Reply and changes made to reviewer comments on '*Land–sea coupling of Early Pleistocene glacial cycles in the southern North Sea exhibit dominant Northern Hemisphere forcing*'

Donders, T.H. et al.

We thank the reviewers for their constructive and specific comments and have used them to improve the interpretation and data representation. Here we provide a full reply to the comments and indicate where we have made adjustments, and provide additional information to support our interpretations. We have checked references in detail and added doi numbers. We feel that with extension of the discussion and added detail as indicated below we are able to meet the concerns of all reviewers.

Reviewer #1: Stijn de Schepper

Comment on validity of age model: While the presented work is underpinned by previously published papers and insights into depositional environment (papers by Kuhlmann and co-authors), aspects of the age model can be questioned. The authors rely here on the G/M reversal and the X-event for constraining the age of their studied interval (L152–155). Kuhlman and Wong (2008) discuss in fact 4 different possible interpretations of the pmag. It seems very questionable to me that the very short-lived X-event (2.420–2.441 Ma, Cande and Kent, 1995) can be detected in the sedimentary record of a shallow sea by measuring the magnetic signal of discrete samples (Kuhlman and Wong, 2008). This event does not show up in u-channeled, high-resolution pmag records of the North Atlantic (e.g. Hoddell and Channell 2016; Channell et al 2016), neither has it been tied to the LR04 Marine Isotope Stratigraphy. The dinocyst bioevents generally point to the Plio-Pleistocene, but the events are not well-recognised (e.g. Barssidinium, M. choanophorum) or not calibrated (e.g. I. multiplexum) outside the North Sea Basin. This questions the age assigned to these events and thus also the age model. Using additional/different tiepoints that have been calibrated outside the North Sea Basin could provide more credibility to the age model used (see below). Based on these concerns about the age model, it remains uncertain 1) whether the cycles visible in the gamma-ray reflect the interval MIS102–96 and 2) whether these are truly, consecutive (i.e. no erosional events in between) G-IG cycles.

Reply: The comments of the reviewers regarding the age model focus on three aspects;

1. the sedimentary setting and validity of the paleomagnetic signal and, consequently,
2. the completeness and correct assignment of the stratigraphy at A15-3/4 to MIS 102-96, and
3. the use of the dinocyst biozonation.

1: Firstly, based on the combined stratigraphic and detailed 3D seismic interpretations and overall fine grained (clays to silts) deposits all point to a continuously aggrading system in the interval we report. There is evidence of small hiatuses above (first around 2.1 Ma) and significant hiatuses below (intervals within the Early Pliocene and Miocene, particularly the Mid Miocene Unconformity) the selected interval, which is why we excluded these intervals in this publication. Indeed, in the excluded intervals erosional surfaces (beside the obvious MMU) are well recognizable in the seismic property data (Kuhlmann and Wong, 2008), where the high-resolution 3D volume resolves e.g. (iceberg) scour marks and truncated clinoforms. The seismic data thus serve as an important control on our stratigraphic interpretation. In the intervals with erosive signals, the associated palynological signals point to much more shallow and near terrestrial conditions that are typically associated with erosive conditions (Kuhlmann et al., 2006a).

For the reported MIS102-96 interval, the typical cyclic pattern of the gamma ray is traceable across several wells in the central part of the entire southern North Sea (see Kuhlman et al. 2006ab as well as in the seismic interpretations presented in our supplementary data). Crucially, the Pmag has been measured first by a continuous paleomagnetic downhole logging tool, Geological High-resolution Magnetic Tool (GHMT) by Schlumberger, in wells A15-3 and B16-1 (see description in Kuhlmann et al., 2006a), which is a rarely available tool and therefore an important addition to the interpretation. This continuous signal is present in **two** wells in the same log zone and has subsequently been verified by discrete samples taken from continuous cores in well A15-3 (Kuhlmann et al., 2006a), and the interpretation relies on the combined signal from borehole logging and core measurements. Secondly, owing to the coastal proximity, the thickness of the North Sea succession and therewith sedimentation rates of the investigated interval is far higher than any North Atlantic site, which greatly increases the chance of recovery of the X-event. Our approximately 250 kyr record is represented by a sediment thickness of over 160 m of fine-grained sediment.

2: While the independent position of the X-event is not included in i.e. the LR stack, there is additional recent evidence that supports our interpretation. Noorbergen et al. (2015) has carried out a detailed study of a land-based section (Noordwijk well) that represents approximately the same interval as our 15-3/4 study. The Noordwijk record contains both palynology and detailed stable isotope stratigraphy, and it includes a direct correlation with the A15-3 well, including the quantitative abundance signals on palynology. At this site, carbonate preservation was much better and more sample material was available, providing a much more complete benthic isotope record. Based on the Noordwijk data, Noorbergen et al (2015) established a tuning to LR04, which is valid for A15-3/4 as well. The 4 options for paleomagnetic interpretation in Kuhlman and Wong (2008) pointed at by the reviewer, are already presented in Kuhlmann et al. (2006a), and represent the theoretical ties when only Pmag data would be considered. The key to our record is an integrated Pmag, isotope stratigraphic, seismic stratigraphic and palynological biozonation that exclude the other options and all converge on the present interpretation as presented in Table S1 and Figure S2. We recognize that the evidence from the Noordwijk well (Noorbergen et al, 2015) was insufficiently represented in our manuscript and we have incorporated this study in section 3 and the discussion to strengthen our interpretation, and we refer to the available evidence on hiatuses. Also, we recap shortly the available age dating information (as outlined here).

3. The bioevents in the North Sea basin, specifically the acmes, indeed have a clear regional character, but within the basin allow a high resolution well correlation (Kuhlmann et al., 2006b). While the age model and bioevents have been discussed in Kuhlmann et al. (2006a) and are used for this publication, their validity is significantly strengthened by the tuning approach of Noorbergen et al. (2015). That paper describes the occurrence of *I. multiplexum* in both the A15-3 well and Noordwijk well, which has been tied to an acme in MIS 97/98 in this basin. Based on the comments, we have reviewed the dinocyst

events and the suggested inclusion of the additional markers strengthens our interpretation. In the revision, we provide a new Table S1 with the age and sources of the bioevents used, and have updated the age-depth model where needed to included uncertainties explicitly. As expected, the revision did not alter the age interpretations of the MIS102-92 interval.

Comment: The leads/lags between climate proxies and sea level are not so clearly visible as the authors claim in the abstract and conclusions. The leads/lags are not clearly demonstrated on a figure, or more importantly using statistical techniques.

Reply: Lead –lags signals that we infer are mainly based on the G-IC cycle (MIS 98-97-96) in our record that is best resolved in all available proxies. A statistical approach would require multiple of these successions with similar sampling resolution which, unfortunately, is not available. The stratigraphic record is not fully cored, but only in part (see fig 2) and part of the proxies (palynology and organic geochemistry) supplemented by side wall cores. The strength and value of the record is in the expanded nature and good reflection of both marine and terrestrial signals, which is a rare occasion. Based on the available evidence we infer a lead-lag relation of (crucially) signals that are all coming from the same source material. While the overall climate signal between land, sea surface and sea level is indeed in phase ("vary in concert"), there are small lead –lags relations in the data that we point to. The best resolved and across alonger portion of the record is that of the AP% and T/M ratio that, crucially, are based on the same palynological analysis. Based on the available records, AP% declines with a lead of between 3-8 kyr relative to the T/M increases based on the present age model. While we have confidence in our age model, the exact duration of the glacial vs interglacial part of each sedimentary cycle is not constrained, only the transitions. For this reason we want to refrain from providing too exact numbers on the lead-lag relations, but have added further discussion in 6.1 on the AP% and T/M lead-lags and indicated the offsets in Fig S2.

Comment: What is the effect of using cutting samples (caving, reworking) on your interpretations?

Reply: The effect of the cuttings is very minimal as the majority of the samples is from cores or side wall cores (which are intact samples obtained after drilling). The cuttings are used here to increase resolution of the palynological samples, and are based on larger chips that have been cleaned before treatment. Importantly, no PDC (power drill bit) has been used so the cutting material has not been ground into a fine paste as is a common practice in many recent wells. The expanded sediment package helps limit the caving problems as the time resolution is high. We will provide a table with exact sample type and proxy, but we can state that all organic and carbonate proxies have been measured on core or sidewall cores and the key conclusions are not depending on cutting material. Other wells in the region that have been studied (by TNO Geological Survey of the Netherlands), internal reports) on cutting material could be correlated confidently to A15-3/4, and independently verified by 3D seismic interpretations. We added some explanation on the use of the cutting material.

Comment: Environmental signal from dinocysts; The 4 species used to indicate a warm water signal are all coastal, shallow water species (L225–227). Their distribution in the shallow North Sea Basin

could be strongly affected by SL fluctuations at the beginning of the Early Pliocene. Versteegh (1994) therefore does not include these taxa in a warm-cool index. Furthermore, L. machaerophorum is often used to indicate river input and sea level fluctuations (Holzwarth et al. 2010). How do you disentangle the effect of sea level and temperature for these 4 species, when their distribution could be affected by both? The T/M ratio is interpreted as a relative SL indicator. While this intuitively seems correct, I wonder if the relation is that simple? Terrestrial palynomorphs are affected by transport patterns (wind, position of rivers) and could thereby influence the sea level interpretation?

Reply: The reviewer is absolutely right that the 4 selected dinocyst taxa indicate largely coastal conditions. In fact this is our main purpose for displaying them, and conclusions based on their abundance refer to their indication of coastal conditions. Our climatic interpretations regarding dincysts rely on solely the cool water taxa as we tried to optimally separate the in-/offshore and climatic trends. The confusion is in our use of the phrase " *… indicate generally warm, coastal waters*", while we principally use them for the latter. We have explained this point better in the revision.
On the second point regarding the T/M ratio: The principal source of the terrestrial palynomorphs is from the Eridanos paleoriver (as verified in a source area study by Kuhlmann et al., 2004). The detailed seismic interpretation provides further important control on the direction of river progradation. The component most sensitive to the T/M index related to differential transport processes, the bisaccate pollen, are here tested for their effect on the ratio by including and excluding them (Fig. 1). The resulting ratio with bisaccate pollen excluded is slightly lower, but the relation between both ratios is very strong and hence no indications for phases of differential transport are present that impact the T/M ratio. This explanation was added to the discussion and the additional figure was included in the supplementary data (Fig. S5).

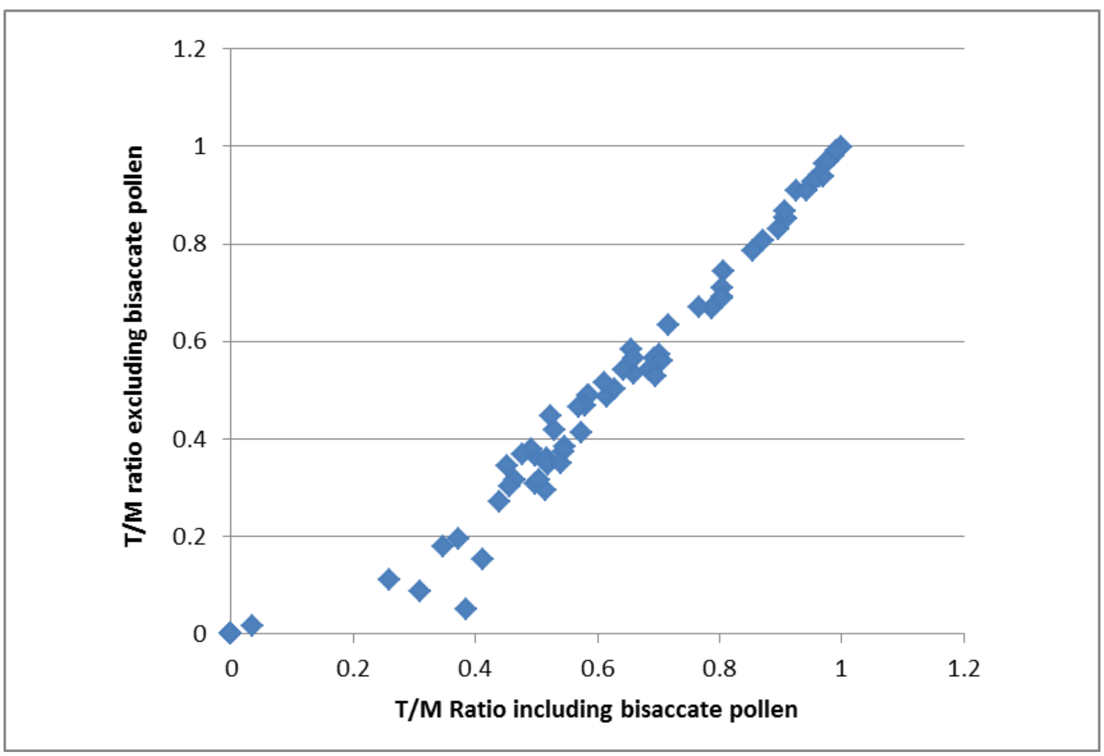


Figure 1: terrestrial / marine palynomorph ratios with in- and exclusion of bisaccate pollen.

Minor points

L45 There is hardly proxy data to say something about MIS 100 Reply: 100 excluded and 94 was included in the summary

L47 Freshwater flux is not really supported by the fresh water algae. Reply: statement changed to the record of stratification from *L. machaerophorum,* better reflecting the discussion

L50-51 Confusing. Please rephrase. Reply: rephrased to "The record provides evidence for a dominantly NH driven cooling that leads the glacial build up and varies on obliquity timescale."

L52 SST is not a good indicator of migration of a watermass. Microfossil assemblage could help you with identifying such migration, but not SST alone. Reply: rephrased, the SST signal from the microfossil assemblage was indeed meant. "indicated by cool-water microfossil assemblages"

L73 space missing before "and"
Reply: corrected

L105 rephrase "but which stratigraphic position"
Reply: changed to "although its stratigraphic position and original definition are not well defined"

L110 During the Neogene, there could have been a southerly connection between the North Sea and Atlantic (see reconstructions of e.g. Gibbard and Lewin 2003, 2016). It might be worth to use the more recent Gibbard and Lewin 2016 palaeogeographic reconstruction instead of Zeigler 1990 (Figure 1).
Reply: The suggested use of the Gibbard and Lewin 2016 paleogeographic reconstruction was considered but to display the center of deposition we prefer to use the current geographic boundaries with the current sedimentary infill and overlay of paleoflows, and refer to the paleogeographic reconstructions for more detail.

L121 "different water types": water masses in Fig 1 refer mostly to the origin of the fresh water inflows
Reply: caption Fig. 1 corrected

L126–128 Please provide a timeframe:
Reply: changed to the Eridanos delta was active during most of the Neogene and Early Pleistocene, and progressively prograded towards the study site

L157–162 This (depositional) model would get more credibility if this has also been demonstrated for late Pleistocene glacial/interglacial cycles. Would the SL drop of up to 60 m in these glacials (e.g. Miller

et al. 2005; Bintanja et al. 2005) not provide a stronger control on the sedimentation (rather than hydrography)?

Reply: the relation between grain size and G-IG cycles is regionally only and valid as long as the site is permanently marine. Available foraminifera and seismic data indicate water depths of 300-100 m in the reported interval (Kuhlmann et al., 2006a; Huuse et al., 2001). In later glacial stages as the Eridanos system is abandoned and more extensive glaciations cover the Scandinavian shield and the Southern North Sea basin is either dry or very shallow this depositional system proposed by Kuhlmann and Wong (2008) is no longer valid. Also the study by Noorbergen et al (2015) on the Noordwijk well confirms that "*… the finer grained intervals coincide with d18O maxima implying increased ice sheet volume and lowered eustatic sea levels*." Reference to the Noordwijk study has been included

L165 How was the age model transferred to LR04 MIS?
Reply: GR breaks were picked as inflection points of the LR04 MIS transitions (allowing for a 20 kyr uncertainty around individual ties) and interpolated through a smoothing spline; this is now clarified clearly in section 3 and Table S1.

