Triggers of widespread anoxia in the Western Interior Seaway during Oceanic Anoxic Event 2

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ABSTRACT

Anthropogenic activity has affected the world's oceans in various ways, causing warming, acidification and deoxygenation. Mechanisms driving and maintaining the latter can be understood by studying similar changes that occurred in the Earth's past. This palynological study of Mid-Cretaceous (~94Ma) sediments from northern Canada sheds light on the drivers of anoxia and its development at higher latitudes. Changes in the palynological assemblages indicate that increased density stratification, through enhanced freshwater input and precipitation, were presumably the most important drivers. Changes in sea-level may have enhanced or counteracted the effects of stratification.

Keywords
Ocean anoxia, Cretaceous, productivity, preservation, stratification, Mesozoic

INTRODUCTION

Deoxygenation of the world's oceans is one of the effects of human-induced environmental changes, such as eutrophication and global warming, and a major issue in our times. Heterotrophic marine organisms, such as fish, require dissolved oxygen (O_2) for survival and become stressed under lowered concentrations. Some of these organisms are important for worldwide fisheries which will suffer from the decline of stocks [1]. Therefore it is important to study how and why aquatic systems become anoxic (i.e., absence of dissolved oxygen), especially within the context of a progressively changing climate.

Ocean anoxia is not exclusively a modern phenomenon. In the past, sections of the ocean experienced low oxygen conditions and in some cases the extent of anoxia could be considered global. Most of the major anoxic events occurred during the Mesozoic Era (251 to 66 Ma). These are collectively termed Oceanic Anoxic Events (OAE) [2] and have been studied extensively as analogs for modern-day ocean deoxygenation. OAE2 [3], which occurred across the boundary between the Cenomanian and Turonian stages (CTB; 93.9 Ma), is one of the best-studied and most extensive OAEs, with sedimentary records recovered globally [4]. This event is often recognized in the sedimentary record by deposits rich in organic carbon, and a positive excursion in the stable carbon isotopic composition (CIE) [4]. This excursion is caused by globally enhanced burial of organic material, which is relatively rich in the lighter ^{12}C isotope. This leads to less negative values in the remaining reservoir, recorded in organic matter and carbonates.

The causes of OAE2 are still under debate and there may have been large variations between the different ocean basins. Unfortunately most of the investigated sedimentary records are located in temperate and (sub)tropical regions, resulting in a lack of knowledge concerning the high latitudes. Therefore in this study the development of OAE2 in the northern the Western Interior Seaway (WIS), Canada. The WIS was a shallow seaway stretching across North America, from the Gulf of Mexico to the Arctic Ocean [5]. The use of palynology, the study of organic microfossil assemblages, provides insight into the magnitude and cause of anoxia in the high latitudes. It could also provide an analog for future cases of anoxia.

Causes of anoxia

There are a number of different mechanisms that can cause oxygen depletion in the oceans [6]. The first of these relates directly to the diffusion of oxygen from the atmosphere into the surface ocean. This process is slowed down by rising temperatures. Additionally, warmer waters can hold less dissolved oxygen. Therefore, warming leads to decreasing ocean oxygenation.

Eutrophication is another factor. When the input of nutrients in a system increases, so does the production of organic material (OM). This material will eventually be remineralized with the use of oxygen. Thus, increased export productivity of OM will demand more oxygen and thereby lower O_2 levels.

Another important factor is the vertical structure of the ocean. Deeper water layers are dependent on contact with surface layers for their supply of oxygen, through mixing and circulation. If the density stratification of the water column increases, deeper layers can become isolated and their oxygen concentration will decrease. Changes in density stratification are chiefly caused by changing temperature or salinity of the involved water masses, which can in turn be caused, for example, by changes in precipitation.

