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Late Cretaceous (Late Campanian–Maastrichtian) sea surface temperature record of the Boreal Chalk Sea

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Abstract

The last 8 Myr of the Cretaceous greenhouse interval were characterized by a progressive global cooling with superimposed cool/warm fluctuations. The mechanisms responsible for these climatic fluctuations remain a source of debate that can only be resolved through multi-disciplinary studies and better time constraints. For the first time, we present a record of very high-resolution (ca. 4.5 kyr) sea-surface temperature (SST) changes from the Boreal epicontinental Chalk Sea (Stevns-1 core, Denmark), tied to an astronomical time scale of the late Campanian–Maastrichtian (74 to 66 Myr). Well-preserved bulk stable isotope trends and calcareous nannofossil palaeoecological patterns from the fully cored Stevns-1 borehole show marked changes in SSTs. These variations correlate with deep-water records of climate change from the tropical South Atlantic and Pacific oceans but differ greatly from the climate variations of the North Atlantic. We demonstrate that the onset and end of the early Maastrichtian cooling and of the large negative Campanian–Maastrichtian boundary carbon isotope excursion are coincident in the Chalk Sea. The direct link between SSTs and $\delta^{13}\text{C}$ variations in the Chalk Sea reassesses long-term glacio-eustasy as the potential driver of carbon isotope and climatic variations in the Maastrichtian.

1 Introduction

Superimposed on the long-term cooling trend of the latest Cretaceous, two benthic foraminiferal positive oxygen isotope excursions have been documented in the early and late Maastrichtian at low and mid-latitudes of the North and South Atlantic, Indian Ocean and central Pacific (Barrera and Savin, 1999; Friedrich et al., 2009). These positive excursions, which likely reflect bottom water cooling, have been tentatively correlated to 3rd order sea-level falls and associated with changes in the mode and direction of thermohaline oceanic circulation, possibly caused by the build-up of small ephemeral Antarctic ice sheets (Barrera and Savin, 1999; Miller et al., 1999). Alterna-

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tively, these climatic changes have been associated with shifts in the source of deep water formation from low to southern high latitudes, linked to the opening of deep-sea gateways in the South Atlantic (Friedrich et al., 2009; Robinson et al., 2010). In addition, the latest Maastrichtian was characterized worldwide by a brief greenhouse warming pulse, linked to Deccan volcanism (Li and Keller, 1998a; Robinson et al., 2009). This latter event is well-recorded in oxygen isotopes of benthic foraminifera but is poorly expressed in their planktonic counterparts (Li and Keller, 1998a, b; Barrera and Savin, 1999; Abramovich et al., 2003). Nevertheless, changes in the marine plankton community at the end of the Maastrichtian suggest a drastic, but as yet poorly constrained, increase in global sea-surface temperatures (SSTs, Abramovich et al., 2003; Thibault and Gardin, 2010).

Regionally divergent climatic patterns have been previously underlined in the Maastrichtian. In the southern South Atlantic, cooling is gradual, pronounced and only interrupted by the end-Maastrichtian warming (Barrera and Savin, 1999; Friedrich et al., 2009). In the North Atlantic, an apparent overall warming is inferred from low-resolution planktonic foraminiferal $\delta^{18}\text{O}$ data, while climate was globally cooling in all other oceanic basins (MacLeod et al., 2005). These regional differences emphasize the need for well-calibrated high-resolution data from different basins, and from open ocean and epicontinental seas in order to provide a reliable picture of past climates. Data from the mid-latitude Boreal epicontinental Chalk Sea are particularly critical as this basin was connected to the North Atlantic Ocean to the West, to the Tethys to the southeast and possibly to the Arctic Ocean to the North (Fig. 1).

To investigate climate change in the Boreal Chalk Sea, we generated a calcareous nannofossil temperature index (NTI) and a new record of 1932 bulk carbonate stable isotopes across the late Campanian–Maastrichtian of the Stevns-1 core, Denmark. The sedimentology and stratigraphy of Stevns-1 are described in detail in Rasmussen and Surlyk (2012) and Surlyk et al. (2013). Carbon isotope stratigraphic correlations with ODP Site 762C have been used to tie the Stevns-1 record to the astronomical time scale of the late Campanian–Maastrichtian (66 to 74.5 Myr, Fig. 2).

