea, in the south-west Atlantic (Ludwig & Krasheninnikov, 1983). This area is of interest because it is connected to the 'Iceberg Alley', an area with the highest iceberg density, that can potentially flow north of 63°S into subantarctic waters (Lin et al., 2011).

One question to support the research objective is; how does the cysts morphology relate to density and sea surface temperature (SST) during the Eocene-Oligocene transition? As the morphology is a proxy for sea water density, and SST is reconstructed for the research area, the salinity pattern during the EOT can be estimated. In order to find the volume of the early Oligocene ice sheet in comparison to today's ice-sheet (Bohaty et al., 2012), we elaborate on modern density values representing the research area. Lastly, the morphology change will be to the abundance of another dinocyst, *Phtanoperidinium*, as this dinoflagellate thrives in freshwater conditions.

# Background

#### Eocene Oligocene transition to icehouse

The transition from greenhouse during Eocene to icehouse during the Oligocene marked the establishment of large permanent Antarctic ice sheets (Katz et al., 2008). The transition is evident in deep-sea stable isotope records and occurred in steps. The first step of 0,5‰ indicated a cooling signal around 33,8 Ma, called the 'precursor event' (Katz et al., 2008). Whereas the second step of 1‰ was an effect of growing ice volume around 33,54 Ma, called the Oi1 event (Katz et al., 2008).

During the Eocene, Antarctica housed small ephemeral ice sheets (Scher et al., 2014). The transition towards the Oligocene meant the development of continent sized ice sheets and extensive sea ice (Miller et al., 2009). However, the volume of the ice sheet is still unknown. The SST was still high at the early Oligocene (Hartman et al., 2018), so one would not expect large ice sheets. A large range of SST (5°C) is estimated for the EOT, but in any way it was warmer than modern times (Hartman et al., 2012). As the rate of calving is depended on the ocean temperature, higher SST means more calving (Luckman et al., 2015), in case of a marine-terminating ice-sheet during the EOT, the calving rate would have been high.

#### Topographic and oceanographic setting

This research focusses on the Scotia Sea, one of two regions where the Antarctic continent is close to another land mass (Figure 2-2). The Scotia Sea is confined by the North and South Scotia Ridge, a series of islands and continental crust down to 1000 m deep (Lodolo et al., 2006). The area is researched based on an DSDP core taken at the Falkland Plateau, continental crust above the Scotia Sea (Ludwig & Krasheninnikov, 1983).

The 'iceberg alley', the western edge of the Weddell Sea gyre, terminates in the Scotia Sea, delivering the freshwater signals that are the focus of this study. The icebergs that break off from the Antarctic ice shelf flow through the Iceberg Alley and then move north or east into the South Atlantic Ocean (Lin et al., 2011). Nowadays, 26% of the calvedice mass is transported north of 63°S, drifting into the Scotia Sea and potentially to the research area (Figure 2-1; Silva et al., 2006).



Figure 2-1 Giant iceberg pathways around Antarctica between 1987 and 2003. The area east of the Antarctic peninsula with dense pathways is the Iceberg Alley. From Silva et al., 2006.

Ivany et al. found diamict, sediments deformed by overriding ice, exposed on Seymour Island (2006) and its origin is close to the EOT. This is partly based on findings of Brinkhuis et al. (2003). According to the beforementioned study, *Spinidinium macmurdoense, Vozzhennikovia rotunda* and *Alterbidinium distinctum* are found on top of the diamict, of which the former and the latter have their last occurrence around 33,5Ma in Southern Hemisphere high latitudes (Ivany et al., 2006). It is the first evidence of glaciation on the Antarctic Peninsula.

Nowadays, the Antarctic Circumpolar Current (ACC) transports icebergs. During the Eocene-Oligocene transition however, this current was not yet flowing in all depths of the Southern Ocean. Until 22 Ma, the Shackleton Fracture Zone would have obstructed the deep flow into the Scotia Sea (Lodolo et al., 2006). The other important water circulation in the research area is the wind-driven Weddel Sea Deep Water (Figure 2-2). This circulation originates in the Weddel Sea where deep water is formed, flows into the Scotia Sea and then moves westward (Lodolo et al., 2006). Thus, we can assume that icebergs could reach the research area during the EOT.



Figure 2-2 Overview of the research area in mordern times. WSDW = Weddel Sea Deep Water, CDW = Central Deep Water, ACC = Acrtic Circumpolar Current and WG is Weddel Gyre. SFZ in the Drake Passage is Shackleton Fracture Zone. From Lodolo et al., 2006.

#### Palynology as paleosalinity proxy

Sedimentary dinocysts can be products from either cosmopolitan or endemic dinoflagellates. The dominance of cosmopolitan species in the assemblage, indicates influence of the southeast Pacific, probably from the early Oligocene. Endemic dinocysts, such as *Enneadocysta*, *Deflandrea*, *Vozzhennikovia*, and *Spinidinium* (Guerstein et al., 2016), signify influence of from the southwest Atlantic. During the late Eocene, these species got less abundant (Guerstein et al., 2016). This is also found by Houben et al., that have already produced dinocysts assemblages for the research area (2018). During the late Eocene and EOT, *Deflandrea*, *Vozzhennikovia*, and *Spinidinium* and other peridinioid cysts are abundant. Between the EOT and Oi1, *Phthanoperidinium* cysts are dominating the assemblage. After Oi1, gonyaulacoid cysts are more abundant, such as *Cerebrocysta*, *Impagidinium* and *Operculodinium*.