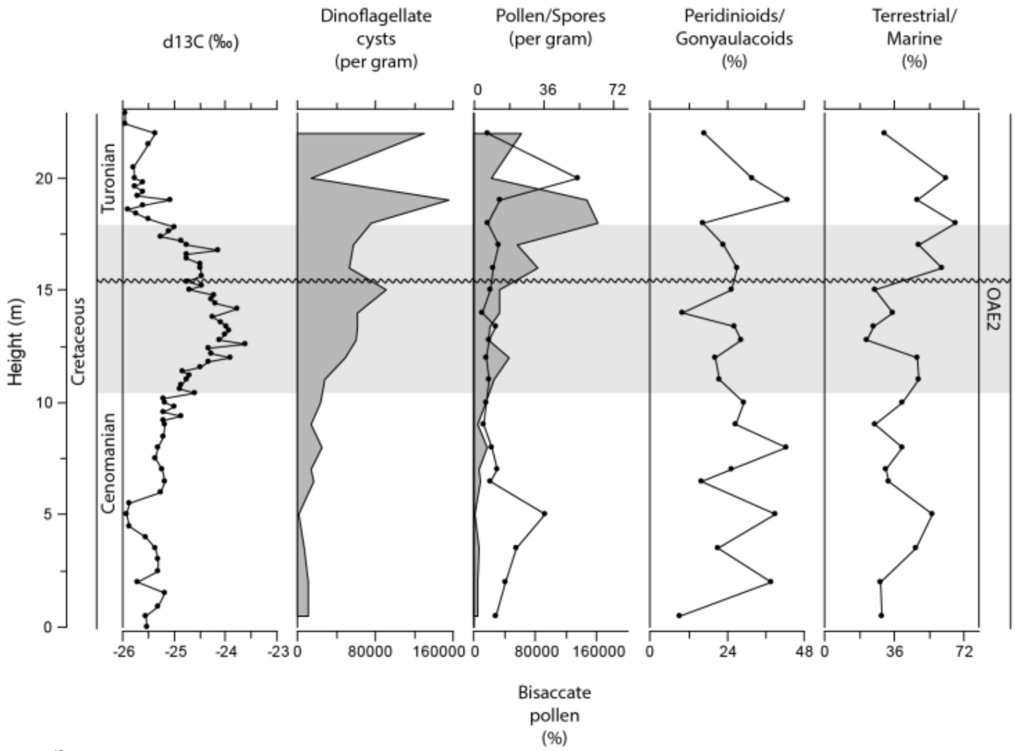

Figure 1. $\delta^{13}C$, absolute abundance of dinoflagellate cysts and pollen/spores (silhouettes), relative bisaccate abundance (dots), P/G and T/M ratios. The grey area marks the extent of OAE2 and the line represents the unconformity on the Cenomanian-Turonian boundary.

In order to better understand why oceans become anoxic, it is important to distinguish between different factors and in particular productivity and stratification.

MATERIALS AND METHODS

Site Description

This study focusses on a site in the northern WIS, Pratt's Landing, Alberta, Canada (56 01'14.09N 118 48'47.9W). At this site, located on the banks of the Peace River, 23 meters of upper Cenomanian to lower Turonian thinly bedded silt- and claystones are exposed, which were sampled with a resolution of 20 cm.Palynology

Palynology

The principle of palynology is based on the study of fossil assemblages of palynomorphs, including pollen, spores and dinoflagellate cysts. Changes in, within and between these assemblages provide clues to the paleoenvironment in which they were deposited.

Dinoflagellates are single-celled predominantly marine eukaryotic plankton able to produce organic resting cysts, which can be regarded as a sort of bio-plastic. Therefore these cysts are often preserved in sediments. Due to taxon-specific preferences for environmental conditions, the total and relative abundance of different cysts in an assemblage are a reflection of the original marine paleoenvironment.

The ratio between peridinioid (heterotrophic) and gonyaulacoids (autotrophic) dinoflagellates (P/G ratio) can be used as an indication for changes in marine productivity.

Other fossil palynomorphs can provide clues about the terrestrial environment and its link to the marine setting under which an assemblage was deposited. Such palynomorphs include pollen and spores, which can be transported to the ocean by different pathways. The ratio between terrestrial and marine palynomorphs (T/M ratio) can be used as an indicator for changes in sea level (or shore proximity) and the input of terrestrial organic matter (OM) through river influx. Bisaccate pollen can be used as an indicator of dry conditions and decreased precipitation, and are thus also an indirect proxy for sea surface salinity.