2 Methods

2.1 Age model

The age model is based on the correlation of magnetostratigraphic records at Sites 762C and 525A and carbon isotope curves of Stevns-1, 762C and 525A as presented in Thibault et al. (2012a). Numerical ages are derived directly from the correlation with the astronomically calibrated Site 762C (Fig. 2). A small hiatus characterizes the K–Pg boundary interval in the Stevns-1 core. Another hiatus is suspected at the boundary between the Sigerslev and Højerup Members situated 2.2 m below the base Danian. Based on the comparison of global climatic trends, it is estimated here that together, these two hiatuses correspond approximately to the last 150 kyr of the Cretaceous (see Sect. 3.3). For simplification of the age-model, a total gap of 150 kyr was accounted for at the top of our record and the uppermost sample of the Maastrichtian was assigned an age of 66.15 Myr, considering an age of 66 Myr for the K–Pg boundary as in Thibault et al. (2012a). The late Campanian–Maastrichtian succession of Stevns-1 accounts for a total duration of ca. 8.15 Myr with an inferred average sedimentation rate of 5.5 cm kyr⁻¹ over the entire interval. This gives an average resolution of ca. 100 kyr for the 89 samples analyzed for nannofossil palaeoecology and ca. 4.5 kyr for the isotopic data. This oxygen isotopic dataset is the highest resolution record so far published for this interval.

2.2 Isotopic measurements and palaeotemperature reconstruction

Oxygen and carbon isotopic ratios of bulk carbonates were measured on a micro-mass isoprime spectrometer. Analytical precision is calculated to 0.1 ‰ for $\delta^{18}\text{O}$ and 0.05 ‰ for $\delta^{13}\text{C}$. Sea-surface temperature estimates (Fig. 3) are based on Anderson and Arthur (1983) for bulk carbonates of Stevns-1 and Eq. (1) of Bemis et al. (1998) for foraminiferal data of Site 525A, using a $\delta^{18}\text{O}_{\text{sw}}$ of Late Cretaceous seawater of -1.0‰ SMOW for an ice-free world. Resulting average SST estimates of ca. 15.5 °C

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in the early Maastrichtian of Denmark is in agreement with the global compilation of Zakharov et al. (2006). In addition, we provide temperature estimates for the bulk carbonate of Stevns-1 using an average $\delta^{18}\text{O}_{\text{sw}}$ of Late Cretaceous seawater of -0.5% SMOW (Fig. 3) assuming glacio-eustatic variations in the range of 25–75 m in the Maastrichtian by comparison with the extent of coincident $\delta^{18}\text{O}_{\text{sw}}$ and sea-level variations in the Oligocene to early Miocene (Billups and Schrag, 2002).

2.3 Calcareous nannofossil data

A total of 89 nannofossil slides were prepared following the method described in Thibault and Gardin (2006). Slides were analyzed for quantitative counts. Preservation of the assemblage is moderate in all samples. Relative abundances have been calculated for a total of more than 400 specimens. The nannofossil temperature index (NTI) was calculated as the ratio between warm-water taxa and the sum of warm-water and cool-water taxa identified in the assemblage (see Sect. 3).

3 Results and interpretations

3.1 Calcareous nannofossils

Results from the nannofossil analysis are focused here primarily on potential temperature changes as expressed in the nannofossil assemblage through the abundance of cool- and warm-water taxa. *Ahmullerella octoradiata*, *Gartnerago* spp., *Kamptnerius magnificus*, and *Nephrolithus frequens* are considered as high-latitude taxa, and *Arkhangelskiella cymbiformis* sensu lato has a greater affinity to cool-waters (Wind, 1979; Thierstein, 1981; Pospichal and Wise, 1990; Watkins, 1992; Lees, 2002; Thibault and Gardin, 2006, 2010). *Watznaueria barnesiae* is ubiquitous in Cretaceous assemblages. Several studies have demonstrated that this is a low-nutrient indicator (Erba et al., 1992; Williams and Bralower, 1995). However, during the Maastrichtian, varying abundances and patterns of migration of this species in mid- and high-latitudes