L174–175 Please check also De Schepper et al. 2017.
Reply: added in table S1

L177–L186 Does this paragraph belong in the age model section?
Reply: we think it fits best here as it describes the regional setting and the seismic interpretations provide basin-wide correlations.

L190 C. teretis in italics.

Reply: corrected

L202 How was recrystallization and dissolution determined?

Reply: Preservation was based on a visual inspection and assignment of a relative scale of 1-5 of preservation, after which the poorest 2 classes were discarded. The best preserved specimens (cat. 1) had shiny tests (original wall calcite) and showed no signs of overgrowth. Category 2 specimens showed signs of overgrowth but were not recrystallized and cat. 3 specimens were dull and overgrown by a thin layer of secondary calcite. Cat 4-5 specimens were discarded because primary calcite was (nearly) absent. While we are aware of the importance of SEM work for detailed preservational assessments the aim was to establish the phase relation with the GR cycles. These details have been added to the methods.

L211 de Vernal (no capital D).
Reply: corrected

L270 delete ", dinocysts":

Reply: we deleted “dinoflagellate cyst” as the term dinocyst had already been introduced earlier in the text.

L273 Why were there only relative abundances calculated?
Reply: No *Lycopodium* marker counts were available, needed for calculations of concentrations, due to part industry origin of the datasets.

L304 Delete “For TOC determination”.
Reply: corrected

L359 not convincing (reviewer referring to ‘The *Cassidulina teretis* $\delta^{18}O$ ($\delta^{18}Ob$) confirms the relation between glacial stages and fine grained sediment as proposed by Kuhlman et al. (2006a,b)”)
Reply: Apart from our data, the benthic ($\delta^{18}Ob$) from the nearby Noordwijk well (Noorbergen et al., 2015) now independently confirms the relation between glacial stages and fine grained sediment as proposed by Kuhlman et al. (2006a). This has been added in the text.

L372 diverse.
Reply: corrected

L377 Are herb and heath pollen dominant? Pinus remains the dominant species. Please make clear that you are discussing the pollen record, excluding pine pollen.
Reply: comment added to highlight these are non-bisaccate forms only.

L383 Which fresh water algae did you find?
Reply: *Pediastrum* and *Botryococcus* (see supplementary data)

L401-402 What does the n-C23 Sphagnum biomarker indicate?
Reply: development of boreal (moist/cool) climate and influx, see also the reply to David Naafs.

L413 MIS 96/95 (space missing)

Reply: corrected

L422 Tables S and 2?
Reply: corrected and updated

Fig. 3 The Lingulodinium machaerophorum record should be presented separately – difficult to see now.
Reply: we refrain from doing so as we do not want to expand the diagram any more. Also, the L. machaerophorum record is not critical to the interpretation.

L428–: : : Chapter 6.1 is confusing and does not really deal with paleoenvironment. It is

not clear which MIS is discussed, and the switching between proxies (e.g. L429–433) and time intervals (all glacial/interglacials, MIS 98/97, 94 and 92) makes this difficult to follow.

Reply**:** we have added discussion on the paleoenvironmental setting, revised the text for inconsistencies and changed the heading. We have also subdivided the chapter, see also the reply to the comment by reviewer 3.

L432 depend (not depends)

Reply; this suggestion is not correct. Pollen is a *singulare tantum*, it has no plural

L434 Effect of SL on pollen is addressed here, but the effect of SL on the dinocyst record is not discussed in the MS

Reply: the coastal dinocyst index is especially included to document the combined influence of coastal progradation and sea level change. Due to the earlier confusion on the use as warm water indicators, this point was perhaps overseen by the reviewer.

L485, L535 Onset/intensification have been used intermixed

Reply: valid point that we have adjusted to consistent use of intensification throughout the text

L495–496 What is small – please specify? Please indicate which figure shows the small lead.

Reply: In fig. 3, the lead between AP% decline and T/M increase is estimated between 3-8 kyr based on the present age model. This information has been added, see also comment to reviewer 3.

L510 Speculation

Reply: yes, but consistent with the effect of obliquity forcing

518 Severe cooling. Subjective comment, certainly if you know that L. machaerophorum does not occur in regions with summer SST below 15^{o}C. This species is present in all glacials

Reply: the cooling is relative to late Pliocene conditions and in that respect severe, we do not exclude summer temperature above 15^{o}C. In the conclusions we have specified more exactly the amplitude of cooling based on the brGDGT data that, although not always in phase with the other proxies, does give a temperature range for the G-IG cycles. Severe is changed to significant.

Fig. S3 Please provide a list with the tiepoints:

Reply: Table S1 has been added with all tiepoints based on Kuhlmann et al, 2006ab, uncertainties and references, together with an updated age depth model figure S3.

Reviewer #2: David Naafs

General Comment (and Comment Line 82-88): Discussion on the phase relationship "the discussion on this specific topic in this manuscript is rather limited and is missing a discussion of crucial prior work on this topic"
Reply : We originally aimed at providing a compact paper focusing on the evidence on phase relations we can provide from the new data, but we acknowledge that more information is available. We have expanded the introduction and discussion (updated section 6.3) on this matter following the suggestions of the reviewer to provide a more balanced assessment of the forcing mechanisms and available evidence. At the same time, we do not intend to provide a review paper and as such keep the discussion on additional literature limited.

Comment: In addition, I wonder whether the age model is robust enough. The low-resolution benthic d18O record of this site does not always look like the LR04 stack.
Reply: the validity of the age model is addressed in detail in the replies above to Stijn de Schepper, and we include more extensive discussion of records in the same basin, in particular the Noordwijk record from Noorbergen et al., 2015. The key results of our paper however, depend on the internal relations between the proxies from the same record and do not rely on an exact match with the LR04 stack.

Minor comments:

Comment Line 51-55: this is a bit of a weird ending of the abstract, especially in the context of the main focus of the paper that is stated at the beginning of the abstract. The authors should end the abstract with a clear conclusion of what, according to their work, the phase relation is between forcing and climatic response.
Reply: the abstract is adapted to better reflect the conclusion, but the last line is used to indicate that our observations have significance also for AMOC reconstructions, although not the topic of our study.

Comment Line 66: a full review paper on IRD in the North Atlantic during the Plio/Pleistocene is given in (Naafs et al., 2013)
Reply: reference has been added

Comment Line 73-78: somewhere make reference to mechanism proposed
Reply: reference added to proposed evaporation feedback forcing mechanism (Haug et al., 2005)

Comment Line 202: what statistical basis was used to reject samples? What is the distinction between poor and not poorly preserved?
Reply: see reply to comment of S. de schepper on this issue and additional methods in section 4.1

Comment Line 280: cite (Eglinton and Hamilton, 1967) for odd over even predominance of nalkanes.
Reply: we have added Eglinton and Hamilton, 1967 on n-alkanes

Comment Line 289 change sentence to "brGDGTs), produced by bacteria and that are abundant in soils, versus that:.."

Reply: textual comments were adopted

Comment Line 290: add reference

Reply: we have cited Sinninghe Damsté et al., 2002 for crenarchaeol

Comment Line 467: is there any other supporting information for the input of acidic peat input? For example, modern-day acidic peats are characterized by the dominance of the C31ab-hopane (Dehmer, 1995; Pancost et al., 2002), which is normally only present inmature sediments.

Reply: as seen in the expanded pollen diagram (Fig. S2), Sphagnum spores are also mostly enhanced in the glacial MIS intervals in support of the C23 biomarker. We have analyzed part of the samples for the isomers index of the de C31 ab-hopanes. The results (for immature sediment) provide evidence of acidic peat input, although not dominant. Reviewer likely meant Pancost et al., 2003, which we have added

Comment Line 473-477 The authors should provide a ternary plot of the brGDGT distribution t**o rule out a significant non-terrestrial contribution;**

Reply: a ternary brGDGT diagram has been made and added as Figure S6 in the supplement, and it is discussed in section 6.2 (new section heading).

Comment Fig 3 readability

Reply: the aim of the figure is to compare various proxies and they therefore need to be together. The figure is now rotated but will be horizontal in final version, improving visibility

For the supplementary information, can the authors provide the abundances of the individual brGDGTs (and crenarchaeol) so that if the indices used for the soil-calibrations change in the future, the data can be easily recalculated and still be used in future studies.

Reply: We have added the absolute abundances of the individual brGDGTs (and crenarchaeol) to enable recalculations in Table S3

Referee #3: Anonymous

Comment: The arboreal pollen and T/M ratio curve shows large fluctuations and hardly reveal any clear trends. These fluctuations may have resulted from a) the extremely low pollen sum after exclusion of bisaccate pollen, and b) the fact that the pollen results were merged from two different sites.

Reply: as Rev. #3 suggests, the AP curve shows variability. It is however clear that the glacial intervals AP values do not exceed 20%, except for one sample, and are consistently associated with increased Ericaceae. Interglacial AP values are clearly enhanced between 20 and 50 %, so we strongly disagree with the statement that there is no clear trend. The detailed pollen diagram in the supplementary data shows consistent abundance changes for the combined (spliced) dataset for e.g. Ericaceae, ferns, *Picea*. The variability in the *Pinus* curve is also visible in the sections that come from a single core, e.g. in MIS 95 and thus not a product of the splice. The splice is based on the high resolution GR record (verified by the dinocyst events), which provides a total of 15 tie points that produced a completely linear well tie (see Fig. 1). This figure has been added to the supplement as Fig. S4.

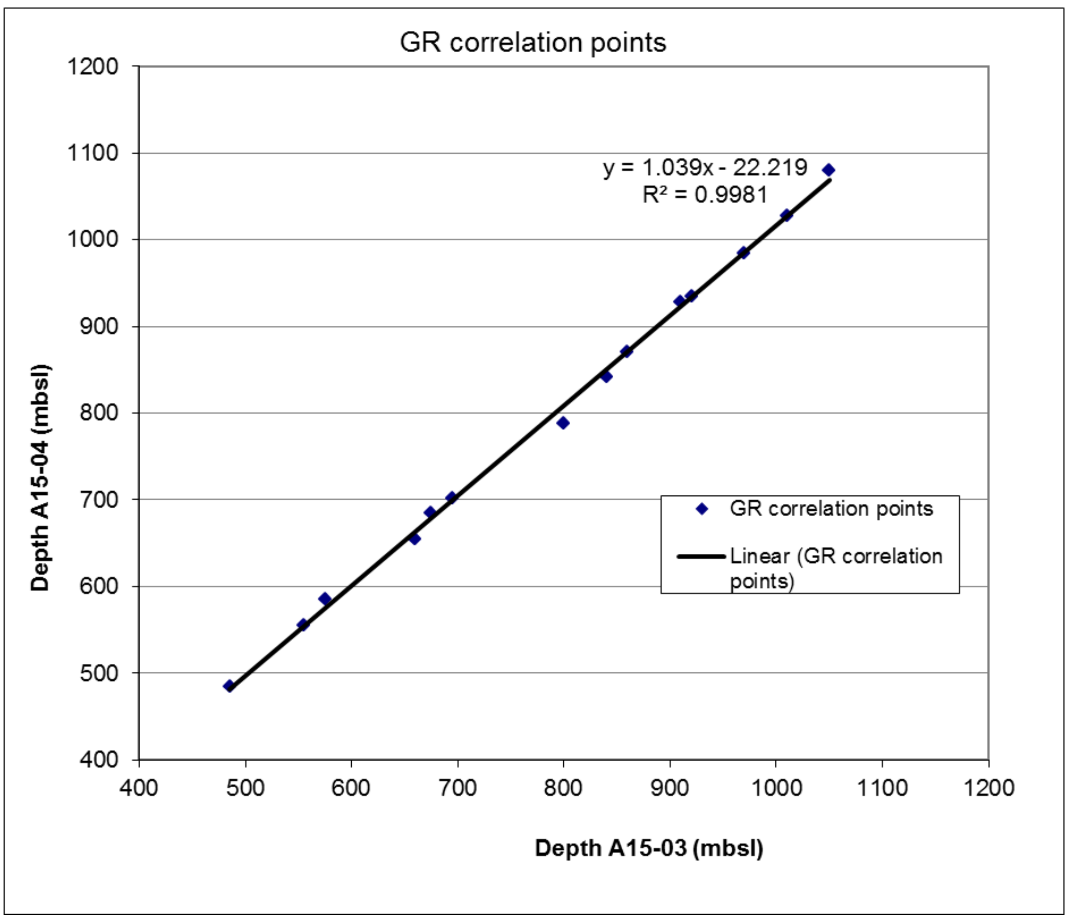


Figure 1: Well tie correlation points indicate a clear linear relation between the wells A15-3 and A15-4

Comment: The enlarged figures show that many proxies were measured at different depths and with gaps, which at least for some intervals hamper a robust identification of leads and lags.
Reply: we have indicated in figure S2 the key time lags between the palynological proxies that we use for the main interpretation of leading temperature change relative to sea level. The variable amount and resolution of samples is something we could not avoid as source material was limited and part was originally only produced for stratigraphic purposes, see also below the reply to comments 2/5.

Comment 1: An excellent age control is critical for all high-resolution studies of leads and lags. The authors should therefore provide more information on how the specific section has been dated.
Reply: Our principal analysis of lead and lags are between proxies from the same record, and so essentially independent of age models, but in any case a solid age model is desirable. See the extensive reply on the age model to reviewer S. de Schepper, including tie points and age model construction. Section 3 has been expanded with additional information on the age model construction, and Table S2 with all chronostratigraphical tie points has been added.

Comments 3&4 The multiproxy approach makes the method chapter the longest section of the entire manuscript. Consider moving parts of the methods into the Supplementary Information and focus mainly on describing what the proxies show and discuss the methodological limitations relevant to this study. The palaeoenvironmental interpretation of the record lacks depth and should be more detailed.

Reply: we do provide the general basis of the interpretations for each proxy in the methods section of the original manuscript. We have expanded the palaeoenvironmental interpretation (and changed the heading), particularly on the pollen data, referring to the general depositional setting before discussing the climatological interpretation. We have retained the present manuscript organisation as it is likely the readers are not familiar with all proxies, and hence need to detailed descriptions.

Comments 2&5 It would be very helpful if the authors could provide a conceptual model describing in detail what they would expect to see in regard to the timing of each proxy, if obliquity forcing were the major driver. The analysis of lead and lags needs to be more detailed in order to provide convincing evidence for the main conclusion. I **also struggle to see the parallel initial decrease of cold water dinocysts and Sphagnum biomarkers (first two curves) and the final decrease in T/M ratio and d18O (last two curves), which, according to the authors, followed with a delay of a few thousand years.**

Reply: Statistical analysis of the lead-lag relations is desirable but unfortunately not possible due to the limits of the record recovery and very variable sample resolution between proxies due to limited source material, hence we choose to focus on the best resolved and completely cored G-IG cycle (MIS 98-97-96). In particular, as questioned by Rev#3; Decreases in cold water dinocysts and *Sphagnum* biomarkers (first two curves) and the final decrease in T/M ratio and $d^{18}O$ are based on high values of the first two in the early half of MIS 98 (shaded interval), after which the T/M increases only in the second half of MIS98 (and correlated LR04 $d^{18}O$ signal, but this detail depends on uncertainty in the age model). The key curves to assess are the cold water dinocysts and **not** the coastal signal, which is probably causing the remarks by rev #3. Additional discussion on this topic in section 6.1 and indication of the main lead-lag relation between AP% and T/M ratio have been indicated in Fig. S2. The conceptual model has been expanded on in the introduction in combination with the more extensive literature discussion requested by reviewer Naafs, see for details the reply to that comment.

Cited references (used in replies to all reviewers)

Haug, G.H., Ganopolski, A., Sigman, D.M., Rosell-Melé, A., Swann, G.E.A., Tiedemann, R., Jaccard, S.L., et al., 2005. North Pacific seasonality and the glaciation of North America 2.7 million years ago. Nature 433, 821-825, doi: 10.1038/nature03332.

Eglinton, G., Hamilton, R.J., 1967. Leaf Epicuticular Waxes. Science 156, 1322-1335, doi: 10.1126/science.156.3780.1322.