Palynological processing

A total of 21 samples were freeze-dried and treated with acids to dissolve carbonates and silicates (with 10% HCl and 38% HF, respectively). The residues were then sieved and mounted on slides for analysis. Dinoflagellate cysts were identified on genus level, with the exception of *Palaeohystrichophora infusorioides* and *Cyclonephelium compactum-membraniphorum*. A minimum of 250 identified cysts were counted per sample. Addition of tablets with a known amount of *Lycopodium clavatum* marker spores during processing of the sediment samples allowed for quantification of absolute abundances per gram sediment. Pollen and spores were counted as one category, except for bisaccate pollen, which were counted separately. Identified reworked palynomorphs were excluded from total counts.

RESULTS

Stratigraphy

The positive CIE, marking the OAE2 interval, was previously found between 10.2 m and 17-18 m at this site (Figure 1). Based on palynological correlation with other sites, the onset is tentatively placed at 10.5 m, after a maximum in the P/G ratio and abundance of *P. infusorioides*. The exact termination of the event is not

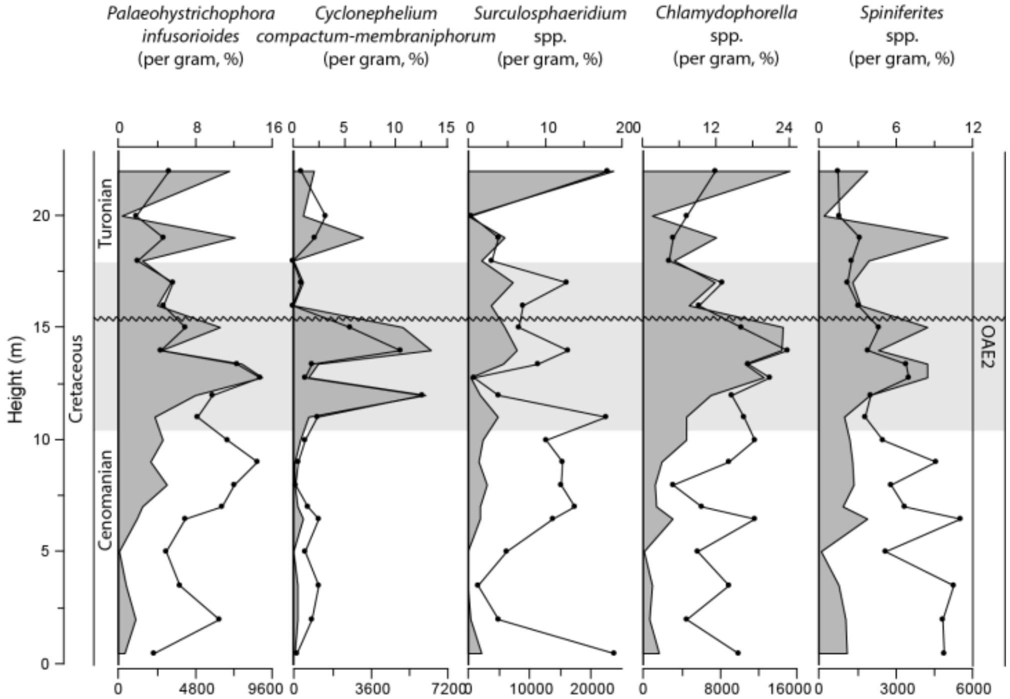

Figure 2. Relative (dots) and absolute (silhouettes) abundances of most important taxa. The grey area marks the extent of OAE-2 and the line represents the unconformity at the Cenomanian-Turonian boundary.

clear and is tentatively placed at 18m, approximately where $\delta^{13}C$ returns to background values.

Palynology

The absolute abundance of most palynomorphs increases throughout the section (Fig. 1) until the end of OAE2(18 m). Both dinoflagellate cysts and non-bisaccate pollen and spores display their absolute maxima at or directly after the termination of OAE2. At the top of the section (22 m) there is a second maximum in absolute abundance of dinoflagellate cysts. Bisaccate pollen display a different pattern to the rest of the terrestrial material, with peaks before and after the event (5.5 m and 20.5 m respectively) and low abundances in between.