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have mainly been linked to temperature changes (Watkins, 1992; Sheldon et al., 2010). Sheldon et al. (2010) and Thibault et al. (2015) have shown that warm intervals in the Boreal Chalk Sea are characterized by an increase in abundance of *W. barnesiae*. Cool-water taxa and *W. barnesiae* clearly show opposite long-term trends throughout the studied succession and highlight three warm intervals in the late Campanian, mid-Maastrichtian and latest Maastrichtian, and two cool intervals in the early and late Maastrichtian (Fig. 3). The palaeoecological affinity of *Ahmuellerella regularis* is unknown and this species has shown to be common both in the tropical and mid-latitude areas. However, in the Stevns-1 core, intervals with lower abundances of high-latitude taxa and higher abundances in *W. barnesiae* also show enrichments in *A. regularis* (Fig. 3). Therefore, in this study, this species was grouped together with *W. barnesiae* among the warm-water taxa. The Nannofossil Temperature Index (NTI) was calculated as follows:

$$\text{NTI} = \frac{(\% W. barnesiae + \% A. regularis)}{[(\% A. cymbiformis \text{ s.l.} + \% A. octoradiata + \% Gartnerago \text{ spp.} + \% K. magnificus + \% N. frequens) + (\% W. barnesiae + \% A. regularis)]} \quad (1)$$

3.2 Validation of Stevns-1 bulk $\delta^{18}\text{O}$ as a proxy for Late Cretaceous SSTs

The nannofossil chalk of the Danish Basin is a very pure carbonate. Carbonate content of the analyzed bulk rock samples is generally over 95 % in all analyzed samples. Scanning electron microscope images of the chalk show numerous calcareous nannofossils with dissolution phenomenon, few recrystallization and small carbonate micro-particles, which likely come from the breakdown of nannofossils (Fig. 4). Recent experiments have shown reduced coccolithophore interspecific differences and less carbon and oxygen-isotope fractionation in large and slow growing species with higher ambient carbon availability, which is expected in the sea water of periods with high CO_2 concentrations such as the Cretaceous (Rickaby et al., 2010; Bolton et al., 2012; Hermoso et al., 2014). Due to its limited diagenetic alteration, the nannofossil

5 long cooling steps are characterized by rapid temperature drops, two of which can also
be observed in the NTI at 72.8 and at 72–71.8 Myr. A cool climate mode with slight os-
cillations in SSTs around 15.5 °C is recorded between 71 and 69.8 Myr. The transition
between the early Maastrichtian cooling and mid-Maastrichtian warming is character-
ized by a rapid 1.5 °C increase in SSTs lasting ca. 300 kyr at 69.8–69.5 Myr. The mid-
10 Maastrichtian warming trend is characterized by SSTs oscillating around 16.5 to 17 °C
between 69.5 and 68.4 Myr. This trend is followed by a late Maastrichtian cooling of
1 °C during which minimal SSTs around 15.5 °C at 67.9 Myr are reached. A concomitant
sharp decrease in $\delta^{18}\text{O}$ and increase of the NTI delineate the end-Maastrichtian warm-
ing from ca. 66.3 Myr up to the K–Pg boundary. This last warming episode accounts for
a total of 2 °C in the Boreal Realm and occurs in two rapid (< 100 kyr) steps of 1 °C each
at ca. 66.3 and 66.2 Myr (Fig. 5). The K–Pg boundary clay is not present in the Stevns-1
core, which suggests a small gap across the K–Pg boundary interval. This small gap is
only local as small basins are developed across the K–Pg boundary. Sections through
15 these basins show a complete development of the K–Pg succession, whereas sections
between the basins contain a small gap spanning the boundary transition and in the
order of several tens of centimetres, i.e. < 30 kyr (Surlyk et al., 2006). In addition, the
presence of a double incipient hardground at the base of the Højerup Member situated
4 to 5 m below the K–Pg boundary at Stevns Klint suggests another potential hiatus
20 within the uppermost Maastrichtian interval (Surlyk et al., 2006). These small gaps
in Stevns-1 partly hinder observation of a globally characterized short cooling event
immediately before the K–Pg event (Li and Keller, 1998a; Thibault and Gardin, 2010;
Punekar et al., 2014; Thibault and Husson, 2015). The duration of this end-Cretaceous
cooling episode has been estimated to be of the order of 100 to 120 kyr and is followed
25 by a ca. 30 kyr short pulse of warming in the Tethys (Punekar et al., 2014; Thibault
and Husson, 2015). A sharp decrease in the relative abundance of *W. barnesiae* and
in the NTI situated within the Højerup Mb. suggests that the onset of the last end-
Cretaceous cooling episode is present in the core (Fig. 3). Therefore, the cumulated
uppermost Maastrichtian gap in the Stevns-1 core is of a limited extent, corresponding