Huuse, M., Lykke-Andersen, H., Michelsen, O., 2001. Cenozoic evolution of the eastern North Sea Basin — new evidence from high-resolution and conventional seismic data. Marine Geology 177: 243–269.

Kuhlmann, G. & Wong, T.E., 2008. Pliocene paleoenvironment evolution as interpreted from 3D-seismic data in the southern North Sea, Dutch offshore sector. Marine and Petroleum Geology 25: 173-189.

Kuhlmann, G., Pedersen, R.-B., de Boer, P., Wong, Th.E., 2004. Provenance of Pliocene sediments and paleoenvironmental change in the southern North Sea region using Sm/Nd (samarium-neodymium) provenance ages and clay mineralogy: Sedimentary Geology 171: 205-226.

Kuhlmann, G., Langereis, C.G., Munsterman, D., van Leeuwen, R.-J., Verreussel, R., Meulenkamp, J., Wong, Th.E., 2006a. Chronostratigraphy of Late Neogene sediments in the southern North Sea Basin and paleoenvironmental interpretations. Palaeogeography, Palaeoclimatology, Palaeoecology 239: 426–455.

Kuhlmann, G., Langereis, C.G., Munsterman, D., van Leeuwen, R.-J., Verreussel, R., Meulenkamp, J.E., Wong, Th.E., 2006b. Integrated chronostratigraphy of the Pliocene–Pleistocene interval and its relation to the regional stratigraphical stages in the southern North Sea region. Netherlands Journal of Geosciences - Geologie en Mijnbouw 85 (1): 19–35.

Naafs, B.D.A., Hefter, J., Stein, R., 2013. Millennial-scale ice rafting events and Hudson Strait Heinrich(-like) Events during the late Pliocene and Pleistocene: a review. Quaternary Science Reviews 80, 1-28, doi: 10.1016/j.quascirev.2013.08.014.

Noorbergen, L. J.; Lourens, L. J.; Munsterman, D. K.; Verreussel, R.M.C.H., 2015. Stable isotope stratigraphy of the early Quaternary of borehole Noordwijk, southern North Sea .Quaternary International, volume 386, pp. 148 - 157

Sinninghe Damsté, J.S., Schouten, S., Hopmans, E.C., van Duin, A.C.T., Geenevasen, J.A.J., 2002. Crenarchaeol: the characteristic core glycerol dibiphytanyl glycerol tetraether membrane lipid of cosmopolitan pelagic crenarchaeota. Journal of Lipid Research 43, 1641-1651, doi: 10.1194/jlr.M200148-JLR200.

Land-sea coupling of early Pleistocene glacial cycles in the southern North Sea exhibit dominant Northern Hemisphere forcing

Timme H. Donders[1,2], Niels A.G.M. van Helmond[3], Roel Verreussel[2], Dirk Munsterman[4], Johan Ten Veen[4], Robert P. Speijer[5], Johan W.H. Weijers[3]*, Francesca Sangiorgi[3], Francien Peterse[3], Gert-Jan Reichart[3,6], Jaap S. Sinninghe Damsté[3,6], Lucas Lourens[3], Gesa Kuhlmann[7] and Henk Brinkhuis[3,6]

[1] Department of Physical Geography, Fac. of Geosciences, Utrecht University, Heidelberglaan 2, 3584CD, Utrecht, The Netherlands.

[2] TNO - Applied Geosciences, Netherlands Organisation of Applied Scientific Research Princetonlaan 6, 3584 CB Utrecht, The Netherlands.

[3] Department of Earth Sciences, Fac. of Geosciences, Utrecht University, Heidelberglaan 2, 3584CS, Utrecht, The Netherlands.

[4] TNO - Geological Survey of the Netherlands, Netherlands Organisation of Applied Scientific Research, Princetonlaan 6, 3584 CB Utrecht, The Netherlands.

[5] Department of Earth and Environmental Sciences, KU Leuven, 3001 Heverlee, Belgium

[6] NIOZ Royal Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB, Den Burg, Texel, The Netherlands

[7] BGR - Federal Institute for Geosciences and Natural Resources, Geozentrum Hannover Stilleweg 2, D-30655 Hannover

* Currently at: Shell Global Solutions International B.V., Grasweg 31, 1031 HW, Amsterdam, The Netherlands

Correspondence to: t.h.donders@uu.nl

Abstract

We assess the disputed phase relations between forcing and climatic response in the early Pleistocene with a spliced Gelasian (~2.6 – 1.8 Ma) multi-proxy record from the southern North Sea basin. The cored sections couple climate evolution on both land and sea during the intensification of Northern Hemisphere Glaciations (NHG) in NW Europe, providing the first well-constrained stratigraphic sequence of the classic terrestrial Praetiglian Stage. Terrestrial signals were derived from the Eridanos paleoriver, a major fluvial system that contributed a large amount of freshwater to the northeast Atlantic. Due to its latitudinal position, the Eridanos catchment was likely affected by early Pleistocene NHG, leading to intermittent shutdown and reactivation of river flow and sediment transport. Here we apply organic geochemistry, palynology, carbonate isotope geochemistry, and seismostratigraphy to document both vegetation changes in the Eridanos catchment and regional surface water conditions and relate them to early Pleistocene glacial-interglacial cycles and relative sea-level changes. Paleomagnetic and palynological data provide a solid integrated timeframe that ties the obliquity cycles, expressed in the borehole geophysical logs, to Marine Isotope Stages (MIS) 103 to 92, independently confirmed by a local benthic oxygen isotope record. Marine and terrestrial palynological and organic geochemical records provide high resolution reconstructions of relative Terrestrial and Sea Surface Temperature (TT and SST), vegetation, relative sea level, and coastal influence.

Deleted: onset

Deleted: ,

Deleted:

During the prominent cold stages MIS 98 and 96, as well as MIS 94 the record indicates increased non-arboreal vegetation, and low SST and TT, and low relative sea level. During the warm stages MIS 99, 97 and 95 we infer increased stratification of the water column together with higher % arboreal vegetation, high SST and relative sea-level maxima. The early Pleistocene distinct warm-cold alterations are synchronous between land and sea, but lead the relative sea-level change by 3-8 thousand years. The record provides evidence for a

Deleted: 100,

Deleted: freshwater influx increases

Deleted: causing

Deleted:

Deleted:

dominantly NH driven cooling that leads the glacial build up and varies on obliquity timescale. Southward migration of Arctic surface water masses during glacials, indicated by cool-water dinoflagellate cyst assemblages, is furthermore relevant for the discussion on the relation between the intensity of the Atlantic meridional overturning circulation and ice sheet growth.

Deleted: and

Deleted: which

Deleted: is

Deleted: driven

Deleted: Timing of s

Deleted: relative SST

Deleted: are

Deleted: in order to identify lead-lags between forcing and response of Early Pleistocene glaciations

Keywords: Glacial-interglacial climate, palynology; organic geochemistry; obliquity, land-sea correlation, Eridanos delta, southern North Sea

1 Introduction

The build-up of extensive Northern Hemisphere (NH) land ice started around 3.6 Ma ago (Ruddiman et al. 1986; Mudelsee and Raymo, 2005; Ravelo et al., 2004; Ravelo, 2010), with stepwise intensifications between 2.7 and 2.54 Ma ago (e.g., Shackleton and Hall, 1984; Raymo et al., 1989; Haug et al., 2005; Lisiecki and Raymo, 2005; Sosdian and Rosenthal, 2009). In the North Atlantic region the first large-scale early Pleistocene glaciations, Marine Isotope Stages (MISs) 100 - 96, are marked by e.g. appearance of ice-rafted debris and southward shift of the Arctic front (see overviews in Naafs et al., 2013; Hennissen et al., 2015). On land, the glaciations led to faunal turnover (e.g. Lister, 2004; Meloro et al., 2008) and widespread vegetation changes (e.g. Zagwijn, 1992; Hooghiemstra and Ran, 1994; Svenning, 2003; Brigham-Grette et al., 2013). Many hypotheses have been put forward to explain the initiation of these NH glaciations around the Plio-Pleistocene transition interval. Causes include tectonics (Keigwin, 1982, Raymo, 1994; Haug and Tiedemann, 1998; Knies et al, 2004; Poore et al., 2006), orbital forcing dominated by obliquity-paced variability (Hays et al., 1976; Maslin et al., 1998; Raymo et al., 2006) and atmospheric CO_2 concentration decline (Pagani et al., 2010; Seki et al., 2010; Bartoli et al., 2011) driven by e.g. changes in ocean stratification that affected the biological pump (Haug et al., 1999). Changes were amplified by NH albedo changes (Lawrence et al., 2010), evaporation feedbacks (Haug et al., 2005), and possibly tropical atmospheric circulation change and breakdown of a permanent El Niño (Ravelo et al., 2004; Brierley and Fedorov, 2010; Etourneau et al., 2010).

Deleted: theories

Key aspects in this discussion are the phase relations between temperature change on land, in the surface and deep ocean, and ice sheet accretion (expressed through global eustatic sea-level lowering) in both Northern and Southern Hemispheres. According to Raymo et al.

Deleted:

(2006), early Pleistocene obliquity forcing dominated global sea level and $\delta^{18}O_{benthic}$, because precession-paced changes in the Greenland and Antarctic ice sheets cancelled each other out. In this view, climate records independent of sea-level variations should display significant variations on precession timescale. Recent tests of this hypothesis indicate that early Pleistocene precession signals are prominent in both Laurentide ice sheet meltwater pulses and iceberg-rafted debris of the East Antarctic ice sheet, and decoupled from marine $\delta^{18}O$ (Patterson et al., 2014; Shakun et al., 2016). Alternatively, variations in the total integrated summer energy, which is obliquity controlled, might be responsible for the dominant obliquity pacing of the early Pleistocene (Huybers, 2011; Tzedakis et al., 2017). The dominance of the obliquity component has been attributed to feedbacks between high-latitude insolation, albedo (sea-ice and vegetation) and ocean heat flux (Koenig et al., 2011; Tabor et al., 2014). Sosdian and Rosenthal (2009) suggested that temperature variations, based on benthic foraminifer magnesium/calcium (Mg/Ca) ratios from the North Atlantic, explain a substantial portion of the global variation in the $\delta^{18}O_{benthic}$ signal. Early Pleistocene North Atlantic climate responses were closely phased with $\delta^{18}O_{benthic}$ changes, evidenced by dominant 41-kyr variability in North American biomarker dust fluxes at IODP Site U1313 (Naafs et al., 2012), suggesting a strong common NH high latitude imprint on North Atlantic climate signals (Lawrence et al., 2010). Following this reasoning, glacial build-up should be in phase with decreases in NH sea surface temperatures (SST) and terrestrial temperatures (TT).

To explicitly test this hypothesis we perform a high-resolution multiproxy terrestrial and marine palynological, organic geochemical, and stable isotope study on a marginal marine sediment sequence from the southern North Sea (SNS) during the early Pleistocene "41 kyr-world". We investigate the leads and lags of regional marine vs. terrestrial climatic cooling

Deleted:

Formatted: Superscript

Deleted: 06

Deleted: during the

Deleted: Early Pleistocene

Deleted: ,

during MIS 102-92, and assess the local sea-level response relative to global patterns from the $\delta^{18}O_{benthic}$ stack of Lisiecki and Raymo (2005; LR04). In a dominantly, NH obliquity driven scenario, we expect the marine and terrestrial temperature proxies to be in phase on obliquity timescales with a short (less than 10 kyr) lead on sea-level variations. In addition, the record can better constrain the signature and timing of the regional continental Praetiglian stage (Van der Vlerk and Florschütz, 1953; Zagwijn, 1960) that is still widely used, although its stratigraphic position and original description are not well defined (Donders et al., 2007; Kemna and Westerhoff, 2007).

Deleted:

Deleted: but which

Deleted: definition

Deleted: is questionable

2 Geological setting

During the Neogene the epicontinental North Sea Basin was confined by landmasses except towards the northwest, where it opened into the Atlantic domain (Fig. 1) (Bijlsma, 1981; Ziegler, 1990). Water depths in the central part were approximately between 100 to 300 m as deduced from seismic geometry (Huuse et al., 2001; Overeem et al., 2001). In contrast, the recent North Sea has an average depth between 20-50 m in the south that deepens only towards the shelf edge towards 200 m in the north-west (e.g., Caston, 1979). From the present-day Baltic region a formidable river system, known as the Eridanos paleoriver, developed which built up the Southern North Sea delta across southern Scandinavia (Sørensen et al., 1997; Michelsen et al., 1998; Huuse et al., 2001; Overeem et al., 2001).

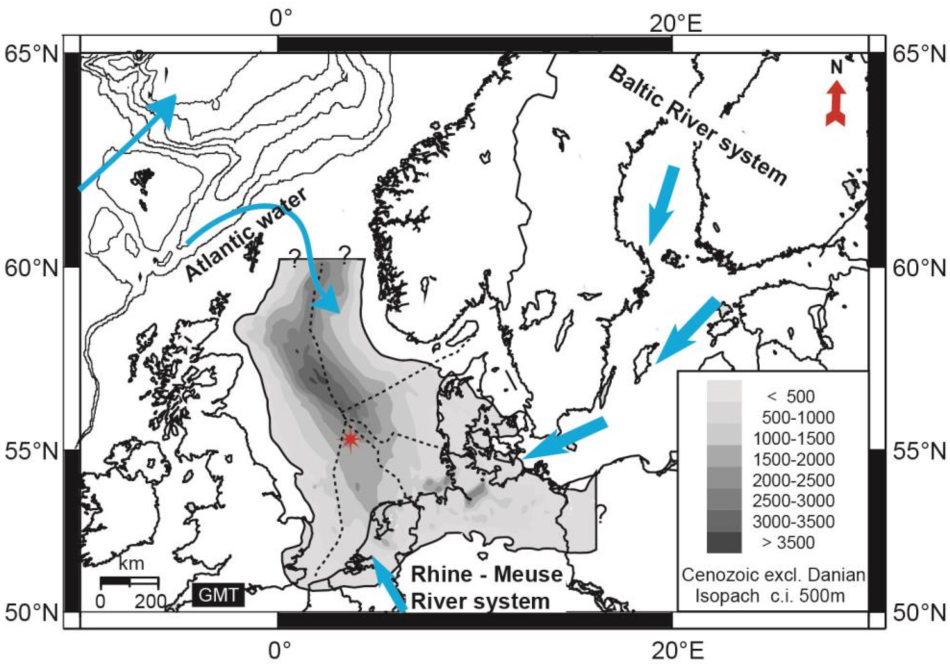


Figure 1: Geographical map of the present day North Sea region with the superimposed thickness of Cenozoic sediment infill after Ziegler (1990) and the offshore sectors (dashed lines). The reconstructed different water sources (see Gibbard and Lewin, 2016) that influenced the Pliocene and early Pleistocene North Sea hydrography, including the freshwater supply of the Baltic river system, the Rhine-Meuse river system and Atlantic surface waters are indicated with blue arrows. The location of both boreholes A15-3 (UTM X 552567.1, Y 6128751.6) and A15-4 (UTM X 557894.4, Y 6117753.5) is marked by an asterisk, see Fig. S1 for details.

Deleted: *types*

Deleted: *influencing*

Deleted: *i*

Deleted: *black*

Deleted: *the*

Deleted: *also*

This delta was characterized by an extensive distributary system that supplied large amounts of freshwater and sediment to the shelf sea during the Neogene and early Pleistocene (Overeem et al., 2001), resulting in a sediment infill of ~1500 m in the central North Sea Basin (Fig. 1). This system was fed by rainfall as well as by melt-water originating from Scandinavian glaciers (Kuhlmann et al., 2004), principally from the Baltic Shield in the east with some contribution from the south (Fig. 1) (Bijlsma, 1981; Kuhlmann, 2004). The sedimentation rates reached up to 84 cm/kyr at the studied locations (Fig. 2) (Kuhlmann et al., 2006b). Today, the continental river runoff contributes only 0.5 % of the water budget in the North Sea (Zöllmer and Irion, 1996) resulting in sedimentation rates ranging between 0.4 to 1.9 cm/kyr in the Norwegian Channel, and 0.5 - 1 cm/kyr in the southern part of the North Sea (de Haas et al., 1997).