Ocean circulation and oceanographic setting is reconstructed based on a variety of proxies, of which dinocyst assemblages are one. For sea surface temperature, several proxies exist, but paleo-salinity is more difficult to reconstruct (Wit et al., 2013). *Operculodinium* cysts can be used for density reconstructions, from which salinity can be deducted. The cyst is tolerant to rapid changes and occurs in high to low salinity environments (Santos et al., 2017), and oceanic to restricted marine conditions (Brinkhuis, 1994). Mertens et al., hypothesized that the longer processes enable clustering of the cysts and by that they sink to the bottom quicker in high salinity conditions (2009).

*Phthanoperidinium* cysts happen in low-salinity conditions such as in coastal and upwelling zones with high nutrient supply (Frieling et al., 2018 and references therein). High abundances of this cyst therefore links to freshwater influx (Barke et al., 2011). Because of the transparent colour, the cyst is thought to be heterotrophic (Sluijs et al., 2005), which might explain its occurrence during increased nutrient availability periods.

#### Stable oxygen Isotopes

Freshening of the surface water by iceberg melting could potentially also be detected in  $\delta$ 180 of surface carbonate, such as from surface-dwelling foraminifera or nannoplankton. This is because the  $\delta$ 180 of icebergs is extremely negative (-42; compared to around 0 for ocean water); meltwater from icebergs would therefore make surface  $\delta$ 180 lighter. Two  $\delta$ 180 records are available from Site 511 (Figure 2-4, Bohaty, pers. comm.): one measured on Subbotina, a foraminifer which lived at the thermocline at around 100 meter water depth (Houben et al., 2019). The second is measured on bulk carbonate. In many ocean sediments, bulk carbonate consists mostly of nannoplankton remains and therefore represents a surface water signal. A negative bulk carbonate  $\delta$ 180 compared to Subbotina  $\delta$ 180 would therefore be indicative of surface-water freshening.

Normally in the high latitudes, surface density is lower than the density at 100 meter water depth (Figure 2-3; Dong et al., 2004). This is represented by lighter isotopes at the surface. Moreover, during periods of fresh water influx from melting sea ice, the isotopes at the surface are much lighter than the ones at the thermocline. Thus, during times of fresh water influx, the negative value for  $\delta$ 180 bulk minus  $\delta$ 180 Subbotina should increase. In the instances that  $\delta$ 180 bulk is higher than  $\delta$ 180 Subbotina is positive, the thermocline was very shallow or high salinity water form low latitudes might have influenced the signal.



Figure 2-3 Salinity profile for south-east Pacific and the vicinity of the ACC (dashed line) and southwest Pacific (solid line), as result from the ACC. From Dong et al., 2008.



Figure 2-4  $\delta$ 180 records for the sea surface (bulk; in blue) and thermocline (Subb; in red) (Bohaty, pers. comm., 2019). The EOT is visible around 140 mbsl, of which not data was present. Oi1 is at the dashed line at 101 mbsl (Houben et al., 2019).

The difference between  $\delta$ 180 of surface and thermocline is very small (Figure 2-4), this makes it difficult to find a fresh-water signal. The two records might be as much alike because of the circumstances on the Falkland Plateau causing turbidites and contourites (Unzelmann-Neben, 2006). Since the deep-drafted ACC is running over the Plateau, nannofossils are influenced by the winnowing and never reach the bottom where they can be incorporated in the cores. The only sediments left for the bulk fraction is carbonate from the thermocline.

# Methodology

## Collected and prepared material

The material used for this research is retrieved in 1980, as part of the Ocean Drilling Project (DSDP) leg 71 at Site 511. The cores are taken at the eastern margin of the Falkland Plateau, at a water depth of 2589 meter (Ludwig & Krasheninnikov, 1983). The length of the recovered sequence is 385.62 meter and the oldest sediments are of Late Jurassic age. The material is of Late Eocene and Early Oligocene age (from 10 to 180 mbsf; cores 3 to 20), a period of 3,66 million years, from 35,94 Ma to 31,87 Ma. The material was prepared for palynological research (Houben et al., 2013). Due to poor core recovery, the sampling was highly irregular. The dinocysts present on the palynological slides were analysed using a light microscope. Taxonomy follows that cited in (Williams et al., 2017); and environmental preferences (Frieling et al, 2018; Bijl et al., 2018; Sluijs et al., 2005).

#### Counting cysts

Using an Olympus light microscope type CS21FS1, the slides are analysed for the occurrence of *Operculodinium* cysts with a x40 objective. The *Operculodinium* cysts are counted and categorized until at least 60 specimens per slide, to enable a reliable signal of the dominance of one morphotype. Only whole specimens are counted since only then it is possible to evaluate the process length properly. It would not be possible to determine the relative process length when the cyst is incomplete.