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episodes highlighted at Stevns-1 (Fig. 5). Although no direct evidence of glaciation, such as dropstones and ice-rafted debris, have been found in the late Campanian–Maastrichtian of the Southern Ocean (Price et al., 1999), examination of diatom-rich sediments from the Alpha Ridge, and palynomorph records from southeastern Australia and Seymour Island support the development of winter sea ice in the Arctic Sea and around Antarctica, and the waxing and waning of ephemeral Antarctic ice sheets at that time (Gallagher et al., 2008; Davies et al., 2009; Bowman et al., 2013). The development of ephemeral ice sheets in Antarctica can explain the $\delta^{18}\text{O}$ excursions through a drop in seawater $\delta^{18}\text{O}$ accompanied by a global cooling of water masses (Barrera and Savin, 1999; Li and Keller, 1999). Sea-level changes could trigger the onset and termination of the late Campanian–early Maastrichtian CIE by shifting calcium carbonate accumulation and organic-matter burial from shelf to open-ocean areas (Barrera and Savin, 1999; Friedrich et al., 2009). The occurrence of the CIE and the early Maastrichtian cooling have been recently explained mainly by a global change in the source of intermediate and deep-water masses and the onset of deep-water formation in the Southern Ocean, favoured by the opening of tectonic gateways (Robinson et al., 2010; Koch and Friedrich, 2012). However, a reorganization in the global oceanic circulation is actually compatible with a glacio-eustatic scenario and could have been triggered both by tectonics and glaciation. In such a scenario, changes in the seawater $\delta^{18}\text{O}_{\text{sw}}$ within a range of 25 to 75 m glacio-eustatic variations may have followed a rather similar evolution as for the Oligocene–Miocene interval (Billups and Schrag, 2002). Palaeotemperature calculations should progressively and cyclically shift from an equation that assumes a sea-water $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{sw}}$) of -1‰ to potential $\delta^{18}\text{O}_{\text{sw}}$ down to ca. -0.5‰ (Billups and Schrag, 2002). Minimum temperatures of 15.5°C for the SSTs of the Boreal Chalk Sea during the early and late Maastrichtian coolings could thus be underestimated and may rather be around 17.5°C (Figs. 3 and 5).

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5 Conclusions

High-resolution bulk stable isotopes and calcareous nannofossil data from the fully cored Stevns-1 borehole provide fundamental insights into the late Campanian–Maastrichtian climate of the Boreal Chalk Sea. Our results show that the evolution of SSTs in the Boreal Chalk Sea parallel that of bottom-water temperatures at low and mid-latitudes of the North and South Atlantic, Indian Ocean and central Pacific. Two major cool intervals are highlighted at 71.6–69.6 (lower Maastrichtian) and 67.9–66.4 Myr (upper Maastrichtian). The onset and end of the late Campanian–early Maastrichtian negative CIE are coincident with the onset of cooling in the late Campanian and with the onset of the mid-Maastrichtian warming, respectively. These data reopen the possibility of a Maastrichtian glacio-eustatic scenario, supporting a causal relationship between changes in eustatic sea level and major shifts in Late Cretaceous $\delta^{13}\text{C}$ as previously suggested by Jarvis et al. (2002). Assuming that the early and late Maastrichtian coolings were caused by glaciation, palaeotemperature estimates should be calculated with two different equations using either a $\delta^{18}\text{O}_{\text{SW}}$ of -1‰ during warm episodes or a $\delta^{18}\text{O}_{\text{SW}}$ of ca. -0.5‰ during cool episodes. In such a scenario, the full extent of the early Maastrichtian SST cooling would thus be 4°C rather than 6°C . Finally, the two sharp stepwise 1°C increases in SSTs of the Chalk Sea at 66.3 and 66.2 Myr are consistent with the second main phase of the Deccan volcanic episode in a series of rapid pulses of flood basalt volcanism and associated release of greenhouse gases (Chenet et al., 2009).