3 Material, core description and age model

Recent exploration efforts in the SNS led to the successful recovery of cored sedimentary successions of marine isotope stages (MIS) 102-92 and continuous paleomagnetic logs (Fig. 2) (Kuhlman et al, 2006ab). For quantitative palynological and geochemical analyses, discrete sediment samples were taken from two exploration wells A15-3 and A15-4 located in the northernmost part of the Dutch offshore sector in the SNS at the Neogene sedimentary depocentre (Fig. 1). An integrated age model is available based on a multidisciplinary geochronological analysis of several boreholes within the SNS (Kuhlmann et al., 2006a,b) and dinocyst biostratigraphy. The magnetostratigraphy, core correlation and age-diagnostic dinocyst events used for this age-model are summarized in Fig. 2 and Table S1. The recovered material mainly consists of fine-grained, soft sediments (clayey to very fine sandy), sampled from cuttings, undisturbed sidewall cores and core sections (Fig. 2). Geochemical analyses were limited to the (sidewall) core intervals, while the cuttings were to increase resolution of the palynological samples, and are based on larger rock chips that have been cleaned before treatment. Clear cyclic variations in the gamma ray signal and associated seismic reflectors across the interval can be correlated across the entire basin (Kuhlman et al., 2006a; Kuhlmann and Wong, 2008; Thöle et al. 2014). Samples from the two boreholes were spliced based on the gamma-ray logs (Figs. 2, S2) and biostratigraphic events to generate a

Moved (insertion) [1]

Moved up [1]: For quantitative palynological and geochemical analyses, discrete sediment samples were taken from two exploration wells A15-3 and A15-4 located in the northernmost part of the Dutch offshore sector in the SNS at the Neogene sedimentary depocentre (Fig. 1).

composite record. The age model is mainly based on continuous paleomagnetic logging supported by discrete sample measurements and high-resolution biostratigraphy. There is evidence of small hiatuses above (~2.1 Ma) and significant hiatuses below the selected interval (within the early Pliocene and Miocene, particularly the Mid-Miocene Unconformity), which is why we excluded these intervals in this study. The position of the Gauss-Matuyama transition at the base of log unit 6 correlates to the base of MIS 103, the identification of the X-event, at the top of log unit 9, correlates to MIS 96, and the Olduvai magnetochron is present within log units 16-18 (Kuhlmann et al., 2006a,b). These ages are supported by dinocyst and several other bioevents (Table S1, updated from Kuhlmann et al., 2006a,b). Consistent with the position of the X-event, the depositional model by Kuhlmann and Wong (2008) relates the relatively coarse-grained, low gamma ray intervals to interglacials characterized by high run off. A recent independent study on high-resolution stable isotope analyses of benthic foraminifera from an onshore section in the same basin confirmed this phase relation (Noorbergen et al., 2015). Around glacial terminations, when sea level was lower but the basin remained fully marine, massive amounts of very fine-grained clayey to fine silty material were deposited in the basin, the waste-products of intense glacial erosion. During interglacials with high sea level more mixed, coarser-grained sediments characterize the deposits, also reflecting a dramatically changed hinterland, retreated glaciers, and possibly (stronger) bottom currents (Kuhlmann and Wong, 2008). Based on this phase relation, detailed magneto- and biostratigraphy, grain size measurements, and previous low resolution relative SST indices (Kuhlmann et al., 2004; Kuhlmann et al., 2006a,b), the finer grained units are consistently correlated to MIS 102 – 92. Based on this correlation of the GR inflection points to the corresponding LR04 MIS transitions, the sequence is here transferred to an age scale through interpolation with a smoothing spline function (Fig. S3).

Deleted: –

Deleted: E

Deleted:

Deleted: t

Deleted: ing

Deleted: and

Deleted: ,

Deleted: which

Deleted: the top of log unit 9

Deleted: (Kuhlmann et al., 2006a,b)

Deleted: Fig. 2

Deleted:)

Deleted: T

Deleted: -

Deleted: ultimate

Deleted: tion

Deleted: warmer periods

Deleted: -

Deleted: based on the corresponding LR04 MIS transitions (Fig. S3)

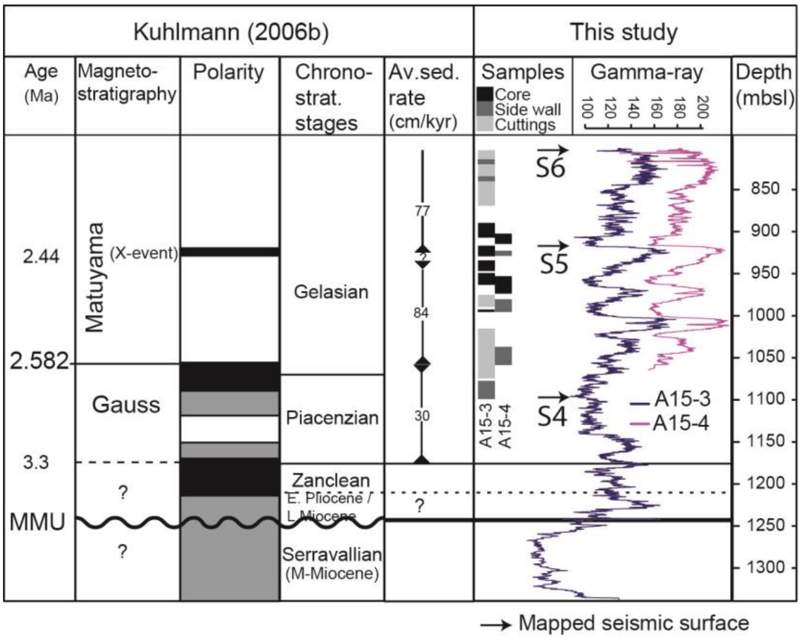


Figure 2: Chronology and mean sedimentation rates as derived from biostratigraphy and paleomagnetic data (Kuhlmann et al., 2006a,b) in combination with the gamma-ray log of A15-3 and A15-4 used in this study on a common depth scale. The position of various sample types and the mapped seismic horizons S4-6 (Fig. S1) are indicated. Material for the sidewall cores is limited, and used only for palynology and organic geochemistry. Bioevents based on Kuhlmann et al. (2006a,b) are listed in Table S1.

Deleted: *LOD/FOD: Last/First occurrence datum. LODs of* M. choanophorum *and* R. actinocoronata *are updated according to De Schepper et al. (2009)*

The regional structure and development of the delta front across the Plio-Pleistocene transition interval is very well constrained by a high-resolution regional geological model that represents the anatomy of the Eridanos (pro-) delta (Kuhlmann and Wong, 2008; Ten Veen et al., 2013). A total of 25 seismic horizons in the Plio-Pleistocene transition interval were mapped using series of publically available 2D and 3D seismic surveys across the northern part of the Dutch offshore sector. For all these surfaces the distribution of delta elements such as of topset-, foreset- and toeset-to-prodelta has been determined, resulting in zonal maps

(250 m grid size) that represent the present day geometry of the surfaces. The paleoenvironmental reconstructions are compared to these maps to constrain the regional setting and aid the interpretations.

4 Paleoenvironmental proxies and methods

4.1 Benthic oxygen and carbon isotopes ($\delta^{18}O_b$ and $\delta^{13}C_b$)

Oxygen and carbon isotopes were measured on tests of *Cassidulina teretis*, a cold water species of endobenthic foraminifera that is generally abundant in the samples and common in fine-grained sediment and relatively low salinities (Mackensen and Hald, 1988; Rosoff and Corliss, 1992). Because of their endobenthic habitat, they record isotope compositions of pore waters, which leads to somewhat reduced ($\delta^{13}C_b$) values compared to the overlying bottom waters. Since the amount of material from the sidewall cores is limited, the isotope data is only produced for the cored intervals with the principal aim to confirm the phase relationship described by Kuhlmann and Wong (2008) between facies and climate. Preservation was based on a visual inspection and assignment of a relative preservation scale of 1-5, after which the poorest 2 classes were discarded because primary calcite was nearly absent. The best preserved specimens (cat. 1) had shiny tests (original wall calcite) and showed no signs of overgrowth. Category 2 specimens showed signs of overgrowth but were not recrystallized and cat. 3 specimens were dull and overgrown by a thin layer of secondary calcite. Between ~20 and 50 µg of specimens per sample was weighed after which the isotopes of the carbonate were measured using a Kiel III device coupled to a 253 ThermoFinnigan MAT instrument. Isotope measurements were normalized to an external standard 'NBS-19' ($\delta^{18}O$ = -2.20‰, $\delta^{13}C$ = 1.95‰).

Formatted: Font: Italic

Deleted:

Deleted: Isotope data from specimens of poor to very poor preservation, due to recrystallization and dissolution, particularly in MIS 96, were rejected

4.2 Palynological proxies

In modern oceans, dinoflagellates are an important component of the (phyto-)plankton. About 15-20% of the marine dinoflagellates form an organic walled cyst (dinocyst) during the life cycle that can be preserved in sediments (Head, 1996). Dinocyst distribution in marine surface sediments has shown to reflect changes in the sea surface water properties, mostly responding to temperature (e.g., Rochon et al., 1999; Zonneveld et al., 2013). Down-core changes in dinocyst assemblages are widely used in reconstructing past environmental changes in the Quaternary (e.g., de Vernal et al., 2009), but also in the Neogene and Paleogene (e.g., Versteegh and Zonneveld, 1994; Head et al., 2004; Pross and Brinkhuis, 2005; Sluijs et al., 2005; Schreck et al., 2013; De Schepper et al., 2011; 2013; Hennissen et al., 2017).

Deleted: is a

Deleted: and successful tool for

Deleted: especially

Deleted: De

Deleted: . However, paleoecology of

Deleted: , Miocene and Pliocene fossil dinocysts has also been established in the last years

Here we use the preference of certain taxa to cold-temperate to arctic surface waters to derive sea surface temperature (SST) trends. The cumulative percentage of the dinocysts *Filisphaera microornata, Filisphaera filifera, Filisphaera sp., Habibacysta tectata and B. tepikiense* on the total dinocysts represents our cold surface water indicator (Versteegh and Zonneveld, 1994; Donders et al., 2009; De Schepper et al., 2011). Interestingly, *Bitectatodinium tepikiense*, the only extant dinocyst among our cold-water species, has been recorded from the mixing zone of polar front oceanic waters with cold brackish meltwaters from glacier ice (e.g., Bakken and Dale, 1986) and at the transition between the subpolar and temperate zones (Dale, 1996). The combined abundance of *Lingulodinium machaerophorum*, *Tuberculodinium vancampoae*, *Polysphaeridium zoharyi* and *Operculodinium israelianum* is used here to indicate coastal waters, although they generally also relate to warmer conditions. In particular, high percentages of *L. machaerophorum* are typically recorded in eutrophic coastal areas where reduced salinity and (seasonal) stratification due to runoff occur (Dale, 1996; Sangiorgi and Donders, 2004; Zonneveld et al., 2009). At present, *T. vancampoae*, *P.*

Deleted: loving

Deleted: generally warm

zoharyi and *O. israelianum* are also found in lagoonal euryhaline environments (Zonneveld et al., 2013), and hence could be used to indicate a more proximal condition relative to *L. machaerophorum* (Pross and Brinkhuis, 2005).

At present, Protoperidinioid (P) cysts are mostly formed by heterotrophic dinoflagellates and the percentage of P-cysts may be used as indicator of high eukaryotic productivity (cf. Reichart and Brinkhuis, 2003; Sangiorgi and Donders, 2004; Sluijs et al., 2005). Here we use the percentage of P-cysts (*Brigantedinium* spp., *Lejeunecysta* spp., *Trinovantedinium glorianum*, *Selenopemphix* spp., *Islandinium* spp., *Barssidinium graminosum*, and *B. wrennii*) to indicate eukaryotic productivity.

Terrestrial palynomorphs (sporomorphs) reflect variations in the vegetation on the surrounding land masses and provide information on climate variables such as continental temperatures and precipitation (e.g. Heusser and Shackleton, 1979; Donders et al., 2009; Kotthoff et al., 2014). A ratio of terrestrial to marine palynomorphs (T/M ratio) is widely used as a relative measure of distance to the coast and thereby reflects sea-level variations and depth trends in the basin (e.g. McCarthy and Mudie, 1998; Donders et al., 2009; Quaijtaal et al., 2014; Kotthoff et al., 2014). Morphological characteristics of late Neogene pollen types can, in most cases, be related to extant genera and families (Donders et al., 2009; Larsson et al., 2011; Kotthoff et al., 2014). In A15-3/4, the relatively long distance between the land and the site of deposition means that the pollen assemblage is not only a reflection of vegetation cover and climate, but includes information on the mode of transport. Assemblages with a relatively high number of taxa, including insect pollinated forms, are indicative of substantial pollen input through water transport (Whitehead, 1983), whereas wind-transported pollen typically show a low-diversity. Sediments of a location proximal to a river delta likely receive

Deleted:

Deleted:

Deleted: *Dionaeacysta* spp.,

Deleted:

Deleted: shallowing

a majority of pollen that is water-transported, while distal locations are dominated by wind-transported pollen and particularly bisaccate taxa (Hooghiemstra, 1988; Mudie and McCarthy, 1994). To exclude these effects, the percentage of arboreal pollen (AP), representing relative terrestrial temperatures, was calculated excluding bisaccate forms. The non-arboreal pollen (NAP; mainly Poaceae and also *Artemisia*, Chenopodiaceae and Asteraceae) consist only of non-aquatic herbs. High AP percentages indicate warm, moist conditions, whereas open vegetation (NAP and Ericaceae) is indicative for cooler, drier conditions consistent with a glacial climate (Faegri et al, 1989).

Deleted: separate

Deleted: y

4.3 Palynological processing

The samples were processed using standard palynological procedures (e.g., Faegri et al., 1989) involving HCl (30%) and cold HF (40%) digestion of carbonates and silicates. Residues were sieved with 15 µm mesh and treated by heavy liquid separation (ZnCl, specific gravity 2.1 g/cm^3). The slides were counted for dinocysts (with a minimum of 100 cysts) and pollen (with a preferable minimum of 200 grains). The dinocyst taxonomy follows Williams et al. (2017). Resulting counts were expressed as percent abundance of the respective terrestrial or marine groups of palynomorphs.

Deleted: dinoflagellate cysts,

4.4 Organic geochemical proxies

We applied three measures for the relative marine versus terrestrial hydrocarbon sources. The Carbon Preference Index (CPI), based on C_{25}-C_{34} *n*-alkanes, originally devised to infer thermal maturity (Bray and Evans, 1961), has high values for predominantly terrestrial plant sources (Eglinton and Hamilton, 1967; Rieley et al., 1991). Values closer to one indicate greater input from marine microorganisms and/or recycled organic matter (e.g., Kennicutt et al., 1987). Furthermore, peat mosses like *Sphagnum* are characterized by a dominance of the

Deleted: two

Deleted:

shorter C_{23} and C_{25} n-alkanes (e.g. Baas et al., 2000; Vonk and Gustafsson, 2009), whereas longer chain n-alkanes (C_{27}-C_{33}) are synthesized by higher plants (e.g., Pancost et al., 2002; Nichols et al., 2006) . Here we express the abundance of *Sphagnum* relative to higher plants as the proportion of C_{23} and C_{25} relative to the C_{27}-C_{33} odd-carbon-numbered n-alkanes. Finally, the input of soil organic matter into the marine environment was estimated using the relative abundance of branched glycerol dialkyl glycerol tetraethers (brGDGTs), produced by bacteria that are abundant in soils, versus that of the marine Thaumarchaeota-derived isoprenoid GDGT crenarchaeol (Sinninghe Damsté et al., 2002), which is quantified in the Branched and Isoprenoid Tetraether (BIT) index (Hopmans et al., 2004). The distribution of brGDGTs in soils is temperature dependent (Weijers et al., 2007; Peterse et al., 2012). Annual mean air temperatures (MAT) were reconstructed based on down-core distributional changes of brGDGT and a global soil calibration that uses both the 5- and 6-methyl isomers of the brGDGTs (MAT_{mr}; De Jonge et al., 2014a). Cyclisation of Branched Tetraethers (CBT) ratios, was shown earlier to correlate with the ambient MAT and soil pH (Weijers et al., 2007; Peterse et al., 2012). The much improved CBT' ratio (De Jonge et al., 2014a), which includes the pH dependent 6-methyl brGDGTs, is used here to reconstruct soil pH. The Total Organic Carbon (TOC) and total nitrogen measurements are used to determine the atomic C/N ratio that in coastal marine sediments can indicate the dominant source of organic matter, with marine C/N values at ~10 and terrestrial between 15 and 30 (Hedges et al., 1997).