The relative abundance of *Pthtanoperidinium* is adopted from Houben pers. comm. (2019). At least three species of *Phthanoperidinium* are present in the slides (Table 1). The most abundant is the P. *amoenum*, recognizable from its oval cyst and small apical horn. Two others found in the research area are the P. *echinatum* and P. *comatum*, characterised by ornamented plate boundaries and long filamentus processes respectively.



Table 1 Examples of three Phthanoperidinium species; amoenum, comatum and echinatum.

## Categorizing Operculodinium

To study the morphological variation of the *Operculodinium* cysts, the process length of the cyst is chosen as distinctive characteristics (e. g. Allegaard, 2000; Mertens et al, 2009). Four morphotypes are established, based on process length (Table 3). According to Wall (1967) the processes range between one-fifth and one quarter of the cell size, but analysing the data proved longer processes occur, namely one-fifth of the complete cyst with processes included.

The categorization of the cysts is made optically. Morphotype A is a completely smooth cyst without processes (Table 2, middle figure, Sildever et al., 2015; Manum et al., 1989). Some pocks are formed in the reticula, which represents the onset of process growth. Type B represents cysts with small processes, accounting for 5% of complete diameter of the cyst including processes. Type C then accounts for the cysts with 12,5% process length. Lastly, type D represents cysts with the longest processes, of 20% of the diameter and longer (see table 3 for examples of all morphotypes). The longest processes on the cysts are chosen as representative for the morphotypes.

# Table 2 Comparison of O centrocarpum cyst with and without processes, coming from the researchmaterial and from Manum et al., 1989.



Although having processes is one of the characteristics of O. *centrocarpum* (Deflandre and Cookson, 1955), the cyst without processes is included in the counting. Table 2 shows that other key characteristics of O. *centrocarpum* are present in the cyst without processes. The large dorsal precingular archaeopyle (3") is present, as is the microgranular reticulate outer cell wall. Similarly looking specimens have been categorized as Tectatodinium sp. because of a thicker and spongier cell wall.

Morphotype	Relative p. length	
A	0%	
В	±5%	
C	<12,5%	
D	<20%	

Table 3 The four morphotypes with their characteristic relative process length and a photo.

#### Measuring processes

For morphotypes B, C and D, twenty specimens are chosen at random for measurements of the cysts and three processes. The measured specimens are found in a selection of six of the slides. The measurements are done with a Leica Light microscope model DM2500 LED with a x63 objective. The Leica Application Suite (LAS) installed on the connected computer enabled measuring the processes accurately to at least  $10^{-5}\mu$ m.

To measure the processes, the focus is on the cross-sectional area of the cyst. The processes originating from the periphery of the cyst can then be measured, starting from the onset of the process to the tip (Figure 3-1). For morphotypes C and D, the three longest processes are measured. In case of morphotype B, three processes of the most abundant size are measured.



Figure 3-1 Measuring processes of a morphotype C specimen.

## Linking process length to sea water density

After counting and categorizing the *Operculodinium* specimens, the qualitative categories are made more quantitative. Firstly, the process measurements are included in the morphotype characteristics. To produce an average length for each morphotype, the mean process length of every measured specimen is calculated. Subsequently, the mean of these twenty values is calculated.

With a mean process length for every morphotype, a value can be given for all the slides that are categorized. The mean process length per time step is calculated with the average length per morphotype and the occurrence of each morphotype.

# Results

## Randomly measured process length

For the purpose of high resolution results, four categories of process length were defined. To test if the four categories are significantly different, some hypothesis tests are conducted. Most tests can only be done on normally distributed data, so first this normality is tested visually (Figure 4-1 and 4-2) and mathimatlically.





*Figure 4-1 Size-frequency spectra of process measurements for morphotypes B, C and D. Median values are stipulated.* 

Scatters of the four morphotypes following the straight lines would have indicated normal distributions. However, only type A follows a straight line since all values are zero (Figure 4-2). The normality of the distributions is tested with the Kolmogorov-Smirnov test and the null hypothesis is rejected for all morphotypes.

Table 4 Statistic parameters of the morphotypes. Morphotype A is not included because all values arezero.

Morphotype	min	max	range	median	Sd
В	1,4970	7.4870	5.9900	3,64	1.4703
С	4,7570	12.4930	7.7360	7,26	1.6856
D	7,8200	15,2830	7.4630	10,12	1.9939



Figure 4-2 Normal probability plot for the four morphotypes, A, B, C and D from left to right.

The testing continues with a Wilcoxon rank sum test. This test evaluates if the morphotypes are samples from continuous distributions with equal medians and assumes the samples are independent. The equality of medians is tested for D and C, C and B and A respectively and results area shown in table 2. From the Wilcoxon test it is concluded that the medians of the four morphotypes are sufficiently unequal to justify the distinctions.

Morphotypes	P-value	h
D and C	3.5400e-13	1
C and B	6.9537e-19	1
B and A	5.6958e-24	1

Table 5 Results of Wilcoxon rank sum test, comparing medians of morphotypes A, B, C and D.