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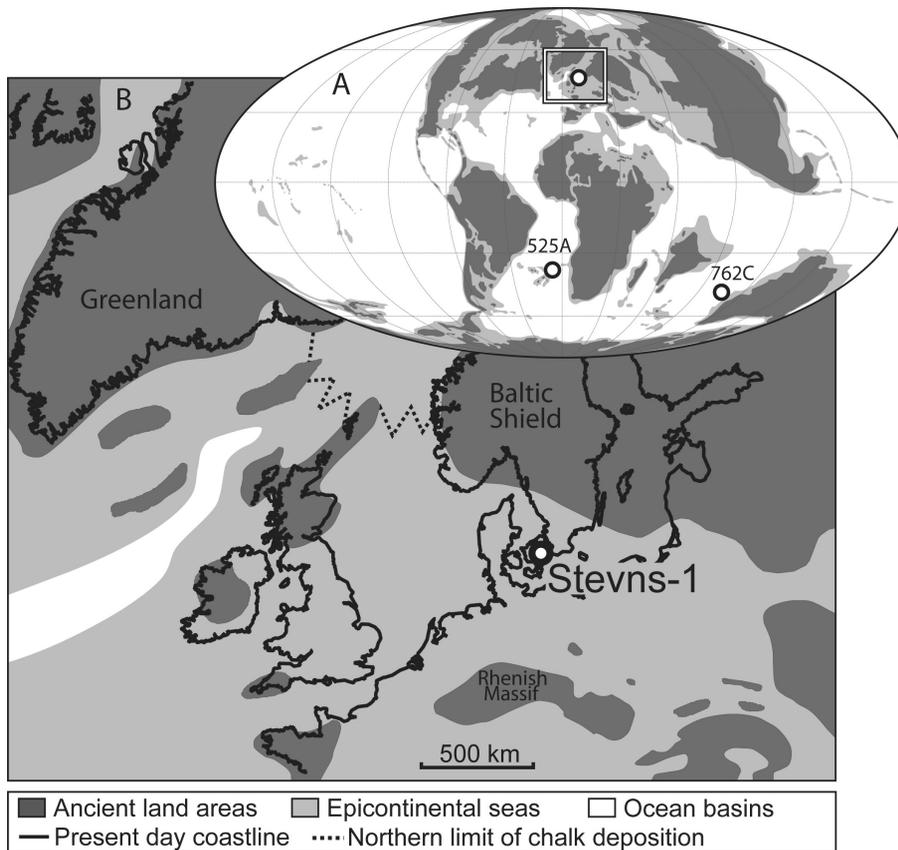


Figure 1. (a) Palaeogeographic reconstruction for the Maastrichtian (66 Myr) showing location of the Boreal Chalk Sea (square) and key localities discussed in the text (after Markwick and Valdes, 2004, modified). (b) Palaeogeographic reconstruction of the Boreal Chalk Sea for the Maastrichtian with location of Stevns-1 (after Surlyk et al., 2003, modified).