Deleted: while the C_{25} n-alkane is characteristic for *Sphagnum* and other mosses in high arctic environments

Deleted: primarily produced by soil bacteria, versus that

Deleted: relative

Deleted: represent

Deleted: preferential

4.5 Organic geochemical processing

Organic geochemical analyses were limited to the core and sidewall core samples. For TOC determination, ~ 0.3 g of freeze dried and powdered sediment was weighed, and treated with 7.5 ml 1 M HCL to remove carbonates, followed by 4 h shaking, centrifugation and decanting. This procedure was repeated with 12 h shaking. Residues were washed twice with

Deleted: on

Deleted: For TOC determination

demineralised water dried at 40-50°C for 96 h after which weight loss was determined. ~15 to 20 mg ground sample was measured in a Fisons NA1500 NCS elemental analyzer with a normal Dumas combustion setup. Results were normalized to three external standards (BCR, atropine and acetanilide) analyzed before and after the series, and after each ten measurements. % TOC was determined by %C x decalcified weight/original weight.

For biomarker extraction ca. 10 g of sediment was freeze dried and mechanically powdered. The sediments were extracted with a Dichloromethane (DCM):Methanol (MeOH) solvent mixture (9:1, v/v, 3 times for 5 min each) using an Accelerated Solvent Extractor (ASE, Dionex 200) at 100°C and ca. 1000 psi. The resulting Total Lipid Extract (TLE) was evaporated to near dryness using a rotary evaporator under near vacuum. The TLE then was transferred to a 4 ml vial and dried under a continuous N_2 flow. A 50% split of the TLE was archived. For the working other half elemental sulfur was removed by adding activated (in 2M HCl) copper turnings to the TLE in DCM and stirring overnight. The TLE was subsequently filtered over Na_2SO_4 to remove the CuS, after which 500 ng of a C_{46} GDGT internal standard was added (Huguet et al., 2006). The resulting TLE was separated over a small column (Pasteur pipette) packed with activated Al_2O_3 (2 h at 150°C). The TLE was separated into an apolar, a ketone and a polar fraction by eluting with n-hexane : DCM 9:1 (v/v), n-hexane : DCM 1:1 (v/v) and DCM : MeOH 1:1 (v/v) solvent mixtures, respectively. The apolar fraction was analyzed by gas chromatography (GC) coupled to a flame ionization detector (FID) and gas chromatography/mass spectroscopy (GC/MS) for quantification and identification of specific biomarkers, respectively. For GC, samples were dissolved in 55 µl hexane and analyzed using a Hewlett Packard G1513A autosampler interfaced to a Hewlett Packard 6890 series Gas Chromatography system equipped with flame ionization detection, using a CP-Sil-5 fused silica capillary column (25 m x 0.32 mm, film thickness 0.12 µm),

Deleted: desulphurized

Deleted: hours

with a 0.53 mm pre-column. Temperature program: 70°C to 130°C (0 min) at 20°C/min, then to 320°C at 4°C/min (hold time 20 mins). The injection volume of the samples was 1 µl. Analyses of the apolar fractions were performed on a ThermoFinnigan Trace GC ultra, interfaced to a ThermoFinnigan Trace DSQ MS using the same temperature program, column and injection volume as for GC analysis. Alkane ratios are calculated using peak surface areas of the respective alkanes from the GC/FID chromatograms.

Deleted: ¶

Deleted: Before GC/MS analyses, 2 µg 5α-androstane standard was added to the apolar fraction for quantification purposes, assuming a similar ionization efficiency for all components.

Prior to analyses, the polar fractions, containing the GDGTs, were dissolved in *n*-hexane : propanol (99:1, v/v) and filtered over a 0.45 µm mesh PTFE filter (ø 4mm). Subsequently, analyses of the GDGTs was performed using ultra high performance liquid chromatography-mass spectrometry (UHPLC-MS) on an Agilent 1290 infinity series instrument coupled to a 6130 quadrupole MSD with settings as described in Hopmans et al. (2016). In short, separation of GDGTs was performed on two silica Waters Acquity UHPLC HEB Hilic (1.7µm, 2.1mm x 150mm) columns, preceded by a guard column of the same material. GDGTs were eluted isocratically using 82% A and 18% B for 25 mins, and then with a linear gradient to 70% A and 30% B for 25 mins, where A is *n*-hexane, and B = *n*-hexane:isopropanol. The flow rate was constant at 0.2 ml/min. The $[M+H]^+$ ions of the GDGTs were detected in selected ion monitoring mode, and quantified relative to the peak area of the C_{46} GDGT internal standard.

5 Results

5.1 Stable isotope data

The glacial-interglacial range in *Cassidulina teretis* $\delta^{18}O$ ($\delta^{18}O_b$) is ~1‰ between MIS 98 and 97, and ~1.3‰ between MIS 95 and 94, but with considerably more variation in especially MIS 95 (Fig. 3). The $\delta^{13}C_b$ data co-vary consistently with $\delta^{18}O_b$ and have a glacial-interglacial

Deleted: The *Cassidulina teretis* $\delta^{18}O$ ($\delta^{18}O_b$) confirms the relation between glacial stages and fine grained sediment as proposed by Kuhlman et al. (2006a,b), but the data are somewhat scattered (Fig. 3).

Formatted: Not Superscript/ Subscript

Deleted: e

range of ~1.1‰, besides one strongly depleted value in MIS 94 (-3.5‰). The MIS 95 $\delta^{13}C_b$ values are less variable than the $\delta^{18}O_b$, pointing to an externally forced signal in the latter. The $\delta^{18}O_b$ confirms the relation between glacial stages and fine grained sediment as proposed by Kuhlman et al. (2006a,b). Although the data are somewhat scattered, the A15-3/4 phase relation to the sediment facies is in agreement with the high-resolution stable isotope benthic foraminifera record of the onshore Noordwijk borehole (Noorbergen et al., 2015). The glacial to interglacial ranges are very similar in magnitude with those reported by Sosdian and Rosenthal (2009) for the North Atlantic, but on average lighter by ~0.5‰ ($\delta^{18}O_b$) and ~1.8‰ ($\delta^{13}C_b$).

Deleted: and

Deleted: MIS 95

Deleted: a

5.2 Palynology

Palynomorphs, including dinocysts, freshwater palynomorphs and pollen, are abundant, diverse, and well-preserved in these sediments. Striking is the dominance by conifer pollen. Angiosperm (tree) pollen are present and diverse, but low in abundance relative to conifers. During interglacials (MIS 103, 99, 97, 95, and 93) the pollen record generally shows increased and more diverse tree pollen (particularly *Picea* and *Tsuga*), and warm temperate *Osmunda* spores, whereas during glacials (MIS 102, (100), 98, 96, and 94) herb and heath pollen indicative of open landscapes are dominant (Fig S2). The % arboreal pollen (AP; excl. bisaccate pollen) summarizes these changes, showing maximum values of >40% restricted to just a part of the coarser grained interglacial intervals (Fig. 3). The percentage record of cold water dinocysts is quite scattered in some intervals but indicates generally colder conditions within glacial stages, and minima during %AP maxima (Fig. 3). After peak cold conditions and a TOC maximum (see below), but still well within the glacials, the % Protoperidinoid consistently increases. Some intervals (e.g., top of MIS 94) are marked by influxes of freshwater algae (*Pediastrum* and *Botryococcus*), indicating a strong riverine input, these data

Deleted: i

Deleted: fied

however do not indicate a clear trend. This robust in-phase pattern of glacial-interglacial variations is also reflected by high T/M ratios during glacials, indicating coastal proximity, and low T/M during (final phases of) interglacials. The Glacial-Interglacial (G-IG) variability in the T/M ratio is superimposed on a long-term increase. The coastal (warm-tolerant) dinocyst maxima are confined to the interglacial intervals and their abundance increases throughout the record. Successive increases of coastal inner neritic *Lingulodinium machaerophorum*, followed by increases in coastal lagoonal species in the youngest part, mirror the shoaling trend in the T/M ratio, which in time correspond with the gradual progradation of the Eridanos delta front (Fig. S1).

Deleted: shoaling trend

Deleted: of the marine environment

Deleted: reflect

5.3 Organic geochemical proxies

The lowest TOC contents are reached in the clay intervals, and typically range between 0.5% in glacials and 1% in interglacials (Fig. 3). Nitrogen concentrations are relatively stable resulting in C/N ratios primarily determined by organic carbon content, ranging between ~8-9 (glacials) and ~14 and 17 (interglacials). The Carbon Preference Index (CPI) is generally high, reflecting a continuous input of immature terrestrial organic matter. Minimum CPI values of ~2.8 - 2.9 are reached at the transitions from the coarser sediments to the clay intervals after which they increase to maxima of 4.5 - 5.0 in the late interglacials. The n-C_{23+25} *Sphagnum* biomarker correlates consistently with the T/M ratio, %AP, and cold water dinocysts (Fig. 3), while the variation in the CPI index is partially out of phase; it is more gradual and lags the % TOC and other signals. Generally lower Branched and Isoprenoid Tetraether (BIT) index values during interglacials (Fig. 3) indicate more marine conditions, i.e. larger distance to the coast and relatively reduced terrestrial input from the Eridanos catchment (cf. Sinninghe Damsté, 2016). As both brGDGT input (run off, soil exposure and erosion) and sea level (distance to the coast) vary across G-IG timescales, for example during

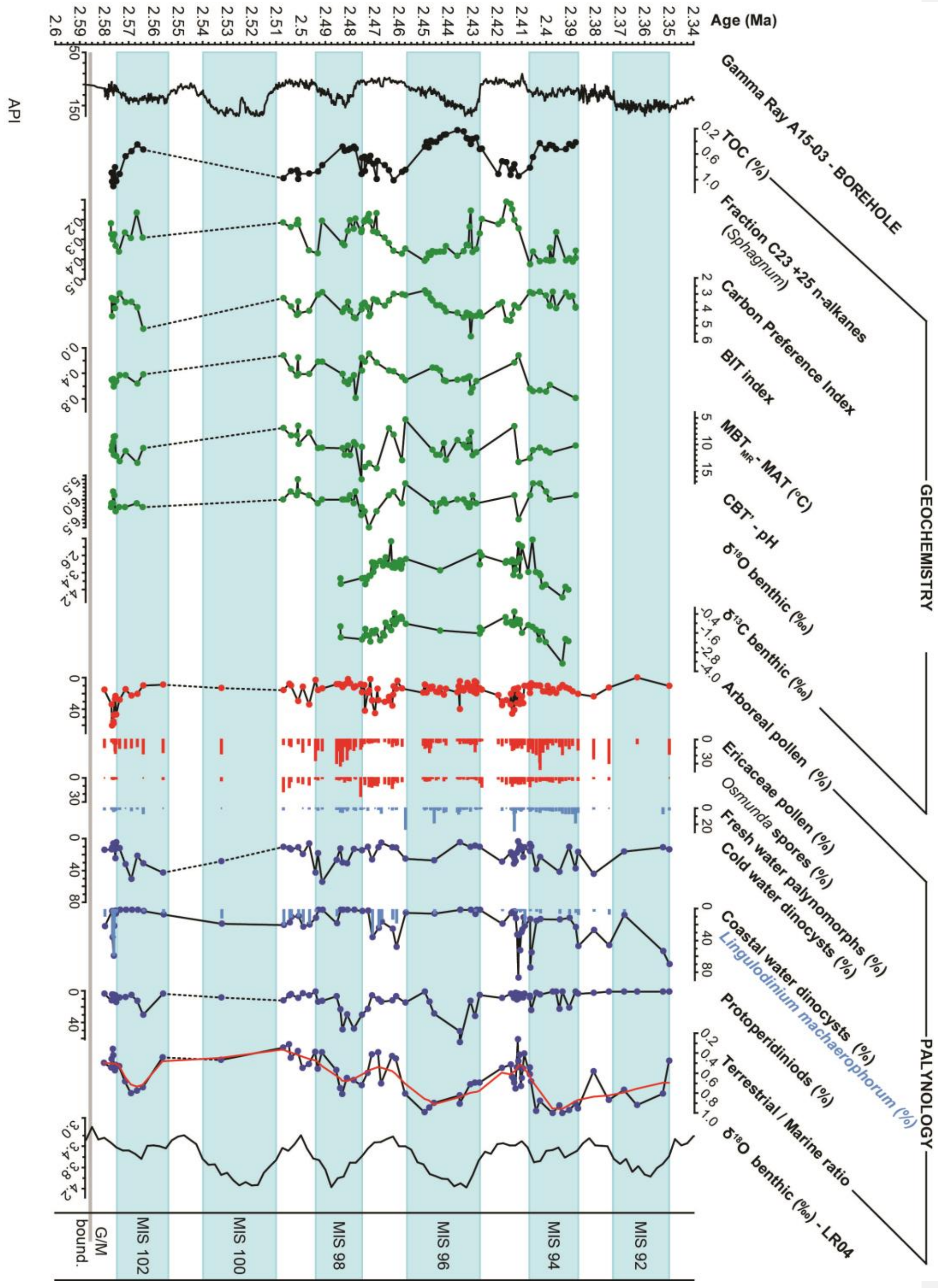
Deleted: weight % values

deglaciation and subsequent reactivation of fluvial transport (Bogaart and van Balen, 2000), the variability of the BIT index is somewhat different compared to the T/M palynomorph ratio (Fig. 3), but is generally in phase with gradual transitions along G-IG cycles. The MAT_{mr}-based temperature reconstructions vary between 5 and 17°C, reaching maximum values in MIS 97. However, in the MIS 99/98 and MIS 96/95 transitions the MAT_{mr} shows variability opposite to the identified G-IG cycles and the signal contains much high-order variability. Low values during interglacials generally coincide with low CBT'-reconstructed soil pH of <6.0 (Fig. 3).

Figure 3: spliced record of A15-3 and A15-4 showing the principal geochemical and palynological indices. Shaded blue intervals represent the identified glacial MIS delimited by the gamma-ray transitions following Kuhlmann et al. (2006a,b). Data density is dependent on type of sample as indicated in Fig. 1. Age scale is based on correlation and LOESS interpolation of the identified MIS transitions to the LR04 benthic stack (Lisiecki and Raymo, 2005) as shown in Fig S3. Data is available in Tables S2 and 3.