#### Operculodinium abundance over time

As the process length is used as a proxy, it is important to know how abundant this dinocyst was in the samples. Interestingly, this abundance has clearly changed after Oi1, as it is a cosmopolitan taxon (Mertens et al., 2010). The climatic changes lead to a more fluctuating relative occurrence of the *Operculodinium* cysts. A large peak is present around 95 meters core depth which decreases again quickly. Other dinocysts genera then dominate the assemblages again. The O cysts start dominating the assemblage until they reach 60% of the occurring cysts, before the Oi-1a. After this the abundance fluctuates core-upward. The fact that the O. cysts are more abundant after the EOT This confirms that the *Operculodinium* is a cosmopolitan dinocyst. The oceanographic settings changed over this period, making the Scotia Sea more favourable for this offshore gonyaulacoid taxon (Houben et al., 2019).



Figure 4-3 A) Abundance of Operculodinium specimens throughout the core, from Houben, pers. comm, 2019. The bar on the y axis shows core recovery. The circles indicate the depth of the palynological samples. The dashed line is Oi1. B) shows the occurrence of the four different morphotypes throughout the core in relative abundance.

A total of 43 palynological slides is analysed, in which 2,240 cysts are categorized. Of the total, 595 morphotype A cysts were found. Another 527 were morphotype B, 599 were morphotype C and lastly 519 cysts categorized as morphotype D were present. The frequency of occurrence of the four morphotypes is similar, but the individual abundances fluctuated over time.

Slides in which less than ten specimens were found, were excluded from the following analysis, as the result was considered not reproducible (Verleye et al., 2012). The remaining 29 slides produced a pattern of process length presented in figure 4-3B.

There is clearly a change to be detected in the morphology composition of the *Operculodinium* cyst (Figure 4-3B). During the latest Eocene, the long-processed cysts dominate the *Operculodinium* specimens. The EOT (between 148 and 129mbsl) marks a period of increased abundance of morphotype B, the cysts with the smallest processes. The cysts with long processes are almost absent at this stage. During Oi1 (101mbsl; Houben et al., 2019) the cysts without processes have increased in number. Around 93 mbsl, the abundance of process-less cysts suddenly increases and cysts with long processes are absent again. Besides, morphotype C cysts are very low in number.

After another large peak of the morphotypes A and B, the cysts with longer processes dominate again. Around Oi1a, the short processes cysts peak, after which morphotype C cysts become most abundant until D cysts take over at the highest part of the core.

## Dinocyst comparison

Beside analysing the *Operculodinium* abundance and process length, *Phthanoperidinium* occurrence is looked into. As stated before, high abundance of this dinocyst indicates fresh water influx which would be a result of melting ice-(bergs), which would coincide with high abundances of morphotypes A and B cysts.



Figure 4-4 A) Average process length of Operculodinium centrocarpum cysts over core depth. The bar on the y axis shows core recovery. The circles indicate the depth of the palynological samples. B)
Abundance of Phthanoperidinium cysts throughout the core, from Houben, pers. comm, 2019. The bar on the y axis shows core recovery. The circles indicate the depth of the palynological samples. The dashed line is Oi1. C) shows the Phthanoperidinium abundance above Oi1 between 0 and 30%.

The process length and *Phthanoperidinium* abundance do not seem to be closely related at first (Figure 4-4). The most remarkable morphological changes of the *Operculodinium* cysts happen after Oi1, whereas the *Phthanoperidinium* abundance peaks before Oi1. Parts A and C show that the two signals do relate for some periods of time during the Oligocene. Correlation during the Eocene is difficult to detect due to the low resolution of *Operculodinium* samples at that interval.

At the lower end of the core, the amount of *Phthanoperidinium* specimens is low and the average process length is high. A low P abundance would indicate marine conditions, therefore high salinity. This corresponds well with the average process length of about 9  $\mu$ m. Shortly after both the process length and P abundance decrease, which is not in line with the theory. At a core depth of about 148 mbsl, the P abundance increases and decreases rapidly. This coincides with the onset of the EOT, a period of stagnating higher isotopic values (Figure 2-4). Due to low abundance of O. specimens during the latest Eocene, the development of process length is unknown or insignificant during the EOT. A second, very high, peak of almost 100%

*Phthanoperidinium* cysts develops at 110 mbsl. This dominance can indicate low salinity conditions, but that cannot be validated with the morphology of O. cysts.

At Oi1, the *Phthanoperidinium* abundance collapses to almost zero percent. The first measurement of process length after the Oi1 is 1,5  $\mu$ m where the P abundance is around 3%. Subsequently, a short-lived increase in process length coincides with an even lower abundance of *Phthanoperidinium* cysts, which is in line with the theory. At 90.75 mbsl the cysts have the smallest processes. This does not coincide with a high abundance of P. cysts, but it is on the rise. The next short process period is at 75 mbsl, and is accompanied by a low abundance of P. cysts, contradicting the relationship. The last peak of short processes occurs around Oi-1a, the period of major glaciation (Katz et al., 2008). The *Phthanoperidiniums* experience the largest peak in abundance since Oi1. After this, the process length gradually increases and P abundance decreases again.