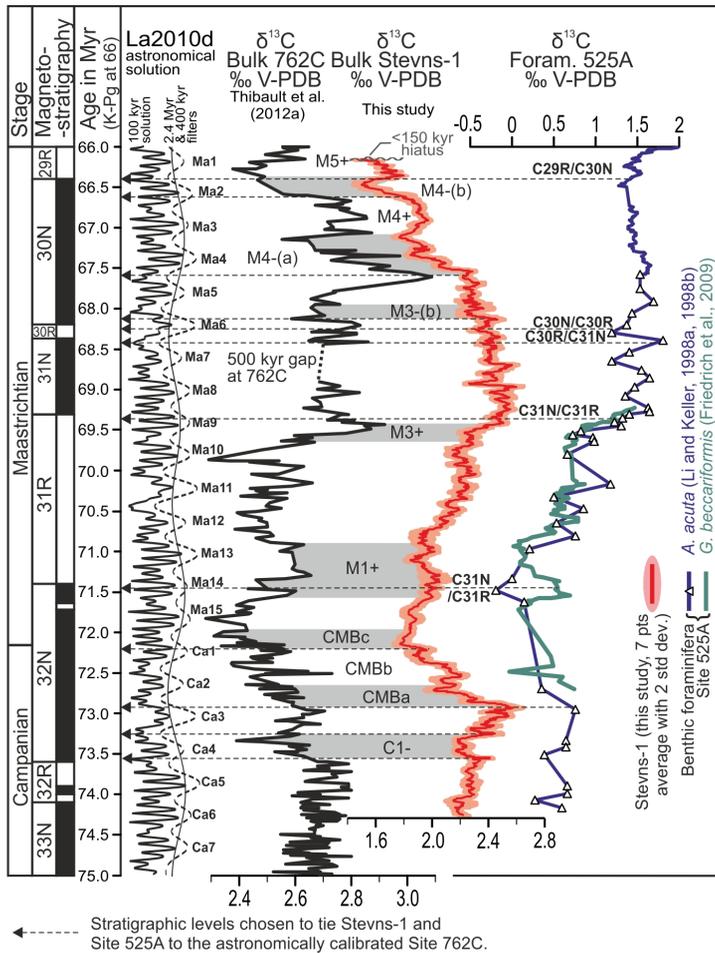


Figure 2. Age-model for the Stevns-1 core based on the correlation of carbon-isotope curves of Stevns-1 with the astronomically calibrated ODP Site 762c and DSDP Site 525a.

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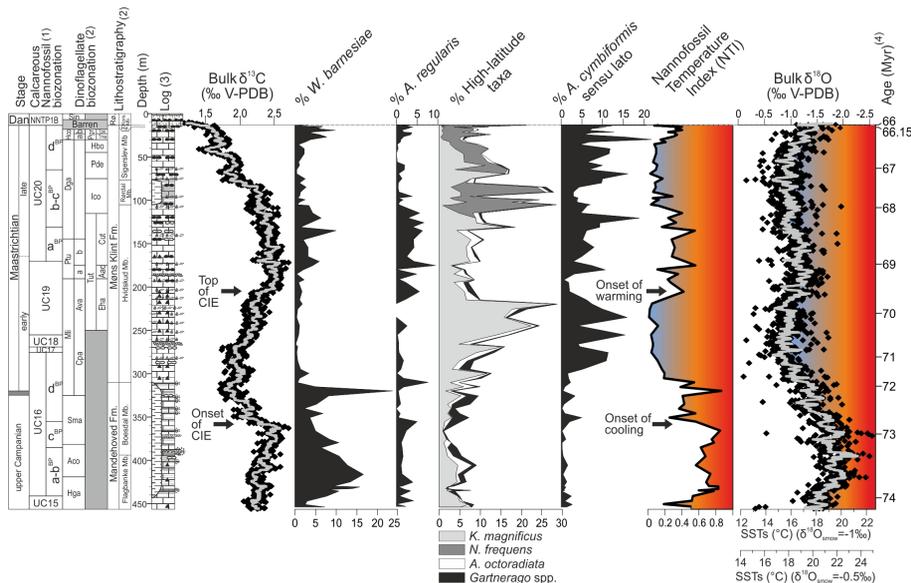


Figure 3. Calcareous nannofossil climatic data and bulk stable isotopes of Stevns-1. Background colours delineate cool and warm climatic trends in the Chalk Sea. (1) Thibault et al. (2012b). (2) Surlyk et al. (2013) for details of the dinoflagellate biozonation and lithostratigraphy. (3) Rasmussen and Surlyk (2012) for the full sedimentological description of the Stevns-1 core. (4) Age model after Thibault et al. (2012a) and correlation of Fig. 2.