The most dominant dinocyst taxa in this section are *Chlamydophorella* spp. (up to 24%) and *Surculosphaeridium* spp. (up to 20%) (Fig. 2). Before the onset of OAE2 the absolute abundance of most genera is low. A number of genera increase in both absolute and relative abundance, before and during the event. *P. infusorioides* and *Chlamydophorella* spp. decrease from the CTB onward. *Spiniferites* spp. becomes progressively less dominant and *C. compactum-membraniphorum* is stable throughout the section with the exception of two peaks within the event (12m and 14m). Some of the highest cyst per gram counts are reached after the termination of OAE2, at the top of the section (22m; *Chlamydophorella* spp. and *P. infusorioides*).

DISCUSSION

The palynological assemblage and its changes through time covered at this site shed some light of the drivers of deoxygenation and OM accumulation in this area, and on the changes that occurred at these latitudes during OAE2.

Productivity

Enhanced production of OM can result in oxygen depletion through increased export productivity. This mechanism has been proposed for OAE2 as well. Throughout the section there is no clear trend in the P/G ratio aside from a minor increase within the event. The T/M ratio appears to increase at the CTB and changes in the abundance of *P. infusorioides*, which has been used to indicate elevated nutrient conditions [7], possibly indicating fluctuating productivity within the event.

Stratification and sea-level

If riverine discharge increased around OAE2, it could have brought a larger influx of terrestrial material, causing an increase in T/M. As noted earlier, such an increase is only found in the second half of the event.

The relative abundance of bisaccate pollen is extremely low from a few meters below the event until a couple above it, indicating a wetter climate with increased precipitation and lower surface water salinity. The coincidence of bisaccate peaks with the lowest values of absolute dinoflagellate abundance further supports this theory. Density stratification in a wet climate could have enhanced preservation of sedimentary organic matter, especially if sea level was high enough to truly isolate deeper water masses [8].

The rise in T/M after the CTB in combination with the drop in the absolute dinocyst abundance could indicate a lower sea level and concomitant disruption of stratification and preservation. Though it is however argued that during regression the WIS was too shallow for stratification to persist [9], changes in precipitation and temperature might have been able to override the sea level effect through stratification.

As there is no indication for increased productivity at this site during OAE2, increased absolute numbers of palynomorphs and organic carbon content should have been driven by preservation due to anoxia. Stratification has been proposed as the major driver of anoxia in shelves and epeiric seas at high latitudes [10]. This appears to be the case for Pratt's Landing as well.

Migration and the Plenus Event

The early stage of OAE2 was disrupted by a colder period, the Plenus Event [11], driven by a drop in atmospheric pCO_2. This drop was probably caused by the enhanced burial of OM and resulted in decreasing temperatures [12]. Here the event appears to be marked by an increase of *C. compactum-membraniphorum*, decrease of *P. infusorioides* and an increase in T/M, similar to what was found on the New Jersey shelf [13]. Therefore, it seems that this event caused similar responses at different latitudes.

CONCLUSION

Knowledge of the mechanisms that cause anoxia are important if we want to mitigate the consequences of anthropogenically induced anoxia. Past events such as OAE2 can provide important insights into the environmental and climatological factors leading to the development of anoxia. Here, the palynological assemblage of Pratt's Landing, Canada provides insight concerning the changes that occurred at high latitudes during this event. A wetter climate would have lowered sea surface salinity and this likely resulted in anoxic bottom waters and enhanced preservation of organic material. Falling sea level may have briefly disrupted these conditions. Productivity does not appear to play a major role in this high latitude setting, unlike what has been found elsewhere.

ROLE OF THE STUDENT

The development of anoxia during OAE2 was one of the central topics studied by dr. N.A.G.M. van Helmond during his PhD. This project was designed by dr. B. van de Schootbrugge and dr. N.A.G.M. van Helmond for Nina Papadomanolaki's Honours-bachelor research, after she had expressed interest in studying past anoxia using palynology. During a period of ten weeks the student performed the palynological analysis for her bachelor thesis. The discussion and conclusions contained therein were formed through discussion with dr. N.A.G.M. van Helmond.

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