On the bigger scale, after Oi1 and before Oi-1a, the average process length is rather high and the P abundance low, so according to the theory this indicates a period of higher densities with some low density interruptions.

# Discussion and conclusion

## Reconstruction of iceberg discharge

Despite of the mild climate during the early Oligocene (Hartman et al., 2018), we have found proof of freshwater influx, indicating the Antarctic ice-sheet was at least the size of the continent during the early Oligocene. Because of the relief of the Antarctic continent, an ice-sheet of 60% of today's volume would only have land-terminating ice sheets and glaciers and thus not discharge icebergs to increase freshwater influx. Therefore, this study proves that the AIS in the early Oligocene was closer to being 130% of today's AIS volume than to being 60% the volume.

The morphology of the *Operculodinium* cysts shows five periods of lower density, confirming waxing and waning of the Antarctic ice-sheet and related oceanographic changes. The first two occur during the 'Earliest Eocene Glacial Maximum' (EOGM, Liu et al., 2004). This suggests that already in the first glaciation of the Oligocene, a marine terminating ice-sheet covered the Antarctic continent. The next low-density water flux is at 75 mbsl. The overall increasing process length in this period indicates higher densities and thus a smaller ice-sheet. The sudden decrease in process length at 80 mbsl might represent the boundary between a marine terminating ice-sheet and a land-terminating one that can therefore not release icebergs.

The largest low-density period is around 47 mbsl. According to the *Phthanoperidinium* abundance profile, this peak represents a large fresh water flux, so we assume this peak represents the largest ice sheet of the researched period. Since icebergs are discharged episodically (Silva et al., 2006), it is at this stage not possible to explain why we see one peak in *Phthanoperidinium* abundance over a longer period of a large ice-sheet.

The effects to freshwater influx on the *Operculodinium* cyst morphology and *Phthanoperidinium* abundance are not simultaneous (Figure 4-4). It seems like the *Phthanoperidinium* abundance lags the development of the process length. An explanation for this discrepancy is that Operculodinium cysts are formed directly at the sea surface, as the motile cell is phototrophic. The Phthanoperidinium cysts, contra, are heterotrophic and might therefore life deeper in the water column, where the freshwater signal might arrive weaker or later.



Figure 5-1 Modern density values for the research area right of the Falkland Islands. From Verleye et al., 2012.

Figure 5-2 Freshwater flux around Antarctica during June, July and august. From Merino et al., 2016.

The density values in Verleye et al.'s study ranges between 1021 and 1027 kg m<sup>-3</sup> (Figure 5-1), relating to sea surface salinities between 32.4 and 36.2 psu. The lowest densities are found close to the coast, where river-runoff provides freshwater and precipitation might deliver freshwater to the area. At the location of the core, east of the Falkland Islands, the density is between 1026 and 1027 kg m<sup>-3</sup> during the austral summer. No influence from discharged icebergs can be found here, which might be because most icebergs are discharged during winter (Merino et al., 2016). Whereas calving does happen during June, July and August (Figure 5-2), meltwater does not seem to reach the research area (Figure 5-2) or is insignificant. Besides, the geographic and oceanographic settings have changed over the last 30 million years (Lodolo et al., 2006; Uenzelmann-Neben, 2006), which could have influenced drifting patterns of the icebergs.

Galeotti has narrowed the range of the early Oligocene AIS volume to between 100% and 125% of nowadays (2016), but with the information provided, we cannot tell if the volume would more likely be approximating the 100 or 125%.

Galeotti et al., reconstructed the behaviour of the Antarctic Ice Sheet (AIS) during the EOT, based on a drill core from close to the present EAIS (2016). They distinguished periods with 'larger AIS' and 'smaller AIS' (Figure 5-3). The lowest values of process length, hence density, are found during the EOGM, the first large AIS period. According to Galeotti et al., the ice sheet only had land-terminating glaciers at that time. The process length curve however proves the presence of marine termini (2016). Besides, Geleotti et al. suggest that the largest ice sheet was present after Oi-1a. The reconstructed SST might give a clue for this discrepancy, in the sense that during the EOGM, the SST increase had a larger influence on the density than the decreasing salinity (2016). A larger ice sheet would have caused more low-salinity fluxes because more ice-bergs could be released. First ice grounding coincides with our major peak and Oi-1a.



Figure 5-3 Operculdodinium morphology with 3 stages of glaciation on the Antarctic continent, adopted from Galeotti et al, 2016. Green is a large ice-sheet, grey is a small ice-sheet, and purple is the largest ice-sheet of the section.

#### Comparison to local SST

We used the process length to reconstruct ocean conditions at and after the Eocene-Oligocene transition. The development of the process length showed that right after the EOT, low density water has reached the research area. This low density, represented by short processes, can be caused by salinity decrease, temperature increase or a combination of the two (Ellegaard et al., 2000; Head et al., 2007; Mertens et al., 2010). A sea surface temperature (SST) reconstruction is visualised to review its relationship to sea water density. The temperature data produced, using a TEX<sub>86</sub><sup>H</sup> calibration. This calibration has an unknown amount of bias towards higher temperatures and has a standard error of 2,5 °C (Houben et al., 2019).