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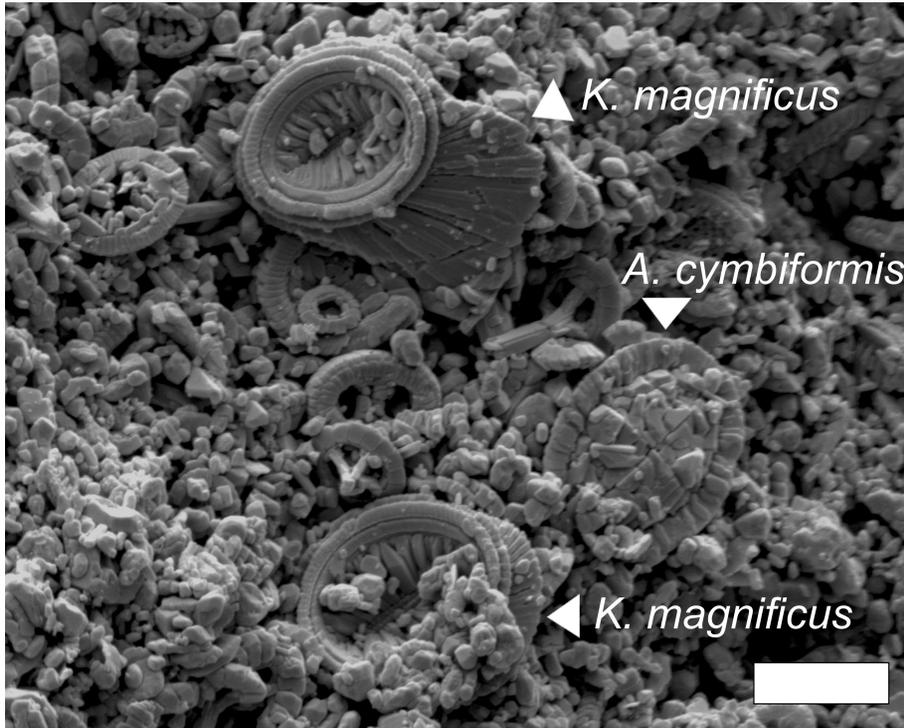


Figure 4. SEM picture of the Stevns-1 chalk. Sample 6146 (late Maastrichtian cooling episode, nannofossil subzone UC20b-c^{BP}, depth: 73.91 m). Two of the main cool-water nannofossils taxa are shown. Bar is 10 μ m.

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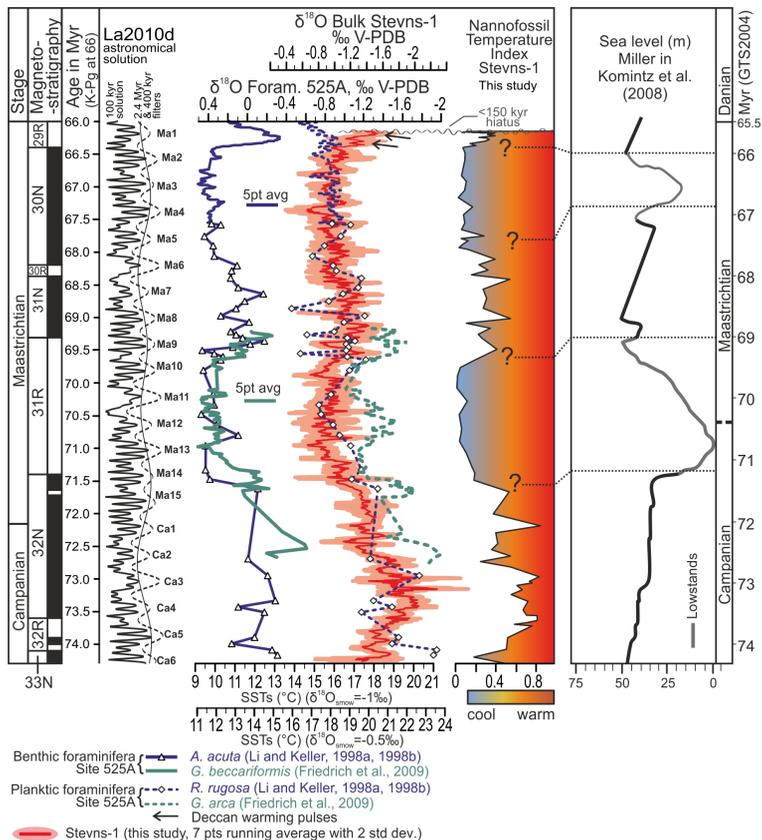


Figure 5. Stable oxygen isotope and calcareous nannofossil data of Stevns-1 compared to data on foraminifers of South Atlantic DSDP Site 525A. The age scale is based on the correlation of carbon isotope curves between Stevns-1, DSDP Site 525A and the astronomically calibrated ODP Site 762C. La2010d: astronomical solution from Laskar et al. (2011). Benthic and planktonic foraminiferal stable isotope data from Li and Keller (1998a, b) and Friedrich et al. (2009).

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