Deleted: *organic*

Deleted: *2*


Age (Ma)
Gamma Ray A15-03 - BOREHOLE
TOC (%)
Fraction C23 +25 n-alkanes (Sphagnum)
Carbon Preference Index
BIT index
MBT'MR - MAT (°C)
CBT' - pH
δ18O benthic (‰)
δ13C benthic (‰)
Arboreal pollen (%)
Ericaceae pollen (%)
Osmunda spores (%)
Fresh water palynomorphs (%)
Cold water dinocysts (%)
Coastal water dinocysts (%)
Lingulodinium machaerophorum (%)
Protoperidiniods (%)
Terrestrial / Marine ratio
δ18O benthic (‰) - LR04
GEOCHEMISTRY
PALYNOLOGY
API
G/M bound.
MIS 102
MIS 100
MIS 98
MIS 96
MIS 94
MIS 92

6 Discussion

6.1 Paleoenvironmental setting and climate signals

The source area study by Kuhlmann et al. (2004) indicated the Eridanos paleoriver as the principal source of the terrestrial deposits. The detailed seismic interpretations indeed show the advancing Eridanos delta front from the east toward the sites (Fig. S1). This trend is captured by the long-term increases in the T/M ratio and the proportion of coastal dinocysts (Fig. 3). In- or exclusion of bisaccate pollen in the T/M index (Fig. S5), the component most sensitive to differential transport processes, indicates no direct influence of differential transport on the T/M ratio. During MIS 103, 99, 97, 95, and 93 the AP% increases indicate generally warmer and more humid conditions than during MIS 102, 98, 96, and 94 (Fig. 3). The cold-water temperature signal based on dinocysts is more variable than the terrestrial cooling signals from the AP%. Pollen assemblages represent mean standing vegetation in the catchment, and also depend on dominant circulation patterns and short-term climate variations (Donders et al., 2009). Due to exclusion of bisaccate pollen, the %AP is generally low but eliminates any climate signal bias due to the direct effect of sea level changes (Donders et al., 2009; Kotthoff et al., 2014). In the record there are small but significant time lags between proxies, which have important implications for explaining the forcing of G-IG cycles. In the best constrained MIS transition (98 to 97), the G-IG transition is seen first in decreases of the cold water dinocysts and n-C_{23+25} n-alkanes predominantly derived from *Sphagnum*. Subsequently the BIT decreases, and MAT_{mr} and the %AP increase, and finally the $\delta^{18}O_b$ and T/M ratio decrease with a lag of a few thousand years (Fig. 3). Changes in the CPI record are more gradual, but generally in line with T/M. The AP% and T/M proxies have the most extensive record and detailed analysis of several glacial-interglacial transitions shows that the declines in AP% consistently lead the T/M increases by 3-8 kyr based on the present age model (Fig. S2). The T/M ratio variability corresponds well to the LR04 benthic stack (Fig.

Deleted: A
Deleted: pollen
Deleted: record
Deleted: s
Deleted: as derived from pollen
Deleted: s
Deleted: s
Deleted: .
Deleted: However, in this way we
Deleted: excluded
Deleted: the
Deleted: Given the average sample distance, on a glacial-interglacial time scale no significant phase differences between the terrestrial and the marine signal appear.
Deleted: and will further be explained in more detail
Deleted: biomarkers
Deleted: ,
Deleted: s
Formatted: Subscript
Deleted: s
Deleted: in
Deleted: s
Deleted: that
Deleted: by
Deleted: The
Deleted: signal
Deleted: is
Moved (insertion) [2]

3), which is primarily an obliquity signal. Within the constraints of the sample availability, our record captures the approximate symmetry between glaciation and deglaciation typical of the Early Pleistocene (Lisiecki and Raymo, 2005).

The high variability and strongly depleted values in $\delta^{18}O_b$ during MIS 95 occur during peak coastal dinocyst abundances, suggesting high run off during maximum warming phases. During cold water dinocysts maxima, the high abundance of Protoperidinioids indicates high nutrient input, and productive spring/summer blooms, which point to strong seasonal temperature variations. This productivity signal markedly weakens in MIS 94 and 92 and the gradual T/M increase is consistent with the basin infill and gradually approaching shelf-edge delta (Fig. S1). As Protoperidinioid minima generally occur during TOC maxima there is no indication for a preservation overprint since selective degradation typically lowers relative abundances of these P-cysts (Gray et al., 2017). Combined, the high TOC and CPI values, coastal and stratified water conditions, and intervals of depleted $\delta^{18}O_b$ document increased Eridanos run-off during interglacials. These suggest a primarily terrestrial organic matter source that, based on mineral provenance studies (Kuhlmann et al., 2004) and high conifer pollen abundance documented here, likely originated from the Fennoscandian Shield. The fine-grained material during cold phases is probably transported by meltwater during summer from local glaciers that developed since the late Pliocene at the surrounding Scandinavian mainland (Mangerud et al., 1996; Kuhlmann et al., 2004).

6.2 Temperature reconstruction and brGDGT input

Whereas the BIT index reflects the G-IG cycles consistently, the MAT_{mr} record, which is based on GDGTs, has a variable phase relation with the G-IG cycles and high variability. The

Deleted: phases

Deleted: of the P-cysts

Formatted: Font: Italic

Deleted: also

Deleted: br

use of MAT_{mr} in coastal marine sediments is based on the assumption that river-deposited brGDGTs reflect an integrated signal of the catchment area. As the Eridanos system is reactivated following glacials, glacial soils containing brGDGT are likely eroded causing a mixed signal of glacial and interglacial material. The lowest MAT_{mr} and highest variability is indeed observed during periods of deposition of sediments with a higher TOC content and minima of CBT'-derived pH below 6 (Fig. 3), consistent with increased erosion of acidic glacial (peat) soil. Additional analysis of the apolar fractions in part of the samples reveals during these periods a relatively high abundance of the C_{31} 17α, 21β-homohopanes, which in immature soils indicates a significant input of acidic peat (Pancost et al., 2002). This suggests that the variability in the MAT_{mr} record is not fully reliable due to (variable) erosion of glacial soils or peats. Alternatively, the terrestrial brGDGT signal may be altered by a contribution of brGDGTs produced in the marine realm. BrGDGTs were initially believed to be solely produced in soils, but emerging evidence suggests that brGDGTs are also produced in the river itself (e.g., Zell et al., 2013; De Jonge et al., 2014b) and in the coastal marine sediments (e.g., Peterse et al., 2009; Sinninghe Damsté, 2016 Based on the modern system, the degree of cyclisation of tetramethylated brGDGTs ($\#rings_{tetra}$) has been proposed to identify a possible in situ overprint (Sinninghe Damsté, 2016). The $\#rings_{tetra}$ in this sediment core is <0.37, which is well below the suggested threshold of 0.7, and thus suggests that the brGDGTs are primarily soil-derived. However, a ternary diagram of the brGDGT distribution show some offset to the global soil calibration that decreases with increasing BIT values (Fig. S6), pointing to some influence of in-situ GDGT production when terrestrial input is relatively low. Finally, selective preservation in the catchment and during fluvial transport may have affected the brGDGT signal, although experimental evidence on fluvial transport processes indicates that these do not significantly affect initial soil-brGDGT compositions (Peterse et al., 2015).

Deleted: input

Deleted: -

Deleted: during

Deleted: transport

Deleted: environment

Deleted:), which, points to significant terrestrial contributions in our record.

Deleted: However,

Deleted: t

Deleted: higher

Moved up [2]: The T/M ratio variability corresponds well to the LR04 benthic stack (Fig. 3), which is primarily an obliquity signal. Within the constraints of the sample availability, our record captures the approximate symmetry between glaciation and deglaciation typical of the Early Pleistocene (Lisiecki and Raymo, 2005).

6.3 Implications for the intensification of Northern Hemisphere glaciations

The classic Milankovitch model predicts that global ice volume is forced by high northern summer insolation (e.g. Hays et al., 1976). Raymo et al. (2006) suggested an opposite response of ice sheets on both hemispheres due to precession forcing, cancelling out the signal and amplifying obliquity in the early Pleistocene. That hypothesis predicts that regional climate records on both hemispheres should contain a precession component that is not visible in the sea level and deep sea $\delta^{18}O_b$ record, and is supported by evidence from Laurentide Ice Sheet melt and iceberg-rafted debris of the East Antarctic ice sheet (Patterson et al., 2014; Shakun et al., 2016). Alternatively, a dominantly obliquity forced G-IC cycle is supported by a significant temperature component in the temperature deep sea $\delta^{18}O_b$ record (Sosdian and Rosenthal, 2009) and dominant 41-kyr variability in North American biomarker dust fluxes. Our results show that the regional NH climate on both land and sea surface vary on the same timescale as the local relative sea level which, with the best possible age information so far (Fig. S3), mirrors the global LR04 $\delta^{18}O_b$ record. The temperature changes lead the local sea level by 3-8 kyr, which is consistent with a NH obliquity forcing scenario as cooling would precede ice buildup and sea level change. Contrary to the model proposed by Raymo et al. (2006), this suggests that the NH obliquity forcing is the primary driver for the glacial-interglacial in the early Pleistocene, although we cannot exclude precession forcing as a contributing factor. Various studies indicate the importance of gradual CO_2 decline in the intensification of NHG (Kürschner et al., 1996; Seki et al., 2010; Bartoli et al., 2011) combined with the threshold effects of ice albedo (Lawrence et al., 2010; Etourneau et al., 2010) and land cover changes (Koenig et al., 2011). Simulations of four coupled 3-D ice models indicate that Antarctic ice volume increases respond primarily to sea-level lowering, while Eurasian and North American ice sheet growth is initiated by temperature decrease (de

Deleted: *2*

Deleted: *onset*

Deleted: suggestion

Formatted: English (U.S.)

Deleted: ies in concert

Deleted: with

Deleted: is consistent

Deleted: with

Deleted:

Deleted: The small lead of the temperature proxies over the local sea level further supports the NH obliquity forcing scenario as cooling would precede ice buildup

Boer et al., 2012). The latter dominate the eustatic sea-level variations during glacials. Our observations agree with the modelled temperature sensitivity of NH ice sheet growth. The dominant obliquity signal further suggests a seasonal aspect of the climate forcing. The combination of high summer productivity, based on increased Protoperidiniod dinocysts, and increased proportions of cold dinocysts during the glacials in the SNS record indicate a strong seasonal cycle. This confirms similar results from the North Atlantic (Hennissen et al., 2015) and is consistent with an obliquity-driven glacial-interglacial signal in a mid-latitudinal setting, likely promoting meridional humidity transport and ice buildup.

The southward migration of Arctic surface water masses indicated by increases in cold water dinocysts (Fig. 3) is furthermore relevant for understanding the relation between the Atlantic meridional overturning circulation (AMOC) intensity and ice sheet growth (e.g. Bartoli et al., 2005; Naafs et al, 2010). Mid-Pliocene increased heat transport and subsequent decrease during NHG due to AMOC intensity changes has been invoked from many proxy records but is difficult to sustain in models (Zhang et al., 2013). Our results indicate that the NW European early Pleistocene climate experienced significant cooling in all temperature-sensitive proxies during sea-level lowstands, which is consistent with southward displacement of the Arctic front and decreased AMOC (Naafs et al., 2010). The MAT_{mr} indicates a 4-6 ^{o}C glacial-interglacial amplitude although the timing is offset relative to the other proxies. The data-model mismatch in AMOC changes might be due to dynamic feedbacks in vegetation or (sea-) ice (Koenig et al., 2011; de Boer et al., 2012) that are prescribed variables in the model comparison by Zhang et al. (2013).

Deleted: severe

In addition, our SNS record provides a well-dated early Pleistocene Glacial-Interglacial succession integrating marine and terrestrial signals improving on the classic terrestrial Praetiglian stage. While conceptually valid, the earliest Pleistocene glacial stages defined in the continental succession of the SE Netherlands (Van der Vlerk and Florschütz, 1953; Zagwijn, 1960) and currently considered text book knowledge, are highly incomplete and locally varied (Donders et al., 2007). This shallow marine SNS record provides a much more suitable reflection of large-scale transitions and trends in NW Europe and merits further development by complete recovery of the sequence in a scientific drilling project (Westerhoff et al., 2016).

7 Conclusions

The independently dated late Pliocene-early Pleistocene sedimentary succession of the southern North Sea Basin provides a record that straddles the intensification of Northern Hemisphere Glaciation and the subsequent climate fluctuations in a shallow marine setting in great detail. The intensification of the glaciation and the correlation to marine isotope stages 103 to 92, including the conspicuous first Pleistocene glacial stages 98, 96 and 94, is well expressed in the marine and terrestrial palynomorph and organic biomarker records of the southern North Sea. The independent relative sea- and land-based temperature records show clearly coeval (at this resolution) expression of glacial-interglacial and sea-level cycles that are well-correlated to the LR04 benthic stack. Critically, both the biomarker signals, %AP, and cold water dinocyst variations show consistent in-phase variability on obliquity time scales, leading sea-level changes by 3-8 kyr, which supports a dominantly direct NH insolation control over early Pleistocene glaciations. Based on this integrated record, NH obliquity forcing is the primary driver for the glacial-interglacial cycles in the early

Deleted: onset

Deleted: onset

Deleted: 100,

Deleted: to

Deleted: 6 representing the first cold Pleistocene stages

Deleted: cold and warm

Deleted:

Deleted:

Pleistocene. Furthermore, our findings support the hypothesis of temperature sensitivity of NH ice sheet growth. The interglacials are characterized by (seasonally) stratified waters and/or near-shore conditions as glacial-interglacial cycles became more expressive and the Eridanos delta progressed into the region. The strong seasonality at mid-latitudes point to a vigorous hydrological cycling that should be considered as a potential factor in ice sheet formation in further investigations.

Deleted: theory

8 Author contributions

THD, HB and GK designed the research. NvH carried out the geochemical analyses under supervision of JW, GJR, FP and JSSD. RV, DM and THD carried out the palynological analyses and interpreted the data together with FS. LL and RPS provided stable isotope data on benthic foraminifera. JtV provided seismic interpretations. THD integrated the data and wrote the paper with contributions from all authors.

Deleted: from GJR, JSSD, JW and FP

9 Acknowledgements

We are grateful the constructive comments of Stijn de Schepper and David Naafs and an anonymous referee that helped to improve the manuscript. We gratefully acknowledge the support in providing the offshore samples to this study and permission to publish by Wintershall Noordzee B.V., and project support by partners Chevron Exploration and Production Netherlands B.V., Total E&P Nederland B.V., Dana Petroleum Netherlands B.V., Oranje-Nassau Energie B.V., and Energie Beheer Nederland (EBN). Arnold van Dijk is thanked for running C/N and stable isotope analyses, and Giovanni Dammers for processing palynological samples. The work was partly supported by funding from the Netherlands Earth

System Science Center (NESSC) through a gravitation grant (NWO 024.002.001) from the Dutch Ministry for Education, Culture and Science to JSSD, GJR, and LL.

10 References

Baas, M., Pancost, R., van Geel, B. Sinninghe Damsté, J.S., 2000. A comparative study of lipids in *Sphagnum* species. Organic Geochemistry 31: 535-539. https://doi.org/10.1016/S0146-6380(00)00037-1

Bakken, K. and Dale, B., 1986. Dinoflagellate cysts in Upper Quaternary sediments from southwestern Norway and potential correlations with the oceanic record. Boreas 15: 185-190. DOI: 10.1111/j.1502-3885.1986.tb00082.x

Bartoli, G., Hönisch, B., Zeebe, R.E., 2011. Atmospheric CO_2 decline during the Pliocene intensification of Northern Hemisphere glaciations. Paleoceanography 26, PA4213. http://dx.doi.org/10.1029/2010PA002055.

Bijlsma, S., 1981. Fluvial sedimentation from the Fennoscandian area into the Northwest European Basin during the Late Cenozoic. Geologie en Mijnbouw 60: 337-345.

Bogaart, P.W., van Balen, R.T., 2000. Numerical modeling of the response of alluvial rivers to Quaternary climate change. Global and Planetary Change 27: 147-163. https://doi.org/10.1016/S0921-8181(01)00064-9

Bray, E.E., and Evans, E.D., 1961. Distribution of n-parrafins as a clue to recognition of source beds. Geochimica et Cosmochimica Acta 22: 2-15. https://doi.org/10.1016/0016-7037(61)90069-2

Brierley, C.M., and Fedorov, A.V., 2010. Relative importance of meridional and zonal sea surface temperature gradients for the onset of the ice ages and Pliocene - Pleistocene climate evolution. Paleoceanography 25: PA2214. DOI:10.1029/2009PA001809.