As predicted by Verleye et al., the SST seems not to be the only trigger for the morphology changes of *Operculodinium* cysts (Figure 5-4; 2012), as the fluctuations of the two patterns are not exactly mirrored. The influence of SST changes on the process length before the EOT is due to the sampling impossible to detect. According to Katz et al., the positive  $\delta$ 18O excursion at the Oi1 event is for one half caused by temperature decrease and the other half by ice-volume increase (2008), as shows from Figure 5-4.



**Figure 5-4A)** Average process length of Operculodinium centrocarpum cysts over core depth. B) SST reconstruction using a **TEX**<sub>86</sub><sup>H</sup> calibration (Bijl, pers. comm., 2019).

After Oi1, around 93 meters core depth, short processes of 1,5  $\mu$ m coincide with temperatures of 18 °C. At the next peak, process length has increased to 3,55  $\mu$ m and the SST decreased to 15 °C. after this period, the temperatures continuous fluctuating between 15 and 16°C., whereas the process length experiences the largest change, around 47 meters deep (Oi-1a). The declined SST influence indicates an increased salinity influence. In turn, this represents larger ice-volume in Antarctica as more fresh water reaches the research are.

We assume that the temperature at 47 mbsl was 16 °C (Figure 5-4), during a morphology change of 2,6  $\mu$ m. According to Verleye et al., such a morphology change relates to a density change of approximately 1 kg m<sup>-3</sup>. Consulting a temperature-salinity diagram indicates that at a stable temperature of 16 °C and a density decrease of 1 kg m<sup>-3</sup>, relates to a salinity change of 2,0 psu, whereas the melting of one giant iceberg changes the psu with around 0,1‰ (Robinson and Williams, 2012). On the other hand, at around 92 mbsl where the morphology and temperature both change, we end up with a decrease of 1 psu. These estimates are very rough and probably too high, as beside density, consisting of temperature and salinity, more factors influence process length such as nitrate and other nutrients (Jansson et al., 2014).

#### Morphology as proxy for salinity change

#### Process measurements

The processes have first been categorized optically, and later on some have been measured to make the process length development more quantitively and reliable. The measuring showed that the four categories of process length were not variable, and therefore it would have been better to measure all cysts without categorizing them. Still, for this location the process lengths do not vary a lot from Verleye et al.'s outcome (2012). The cyst diameter of the 60 random samples is also measured, but not accounted for in the production of process length values.

Secondly, the distribution of the data points prevents the creation of a good overview of the process length. The period towards the EOT has low data density and also a low O. abundance which made it necessary to exclude even more samples. It resulted in comparing 7 data points before the EOT with 22 after. Seeing that the EOT marks a transition in marine condition (ice-free to glaciation), it would be interesting to have more morphology data before the Oi1.

## Conclusion

A reconstruction of Southern Ocean paleoceanographic conditions during the Eocene-Oligocene transition is made. We found low density sea-water conditions immediately following the EOT, probably as a result of ice berg melting. This indicates marine terminating ice sheets existed in the still warm early Oligocene. Therefore, the Antarctic ice-sheet was more likely to be 130% than 60% of today's ice volume during the early Oligocene. Because the process length of *Operculodinium centrocarpum* is only a qualitative proxy for sea surface density, we cannot eliminate more insecurity, as was done in Galeotti et al., 2016.

Combining morphology change with SST data showed that the changes in density have been mostly due to temperature until Oi1, and mostly due to salinity after Oi1, thus relating to ice-volume on the Antarctic continent, as is also suggested by e. g. Katz et al, 2008 and Miller et al., 2009.

# Literature

Barke, J., Abels, H. A., Sangiorgi, F., Greenwood, D. R., Sweet, A. R., Donders, T., ... & Brinkhuis, H. (2011). Orbitally forced Azolla blooms and Middle Eocene Arctic hydrology: Clues from palynology. *Geology*, *39*(5), 427-430.

Bijl, P.K., Houben, A.J.P, Bruls, A., Pross, J., & Sangiorgi, F. (2018). Stratigraphic calibration of Oligocene–Miocene organic-walled dinoflagellate cysts from offshore Wilkes Land, East Antarctica, and a zonation proposal. *Journal Of Micropalaeontology*, *37*(1), 105-138.

Bohaty, S. M., Zachos, J. C., & Delaney, M. L. (2012). Foraminiferal Mg/Ca evidence for southern ocean cooling across the eocene–oligocene transition. *Earth and Planetary Science Letters*, *317*, 251-261.

Brinkhuis, H. (1994). Late Eocene to Early Oligocene dinoflagellate cysts from the Priabonian type-area (Northeast Italy): biostratigraphy and paleoenvironmental interpretation. *Palaeogeography, Palaeoclimatology, Palaeoecology, 107*(1-2), 121-163.

Brinkhuis, H., Munsterman, D. K., Sengers, S., Sluijs, A., Warnaar, J., & Williams, G. L. (2003). Late Eocene to Quaternary dinoflagellate cysts from ODP Site 1168, Off western Tasmania. In *Proceedings* of the Ocean Drilling Program. Scientific Results.

Coxall, H. K., & Wilson, P. A. (2011). Early Oligocene glaciation and productivity in the eastern equatorial Pacific: Insights into global carbon cycling. *Paleoceanography and Paleoclimatology*, *26*(2).

Cramwinckel, M.J., Huber, M., Kocken, I.J., Agnini, C., Bijl, P.K., Bohaty, S.M., Frieling, J., Goldner, A., Hilgen, F.J., Kip, E.L. and Peterse, F., 2018. Synchronous tropical and polar temperature evolution in the Eocene. *Nature*, *559*(7714), p.382.

Dong, S., Sprintall, J., Gille, S. T., & Talley, L. (2008). Southern Ocean mixed-layer depth from Argo float profiles. *Journal of Geophysical Research: Oceans, 113*(C6).

Ellegaard, M. (2000). Variations in dinoflagellate cyst morphology under conditions of changing salinity during the last 2000 years in the Limfjord, Denmark. *Review of Palaeobotany and Palynology*, *109*(1), 65-81.

Enderlin, E. M., & Hamilton, G. S. (2014). Estimates of iceberg submarine melting from high-resolution digital elevation models: application to Sermilik Fjord, East Greenland. *Journal of Glaciology*, *60*(224), 1084-1092.

Frieling, J., Reichart, G. J., Middelburg, J. J., Röhl, U., Westerhold, T., Bohaty, S. M., & Sluijs, A. (2018). Tropical Atlantic climate and ecosystem regime shifts during the Paleocene–Eocene Thermal Maximum. *Climate of the Past*, *14*(1), 39-55.

Galeotti, S., DeConto, R., Naish, T., Stocchi, P., Florindo, F., Pagani, M., ... & Sandroni, S. (2016). Antarctic Ice Sheet variability across the Eocene-Oligocene boundary climate transition. *Science*, *352*(6281), 76-80.

Guerstein, G. R., Daners, G., Palma, E., Ferreira, E. P., Premaor, E., Amenábar, C. R., & Belgaburo, A. (2016, April). Middle Eocene paleocirculation of the southwestern Atlantic Ocean, the anteroom to an ice-house world: evidence from dinoflagellates. In *EGU General Assembly Conference Abstracts* (Vol. 18, p. 10131).

Head, M. J. (2007). Last Interglacial (Eemian) hydrographic conditions in the southwestern Baltic Sea based on dinoflagellate cysts from Ristinge Klint, Denmark. *Geological Magazine*, 144(6), 987-1013.

Houben, A. J., Bijl, P. K., Sluijs, A., Schouten, S., & Brinkhuis, H. (2019). Late Eocene Southern Ocean cooling and invigoration of circulation preconditioned Antarctica for full-scaleglaciation. *Geochemistry, Geophysics, Geosystems*.

Houben, A.J.P., Bijl, P.K., Pross, J., Bohaty, S.M., Passchier, S., Stickley, C.E., Röhl, U., Sugisaki, S., Tauxe, L., van de Flierdt, T., Olney, M., Sangiorgi, F., Sluijs, A., Escutia, C., Brinkhuis, H., Expedition 318 Scientists, (2013). Reorganization of Southern Ocean plankton ecosystem at the onset of Antarctic glaciation. *Science 340* (6130), 341–344.

Ivany, L. C., Van Simaeys, S., Domack, E. W., & Samson, S. D. (2006). Evidence for an earliest Oligocene ice sheet on the Antarctic Peninsula. *Geology*, *34*(5), 377-380.

Jansson, I. M., Mertens, K. N., Head, M. J., de Vernal, A., Londeix, L., Marret, F., ... & Sangiorgi, F. (2014). Statistically assessing the correlation between salinity and morphology in cysts produced by the dinoflagellate Protoceratium reticulatum from surface sediments of the North Atlantic Ocean, Mediterranean–Marmara–Black Sea region, and Baltic–Kattegat–Skagerrak estuarine system. *Palaeogeography, palaeoclimatology, palaeoecology, 399*, 202-213.

Katz, M. E., Miller, K. G., Wright, J. D., Wade, B. S., Browning, J. V., Cramer, B. S., & Rosenthal, Y. (2008). Stepwise transition from the Eocene greenhouse to the Oligocene icehouse. *Nature Geoscience*, *1*(5), 329.

Lin, H., Rauschenberg, S., Hexel, C. R., Shaw, T. J., & Twining, B. S. (2011). Free-drifting icebergs as sources of iron to the Weddell Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, *58*(11-12), 1392-1406.

Liu, Z., Tuo, S., Zhao, Q., Cheng, X., & Huang, W. (2004). Deep-water earliest Oligocene glacial maximum (EOGM) in South Atlantic. *Chinese Science Bulletin*, *49*(20), 2190-2197.

Lodolo, E., Donda, F., & Tassone, A. (2006). Western Scotia Sea margins: improved constraints on the opening of the Drake Passage. *Journal of Geophysical Research: Solid Earth*, 111(B6).