Brigham-Grette, J, Melles, M., Minyuk, P.S., Andreev, A.A., Tarasov, P.E., DeConto, R.M., König, S. Nowaczyk, N.R., Wennrich, V., Rosén, P., Haltia-Hovi, E., Cook, T.L., Gebhardt, C., Meyer-Jacob, C., Snyder, J.A., Herzschuh, U., 2013. Pliocene warmth, polar amplification, and stepped Pleistocene cooling recorded in NE Arctic Russia. Science 340: 1421-1427. DOI: 10.1126/science.1233137

Caston, V.N.D., 1979. The Quaternary sediments of the North Sea. In: Banner, F.T., Collins, M.B., Massie, K.S. (Eds.), The north-west European shelf seas: the sea bed and the sea in motion. I. Geology and Sedimentology, Elsevier Oceanographic Series 24A, p. 195-270.

Formatted: Dutch (Netherlands)

Formatted: English (U.S.)

Formatted: English (U.S.)

Dale, B., 1996. Dinoflagellate cyst ecology: modelling and geological applications. In: J.M.G. Jansonius, D.C. (Editor), Palynology: Principles and Application, vol. 3. American Association of Stratigraphic Palynologists Foundation, College Station, TX: 1249-1275.

de Boer, B., van de Wal, R.S.W., Lourens, L.J., Bintanja, R., Reerink, T.J., 2012. A continuous simulation of global ice volume over the past 1 million years with 3-D ice-sheet models. Climate Dynamics 41, 1365. doi:10.1007/s00382-012-1562-2

de Haas, H., Boer, W., van Weering, T.C.E., 1997. Recent sediment and organic carbon burial in a shelf sea; the North Sea. Marine Geology 144, 131–146. https://doi.org/10.1016/S0025-3227(97)00082-0.

De Jonge, C,.Hopmans, A.C, Zell, C.I., Kim, J.-H., Schouten, S., Sinninghe Damsté, J.S., 2014a. Occurrence and abundance of 6-methyl branched glycerol dialkyl glycerol tetraethers in soils: Implications for palaeoclimate reconstruction. Geochimica et Cosmochimica Acta 141: 97-112. https://doi.org/10.1016/j.gca.2014.06.013.

De Jonge. C., Stadnitskaia, A., Hopmans, E.C., Cherkashov, G., Fedotov, A. and Sinninghe Damsté, J.S., 2014b. In-situ produced branched glycerol dialkyl glycerol tetraethers in suspended particulate matter from the Yenisei River, Eastern Siberia. Geochimica et Cosmochimica Acta 125: 476-491. https://doi.org/10.1016/j.gca.2014.06.013.

De Schepper, S., Head, M.J., and Louwye, S., 2009. Pliocene dinoflagellate cyst stratigraphy, palaeoecology and sequence stratigraphy of the Tunnel-Canal Dock, Belgium, Geological Magazine 146: 92-112. DOI: 10.1017/S0016756808005438.

De Schepper, S., Fischer, E.I., Groeneveld, J., Head, M.J., Matthiessen, J., 2011. Deciphering the palaeoecology of Late Pliocene and Early Pleistocene dinoflagellate cysts. Palaeogeography, Palaeoclimatology, Palaeoecology 309: 17–32. https://doi.org/10.1016/j.palaeo.2011.04.020.

De Schepper, S., Groeneveld, J., Naafs, B.D.A., Van Renterghem, C., Hennissen, J., Head, M.J., Louwye, S., Fabian, K., 2013. Northern Hemisphere glaciation during the globally warm early Late Pliocene. PLoS ONE 8 (12), e81508. http://dx.doi.org/10.1371/journal.pone.0081508.

de Vernal, A., 2009. Marine palynology and its use for studying nearshore environments, From Deep-Sea to Coastal Zones: Methods – Techniques for Studying Paleoenvironments, IOP Conference Series: Earth and Environmental Science, 5, 012002.DOI:10.1088/1755-1307/5/1/012002.

Donders, T.H., Kloosterboer-van Hoeve, M.L., Westerhoff, W., Verreussel, R.H.C.M. & Lotter, A.F., 2007. Late Neogene continental stages in NW Europe revisited. Earth-Science Reviews 85: 161-186. https://doi.org/10.1016/j.earscirev.2007.06.004.

Donders, T.H., Weijers, J.W.H., Munsterman, D.K., Kloosterboer-van Hoeve, M.L., Buckles, L.K., Pancost, R.D., Schouten, S., Sinninghe Damsté, J.S. & Brinkhuis, H., 2009. Strong

Formatted: Dutch (Netherlands)

climate coupling of terrestrial and marine environments in the Miocene of northwest Europe. Earth and Planetary Science Letters 281 (3-4): 215-225. https://doi.org/10.1016/j.epsl.2009.02.034.

Eglinton, G., Hamilton, R.J., 1967. Leaf epicuticular waxes. Science 156, 1322-1335. DOI: 10.1126/science.156.3780.1322.

Etourneau, J., Schneider, R., Blanz, T., Martinez, P., 2010. Intensification of the Walker and Hadley atmospheric circulations during the Pliocene-Pleistocene climate transition. Earth and Planetary Science Letters 297: 103-110. http://dx.doi.org/10.1016/j.epsl.2010.06.010.

Faegri, K., Iversen, J., Kaland, P.E., Krzywinski, K., 1989. Text book of pollen analysis, IV Edition. The Blackburn Press, 328 pp.

Gibbard P.L., and Lewin, J., 2016. Filling the North Sea Basin: Cenozoic sediment sources and river styles. Geologica Belgica 19: 201-217. http://dx.doi.org/10.20341/gb.2015.017

Gray, D. D., Zonneveld, K.A., & Versteegh, G.J., 2017. Species-specific sensitivity of dinoflagellate cysts to aerobic degradation: A five-year natural exposure experiment. Review of Palaeobotany and Palynology 247, 175-187. DOI: 10.1016/j.revpalbo.2017.09.002

Head, M.J., 1996. Modern dinoflagellate cysts and their biological affinities. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principles and Application, vol. 3. American Association of Stratigraphic Palynologists Foundation, College Station, TX, pp. 1197-1248.

Haug, G.H. and Tiedemann, R., 1998. Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. Nature 393 (6686): 673- 676. DOI:10.1038/31447.

Haug, G.H., Sigman, D.M., Tiedemann, R., Pedersen, T.F. & Sarnthein, M., 1999. Onset of permanent stratification in the subarctic Pacific Ocean. Nature 40: 779–782. DOI:10.1038/44550

Haug, G.H., Ganopolski, A., Sigman, D.M., Rosell-Mele, A., Swann, G. E. A, Tiedemann, R., Jaccard, S. L., Bollmann, J., Maslin, M.A., Leng, M.J. and Eglinton, G., 2005. North Pacific seasonality and the glaciation of North America 2.7 million years ago. Nature 433: 821-825. DOI: 10.1038/nature03332.

Hays, J. D., Imbrie, J. & Shackleton, N. J., 1976. Variations in the Earth's orbit: pacemaker of the ice ages. Science 194; 1121–1132. doi: 10.1126/science.194.4270.1121.

Head, M.J., Riding, J.B., Eidvin, T., Chadwick, R.A., 2004. Palynological and foraminiferal biostratigraphy of (Upper Pliocene) Nordland Group mudstones at Sleipner, northern North Sea. Marine and Petroleum Geology 21:277-297. http://dx.doi.org/10.1016/j.marpetgeo.2003.12.002.

Hedges, J.I., Keil, R.G., & Benner, R., 1997. What happens to terrestrial organic matter in the ocean? Organic Geochemistry 27: 195-212. https://doi.org/10.1016/S0146-6380(97)00066-1

Hennissen, J.A.I., Head, M.J., De Schepper, S., Groeneveld, J., 2015. Increased seasonality during the intensification of Northern Hemisphere glaciation at the Pliocene-Pleistocene transition ~2.6 Ma. Quaternary Science Reviews 129: 321–332. https://doi.org/10.1016/j.quascirev.2015.10.010.

Hennissen, J.A.I., Head, M.J., De Schepper, S., Groeneveld, J., 2017. Dinoflagellate cyst paleoecology during the Pliocene–Pleistocene climatic transition in the North Atlantic. Palaeogeography, Palaeoclimatology, Palaeoecology 470: 81-108. https://doi.org/10.1016/j.palaeo.2016.12.023.

Heusser, L.E., and Shackleton, N.J., 1979. Direct marine-continental correlation: 150,000-year oxygen isotope-pollen record from the North Pacific. Science 204: 837-839. DOI: 10.1126/science.204.4395.837.

Hooghiemstra, H., 1988. Palynological records from Northwest African marine sediments: a general outline of the interpretation of the pollen signal. Philosophical Transactions of the Royal Society of London, Series B Biological Sciences 318 (1191): 431–449. DOI: 10.1098/rstb.1988.0018.

Hooghiemstra, H., Ran, E.T.H., 1994. Late Pliocene-Pleistocene high resolution pollen sequence of Colombia: An overview of climatic change. Quaternary International, 21: 63-80

Hopmans, E.C., Weijers, J.W.H., Schefuss, E., Herfort, L., Sinninghe Damsté, J.S., Schouten, S., 2004. A novel proxy for terrestrial organic matter in sediments based on branched and isoprenoid tetraether lipids. Earth and Planetary Science Letters 24: 107–116. https://doi.org/10.1016/j.epsl.2004.05.012.

Hopmans, E.C., Schouten, S., Sinninghe Damsté, J.S., 2016. The effect of improved chromatography on GDGT-based palaeoproxies. Organic Geochemistry 93: 1-6. https://doi.org/10.1016/j.orggeochem.2015.12.006.

Huuse, M., Lykke-Andersen, H., Michelsen, O., 2001. Cenozoic evolution of the eastern North Sea Basin – new evidence from high-resolution and conventional seismic data. Marine Geology 177: 243-269.

Huybers, P., 2011. Combined obliquity and precession pacing of late Pleistocene deglaciations. Nature 480: 229–232. DOI:10.1038/nature10626.

Keigwin, L. D., 1982. Isotope paleoceanography of the Caribbean and east Pacific: role of Panama uplift in late Neogene time. Science 217: 350–353. DOI: 10.1126/science.217.4557.350.

Kemna, H.A., Westerhoff, W.E., 2007. Remarks on the palynology-based chronostratigraphic subdivision of the Pliocene terrestrial deposits in NW-Europe. Quaternary International 164–165: 184–196. https://doi.org/10.1016/j.quaint.2006.10.017.

Formatted: English (U.S.)

Kennicutt II, M.C., Barker, C., Brooks, J.M., DeFreitas, D.A., Zhu, G.H., 1987. Selected organic matter source indicators in the Orinoco, Nile and Changjiang deltas. Organic Geochemistry 11: 41-51. https://doi.org/10.1016/0146-6380(87)90050-7.

Knies, J., Cabedo-Sanz, P., Belt, S.T., Baranwal, S., Fietz, S., Rosell-Mele, A., 2014. The emergence of modern sea ice cover in the Arctic Ocean. Nature Communications 5: http://dx.doi.org/10.1038/ncomms6608.

Koenig, S.J., DeConto, R.M. & Pollard, D., 2011. Late Pliocene to Pleistocene sensitivity of the Greenland Ice Sheet in response to external forcing and internal feedbacks. Climate Dynamics 37: 1247. DOI:10.1007/s00382-011-1050-0.

Kotthoff, U., Greenwood, D., McCarthy, F., Müller-Navarra, K., Prader, S., Hesselbo, S., 2014. Late Eocene to middle Miocene (33 to 13 million years ago) vegetation and climate development on the North American Atlantic Coastal Plain (IODP Expedition 313, Site M0027). Climate of the Past 10: 1523-1539. https://doi.org/10.5194/cp-10-1523-2014.

Kuhlmann, G. & Wong, T.E., 2008. Pliocene paleoenvironment evolution as interpreted from 3D-seismic data in the southern North Sea, Dutch offshore sector. Marine and Petroleum Geology 25: 173-189. https://doi.org/10.1016/j.marpetgeo.2007.05.009.

Kuhlmann, G., Pedersen, R.-B., de Boer, P., Wong, T.E., 2004. Provenance of Pliocene sediments and paleoenvironmental change in the southern North Sea region using Sm/Nd (samarium-neodymium) provenance ages and clay mineralogy. Sedimentary Geology 171: 205-226. DOI: 10.1016/j.sedgeo.2004.05.016.

Kuhlmann, G., Langereis, C.G., Munsterman, D., van Leeuwen, R.-J., Verreussel, R., Meulenkamp, J., Wong, T.E., 2006a. Chronostratigraphy of Late Neogene sediments in the southern North Sea Basin and paleoenvironmental interpretations. Palaeogeography, Palaeoclimatology, Palaeoecology 239: 426–455. https://doi.org/10.1016/j.palaeo.2006.02.004.

Kuhlmann, G., Langereis, C.G., Munsterman, D., van Leeuwen, R.-J., Verreussel, R., Meulenkamp, J.E., Wong, Th.E., 2006b. Integrated chronostratigraphy of the Pliocene–Pleistocene interval and its relation to the regional stratigraphical stages in the southern North Sea region. Netherlands Journal of Geosciences - Geologie en Mijnbouw 85 (1): 19–35. https://doi.org/10.1017/S0016774600021405.

Kürschner, W.A., van der Burgh, J., Visscher, H., and Dilcher, D.L., 1996. Oak leaves as biosensors of late Neogene and early Pleistocene paleoatmospheric CO_2 concentrations. Marine Micropaleontology 27: 299-312. https://doi.org/10.1016/0377-8398(95)00067-4.

Larsson, L.M., Dybkjaer, K., Rasmussen, E.S., Piasecki, S., Utescher, T., and Vajda, V., 2011. Miocene climate evolution of northern Europe: A palynological investigation from Denmark. Palaeogeography, Palaeoclimatology, Palaeoecology 309: 161-175. https://doi.org/10.1016/j.palaeo.2011.05.003.

Lawrence, K.T., Sosdian, S., White, H.E., Rosenthal, Y., 2010. North Atlantic climate evolution through the Plio-Pleistocene climate transitions. Earth and Planetary Science Letters 300: 329-342. http://dx.doi.org/10.1016/j.epsl.2010.10.013.

Lisiecki, L.E., and Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 20: PA1003. DOI:10.1029/2004PA001071.

Lister, A.M., 2004. The impact of Quaternary Ice Ages on mammalian evolution. Philosophical Transactions of the Royal Society of London, Series B Biological Sciences 359, 221-241. DOI: doi: 10.1098/rstb.2003.1436.

Mackensen, A. & Hald, M., 1988. *Cassidulina teretis* Tappan and *C. laevigata* d'Orbigny: their modern and late Quaternary distribution in northern seas. Journal of Foraminiferal Research 18 (1): 16-24. DOI: https://doi.org/10.2113/gsjfr.18.1.16.

Mangerud, J., Jansen, E., Landvik, J., 1996. Late Cenozoic history of the Scandinavian and Barents Sea ice sheets. Global and Planetary Change 12: 11-26. https://doi.org/10.1016/0921-8181(95)00009-7.

Maslin, M.A., Li, X. S., Loutre M. F., & Berger A. 1998. The contribution of orbital forcing to the progressive intensification of Northern Hemisphere Glaciation. Quaternary Science Reviews 17: 411-426. https://doi.org/10.1016/S0277-3791(97)00047-4.

McCarthy, F.M.G. and Mudie, P., 1998. Oceanic pollen transport and pollen:dinocyst ratios as markers of late Cenozoic sea level change and sediment transport. Palaeogeography, Palaeoclimatology, Palaeoecology 138: 187-206. https://doi.org/10.1016/S0031-0182(97)00135-1.

Meijer, T., Cleveringa, P., Munsterman, D.K., and Verreussel, R.M.C.H., 2006. The Early Pleistocene Praetiglian and Ludhamian pollen stages in the North Sea Basin and their relationship to the marine isotope record. Journal of Quaternary Science 21: 307–310. DOI: 10.1002/jqs.956.