Luckman, A., Benn, D. I., Cottier, F., Bevan, S., Nilsen, F., & Inall, M. (2015). Calving rates at tidewater glaciers vary strongly with ocean temperature. *Nature communications*, *6*, 8566.

Ludwig, W. J. & Krasheninnikov, V. A. (1983) *Init. Repts. DSDP*, 71: Washington (U.S. Govt. Printing Office).

Manum, S. B., Boulter, M. C., Gunnarsdottir, H., Rangnes, K., & Scholze, A. (1989). 32. Eocene to Miocene Palynology of the Norwegian Sea (ODP Leg 104). In *Proceedings of the Ocean Drilling Program, Scientific Results* (Vol. 104, pp. 611-662).

Merino, N., Le Sommer, J., Durand, G., Jourdain, N. C., Madec, G., Mathiot, P., & Tournadre, J. (2016). Antarctic icebergs melt over the Southern Ocean: Climatology and impact on sea ice. *Ocean Modelling*, *104*, 99-110. Mertens, K. N., Ribeiro, S., Bouimetarhan, I., Caner, H., Nebout, N. C., Dale, B., ... & Goubert, E. (2009). Process length variation in cysts of a dinoflagellate, Lingulodinium machaerophorum, in surface sediments: investigating its potential as salinity proxy. *Marine Micropaleontology*, *70*(1-2), 54-69.

Mertens, K. N., Dale, B., Ellegaard, M., Jansson, I. M., Godhe, A., Kremp, A., & Louwye, S. (2010). Process length variation in cysts of the dinoflagellate Protoceratium reticulatum, from surface sediments of the Baltic–Kattegat–Skagerrak estuarine system: a regional salinity proxy. *Boreas*, 40(2), 242-255.

Miller, K. G., Wright, J. D., Katz, M. E., Wade, B. S., Browning, J. V., Cramer, B. S., & Rosenthal, Y. (2009). Climate threshold at the Eocene-Oligocene transition: Antarctic ice sheet influence on ocean circulation. *The Late Eocene Earth: Hothouse, Icehouse, and Impacts*, *452*, 169.

Pieńkowski, A., Marret, F., Scourse, J., & Thomas, D. (2013). Organic-walled microfossils from the north-west Weddell Sea, Antarctica: records from surface sediments after the collapse of the Larsen-A and Prince Gustav Channel ice shelves. *Antarctic Science*, *25*(04), 565-574.

Robinson, N. J., & Williams, M. J. M. (2012). Iceberg-induced changes to polynya operation and regional oceanography in the southern Ross Sea, Antarctica, from in situ observations. *Antarctic Science*, *24*(5), 514-526.

Santos, A., de Araujo Carvalho, M., de Oliveira, A. D., & Mendonça Filho, J. G. (2017). Paleoenvironmental changes and influence on Operculodinium centrocarpum during the Quaternary in the Campos Basin, southwestern Brazil. *Journal of South American Earth Sciences*, *80*, 255-271.

Scher, H. D., Bohaty, S. M., Smith, B. W., & Munn, G. H. (2014). Isotopic interrogation of a suspected late Eocene glaciation. *Paleoceanography*, *29*(6), 628-644.

Sildever, S., Andersen, T. J., Ribeiro, S., & Ellegaard, M. (2015). Influence of surface salinity gradient on dinoflagellate cyst community structure, abundance and morphology in the Baltic Sea, Kattegat and Skagerrak. *Estuarine, Coastal and Shelf Science, 155,* 1-7.

Sluijs, A., Pross, J., Brinkhuis, H., (2005). From greenhouse to icehouse; organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene. *Earth- Science Reviews 68* (3–4), 281–315.

Sluijs, A., Bijl, P.K., Schouten, S., Röhl, U., Reichart, G.-J., Brinkhuis, H., (2011). Southern Ocean warming and hydrological change during the Paleocene–Eocene thermal maximum. Climate of the Past 7, 47–61.

Uenzelmann-Neben, G. (2006). Depositional patterns at Drift 7, Antarctic Peninsula: Along-slope versus down-slope sediment transport as indicators for oceanic currents and climatic conditions. *Marine geology*, *233*(1-4), 49-62.

Verleye, Thomas J., et al. "Average process length variation of the marine dinoflagellate cyst Operculodinium centrocarpum in the tropical and Southern Hemisphere Oceans: assessing its potential as a palaeosalinity proxy." *Marine Micropaleontology*86 (2012): 45-58.

Voytenko, D., Dixon, T. H., Howat, I. M., Gourmelen, N., Lembke, C., Werner, C. L., ... & Oddsson, B. (2015). Multi-year observations of Breiðamerkurjökull, a marine-terminating glacier in southeastern Iceland, using terrestrial radar interferometry. *Journal of Glaciology*, *61*(225), 42-54.

Williams, G. L., Fensome, R. A., and MacRae, R. A. (2017) The Lentin and Williams Index of Fossil Dinoflagellates

Wit, J. C., De Nooijer, L. J., Wolthers, M., & Reichart, G. J. (2013). A novel salinity proxy based on Na incorporation into foraminiferal calcite. *Biogeosciences*, *10*(10), 6375-6387.