Meloro, C., Raia, P., Carotenuto, F., Barbera, C., 2008. Diversity and turnover of Plio-Pleistocene large mammal fauna from the Italian Peninsula. Palaeogeography, Palaeoclimatology, Palaeoecology 268: 58-64. https://doi.org/10.1016/j.palaeo.2008.08.002.

Michelsen, O., Thomsen, E., Danielsen, M., Heilmann-Clausen, C., Jordt, H., Laursen, G-V., 1998. Cenozoic sequence stratigraphy in eastern North Sea. In: P.-C. de Graciansky, T. Jacquin, P.R. Vail and M.B. Farley (Eds), Mesozoic and Cenozoic sequence stratigraphy of European Basins: SEPM (Society for Sedimentary Geology) Special Publications 60, 91-118. DOI: https://doi.org/10.2110/pec.98.02.0091.

Mudelsee, M. and Raymo, M.E., 2005. Slow dynamics of the Northern Hemisphere glaciation. Paleoceanography 20, PA4022. DOI: 10.1029/2005PA001153.

Formatted: Dutch (Netherlands)

Formatted: English (U.S.)

Formatted: English (U.S.)

Formatted: English (U.S.)

Formatted: English (U.S.)

Mudie, P.J. and McCarthy, F.M.G., 1984. Late Quaternary pollen transport processes, western North Atlantic: Data from box models, cross-margin and N-S transects. Marine Geology, 118: 79-105. https://doi.org/10.1016/0025-3227(94)90114-7.

Naafs, B.D.A., Stein, R., Hefter, J., Khelifi, N., De Schepper, S., Haug, G.H., 2010. Late Pliocene changes in the North Atlantic current. Earth and Planetary Science Letters 298: 434-442. http://dx.doi.org/10.1016/j.epsl.2010.08.023.

Naafs, B.D.A., Hefter, J., Acton, G., Haug, G.H., Martínez-Garcia, A., Pancost, R., Stein, R., 2012. Strengthening of North American dust sources during the late Pliocene (2.7 Ma). Earth and Planetary Science Letters 317-318. 8-19, doi:10.1016/j.epsl.2011.11.026

Naafs, B.D.A., Hefter, J., Stein, R., 2013. Millennial-scale ice rafting events and Hudson Strait Heinrich(-like) Events during the late Pliocene and Pleistocene: a review. Quaternary Science Reviews 80: 1-28. doi: 10.1016/j.quascirev.2013.08.014.

Nichols, J.E., Booth, R.K., Jackson, S.T., Pendall, E.G. & Huang, Y., 2006. Paleohydrologic reconstruction based on n-alkane distributions in ombrotrophic peat. Organic Geochemistry 37: 1505-13. https://doi.org/10.1016/j.orggeochem.2006.06.020.

Noorbergen, L.J., Lourens, L.J., Munsterman, D. K., Verreussel, R.M.C.H., 2015. Stable isotope stratigraphy of the early Quaternary of borehole Noordwijk, southern North Sea .Quaternary International 386: 148 – 157. DOI:10.1016/j.quaint.2015.02.045.

Overeem, I., Weltje, G. J., Bishop-Kay, C., and Kroonenberg, S. B., 2001. The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: a climate signal in sediment supply? Basin Research 13: 293-312. DOI: 10.1046/j.1365-2117.2001.00151.x.

Pagani, M., Liu, Z., LaRiviere, J., Ravelo, A.C., 2010. High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations. Nature Geoscience. 3: 27-30. http://dx.doi.org/10.1038/NGEO724.

Pancost, R.D., Baas, M., van Geel, B., and Sinninghe Damsté, J.S., 2002. Biomarkers as proxies for plant inputs to peats: an example from a sub-boreal ombrotrophic bog. Organic Geochemistry 33(7): 675-690.

Pancost, R.D., Baas, M., van Geel, B., and Sinninghe Damsté, J.S., 2003. Response of an ombrotrophic bog to a regional climate event revealed by macrofossil, molecular and carbon isotopic data. The Holocene, 13(6): 921-932. https://doi.org/10.1016/S0146-6380(02)00048-7.

Patterson, M.O., McKay, R., Naish, T., Escutia, C., Jimenez-Espejo, F.J., Raymo, M.E.,Meyers, S.R., Tauxe, L., Brinkhuis, H. & IODP Expedition 318 Scientists 2014. Orbital forcing of the East Antarctic ice sheet during the Pliocene and Early Pleistocene. Nature Geoscience 7: 841. DOI: 10.1038/ngeo2273.

Peterse, F., Moy, C.M., and Eglinton, T.I., 2015. A laboratory experiment on the behaviour of soil-derived core and intact polar GDGTs in aquatic environments. Biogeosciences 12: 933–943. DOI:10.5194/bg-12-933-2015.

Formatted: English (U.S.)

Formatted: English (U.S.)

Formatted: English (U.S.)

Peterse, F., Kim, J.-H., Schouten, S., Kristensen, D.K., Koç, N. & Sinninghe Damsté, J.S. 2009. Constraints on the application of the MBT/CBT palaeothermometer at high latitude environments (Svalbard, Norway). Organic Geochemistry 40 (6): 692-699. https://doi.org/10.1016/j.orggeochem.2009.03.004.

Poore, H.R., Samworth, R., White, N.J., Jones, S.M., McCave, I.N., 2006. Neogene overflow of Northern Component Water at the Greenland–Scotland Ridge. Geochemistry Geophysics Geosystems 7. http://dx.doi.org/10.1029/2005gc001085.Q06010.

Pross, J. and Brinkhuis, H., 2005. Organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene; a synopsis of concepts. Paläontologische Zeitschrift, 79(1): 53-59.

Quaijtaal, W., Donders, T.H., Persico, D. & Louwye, S., 2014. Characterising the middle Miocene Mi-events in the Eastern North Atlantic realm - A first high-resolution marine palynological record from the Porcupine Basin. Palaeogeography, Palaeoclimatology, Palaeoecology 399: 140-159. https://doi.org/10.1016/j.palaeo.2014.02.017.

Ravelo, A.C., Andreasen, D.H., Lyle, M., Lyle, A.O., Wara, M.W., 2004. Regional climate shifts caused by gradual global cooling in the Pliocene epoch. Nature 429 (6989): 263-267. DOI:10.1038/nature02567

Ravelo, A.C., 2010. Palaeoclimate: Warmth and glaciation. Nature Geoscience 3: 672–674. DOI:10.1038/ngeo965

Raymo, M.E., 1994. The initiation of Northern Hemisphere glaciation. Annual Review of Earth and Planetary Sciences 22, 353-383. http://dx.doi.org/10.1146/annurev.ea.22.050194.002033.

Raymo, M.E., Ruddiman, W.F., Backman, J., Clement, B. M., and Martinson, D.G., 1989. Late Pliocene variation in Northern Hemisphere ice sheets and North Atlantic Deep Water circulation. Paleoceanography 4: 413–446. DOI: 10.1029/PA004i004p00413.

Raymo, M. E., Lisiecki, L. & Nisancioglu, K.. 2006. Plio–Pleistocene ice volume, Antarctic climate, and the global $\delta^{18}O$ record. Science 313: 492–495. DOI: 10.1126/science.1123296.

Reichart, G.J., Brinkhuis, H., 2003. Late Quaternary *Protoperidinium* cysts as indicators of paleoproductivity in the northern Arabian Sea. Marine Micropaleontology 49 : 303-315. https://doi.org/10.1016/S0377-8398(03)00050-1.

Rieley, G., Collier, R.J., Jones, D.M., Eglinton, G., 1991. The biogeochemistry of Ellesmere Lake, U.K. I: source correlation of leaf wax inputs to the sedimentary lipid record. Organic Geochemistry 17: 901–912. https://doi.org/10.1016/0146-6380(91)90031-E.

Rochon, A., de Vernal, A., Turon, J.L., Mathiessen, J., Head, M.J., 1999. Distribution of recent dinoflagellate cysts in surface sediments from the North Atlantic Ocean and adjacent seas in relation to sea-surface parameters: American Association of Stratigraphic Palynologists Foundation Contributions Series 35, 150 pp.

Formatted: English (U.S.)

Formatted: English (U.S.)

Formatted: Dutch (Netherlands)

Formatted: English (U.S.)

Rosoff, D.B., and Corliss, B.H., 1992. An analysis of Recent deep-sea benthic foraminiferal morphotypes from the Norwegian and Greenland seas. Palaeogeography, Palaeoclimatology, Palaeoecology 91, 13-20. https://doi.org/10.1016/0031-0182(92)90028-4.

Ruddiman, W.F., Raymo, M., McIntyre, A., 1986. Matuyama 41,000-year cycles: North Atlantic Ocean and northern hemisphere ice sheets: Earth and Planetary Science Letters 80: 117-129. https://doi.org/10.1016/0012-821X(86)90024-5.

Sangiorgi, F. and Donders, T.H., 2004. Reconstructing 150 years of eutrophication in the north-western Adriatic Sea (Italy) using dinoflagellate cysts, pollen and spores. Estuarine, Coastal and Shelf Science 60: 69-79. https://doi.org/10.1016/j.ecss.2003.12.001.

Sangiorgi, F., Fabbri, D., Comandini, M., Gabbianelli, G. & Tagliavini, E., 2005. The distribution of sterols and organic-walled dinoflagellate cysts in surface sediments of the North-western Adriatic Sea (Italy). Estuarine, Coastal and Shelf Science 64: 395-406.

Shakun, J.D., Raymo, M.E., Lea, D.W., 2016. An early Pleistocene Mg/Ca-δ^{18}O record from the Gulf of Mexico: Evaluating ice sheet size and pacing in the 41-kyr world. Paleoceanography 31: 1011-1027. DOI: 10.1002/2016PA002956.

Seki, O., Foster, G.L., Schmidt, D.N., Mackensen, A., Kawamura, K., Pancost, R.D., 2010. Alkenone and boron-based Pliocene pCO_2 records. Earth and Planetary Science Letters 292: 201-211. http://dx.doi.org/10.1016/j.epsl.2010.01.037.

Shackleton, N.J. and Hall, M.A., 1984. Oxygen and carbon isotope stratigraphy of Deep Sea Drilling Project Hole 552A: Plio- Pleistocene glacial history. D-G. Roberts. D. Schnitker et al. initial Reports of the Deep Sea Drilling Project 81: 599-609. U.S. Govt. Printing Office, Washington.

Schreck, M., Meheust, M., Stein, R. and Matthiessen, J., 2013. Response of marine palynomorphs to Neogene climate cooling in the Iceland Sea (ODP Hole 907A). Marine Micropaleontology 101: 49-67. https://doi.org/10.1016/j.marmicro.2013.03.003.

Sinninghe Damsté, J.S., Schouten, S., Hopmans, E.C., van Duin, A.C.T., Geenevasen, J.A.J., 2002. Crenarchaeol: the characteristic core glycerol dibiphytanyl glycerol tetraether membrane lipid of cosmopolitan pelagic crenarchaeota. Journal of Lipid Research 43: 1641-1651. doi: 10.1194/jlr.M200148-JLR200

Sinninghe Damsté, J.S., 2016. Spatial heterogeneity of sources of branched tetraethers in shelf systems - The geochemistry of tetraethers in the Berau River delta (Kalimantan, Indonesia). Geochimica et Cosmochimica Acta 186: 13-31. https://doi.org/10.1016/j.gca.2016.04.033.

Sluijs, A., Pross, J., and Brinkhuis, H., 2005. From greenhouse to icehouse; organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene. Earth Science Reviews 68: 281-315. https://doi.org/10.1016/j.earscirev.2004.06.001.

Sørensen, J. C., Gregersen, U., Breiner, M. and O. Michelsen, 1997. High-frequency sequence stratigraphy of Upper Cenozoic deposits in the central and southeastern North Sea areas.

Formatted: English (U.S.)

Marine and Petroleum Geology 14 (2): 99-123. https://doi.org/10.1016/S0264-8172(96)00052-9

Sosdian, S. Rosenthal, Y., 2009. Deep-sea temperature and ice volume changes across the Pliocene-Pleistocene climate transitions. Science 325: 306-310. DOI:10.1126/science.1169938 pmid:19608915.

Tabor, C.R., Poulsen, C.J., Pollard, D., 2014. Mending Milankovitch's theory: obliquity amplification by surface feedbacks. Climate of the Past 10: 41–50. DOI: 10.5194/cp-10-41-2014.

Thöle, H., Gaedicke, C., Kuhlmann, G., and Reinhardt, L., 2014. Late Cenozoic sedimentary evolution of the German North Sea – A seismic stratigraphic approach. Newsletters on Stratigraphy 47: 299–329. DOI: 10.1127/0078-0421/2014/0049.

Tzedakis, P.C., Crucifix, M., Mitsui, T., Wolff, E.W, 2017. A simple rule to determine which insolation cycles lead to interglacials. Nature 542: 427–432 DOI:10.1038/nature21364.

Svenning, J.-C., 2003. Deterministic Plio-Pleistocene extinctions in the European cool-temperate tree flora. Ecology Letters 6: 646–653. DOI: 10.1046/j.1461-0248.2003.00477.x.

Westerhoff, W., Donders, T.H. & Luthi, S.M., 2016. Report on ICDP workshop CONOSC (COring the NOrth Sea Cenozoic). Scientific Drilling 21: 47-51. https://doi.org/10.5194/sd-21-47-2016.

Whitehead, D.R., (1983). Wind pollination: some ecological and evolutionary perspectives. In: Real, L. (Ed.), Pollination Biology. Academic Press, Orlando, pp.

Williams, G.L., Fensome, R.A., and MacRae, R.A., 2017. The Lentin and Williams index of fossil dinoflagellates 2004 edition. American Association of Stratigraphic Palynologists, Contributions Series 48, College Station, TX, 1097 pp. 97–108

Van der Vlerk, I.M, Florschütz, F. 1953. The palaeontological base of the subdivision of the Pleistocene in the Netherlands. Verhandelingen Koninklijke Nederlandse Akademie van Wetenschappen, Afdeling Natuurkunde, 1e Reeks XX(2): 1–58.

Versteegh, G.J.M., Zonneveld, K.A.F., 1994. Determination of (palaeo-)ecological preferences of dinoflagellates by applying detrended and canonical correspondence analysis to late Pliocene dinoflagellate cyst assemblages of the south Italian Singa section. Review of Palaeobotany and Palynology 84: 181–199. https://doi.org/10.1016/0034-6667(94)90050-7.

Vonk, J.E., Gustafsson, Ö, 2009. Calibrating n-alkane *Sphagnum* proxies in sub-Arctic Scandinavia. Organic Geochemistry 40: 1085-1090. https://doi.org/10.1016/j.orggeochem.2009.07.002.

Zagwijn, W.H., 1960. Aspects of the Pliocene and early Pleistocene vegetation in The Netherlands. Mededelingen van de Geologische Stichting, Serie C III-1–5, 1–78.

Formatted: Dutch (Netherlands)

Zell, C., Kim, J.-H., Moreira-Turcq, P., Abril, G., Hopmans, E.C., Bonnet, M.-P., Sobrinho, R. L., and Sinninghe Damsté, J.S., 2013. Disentangling the origins of branched tetraether lipids and crenarchaeol in the lower Amazon River: implications for GDGT-based proxies, Limnology and Oceanography. 58, 343–353. DOI: 10.4319/lo.2013.58.1.0343.

Zhang, Z.-S., Nisancioglu, K. H., Chandler, M. A., Haywood, A. M., Otto-Bliesner, B. L., Ramstein, G., Stepanek, C., Abe-Ouchi, A., Chan, W.-L., Bragg, F. J., Contoux, C., Dolan, A. M., Hill, D. J., Jost, A., Kamae, Y., Lohmann, G., Lunt, D. J., Rosenbloom, N. A., Sohl, L. E., and Ueda, H., 2013. Mid-pliocene Atlantic Meridional Overturning Circulation not unlike modern. Climate of the Past 9, 1495-1504.DOI :10.5194/cp-9-1495-2013

Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe (2nd edition).Shell Internationale Petroleum Maatschappij B.V.; Geological Society Publishing House (Bath), 239 pp.

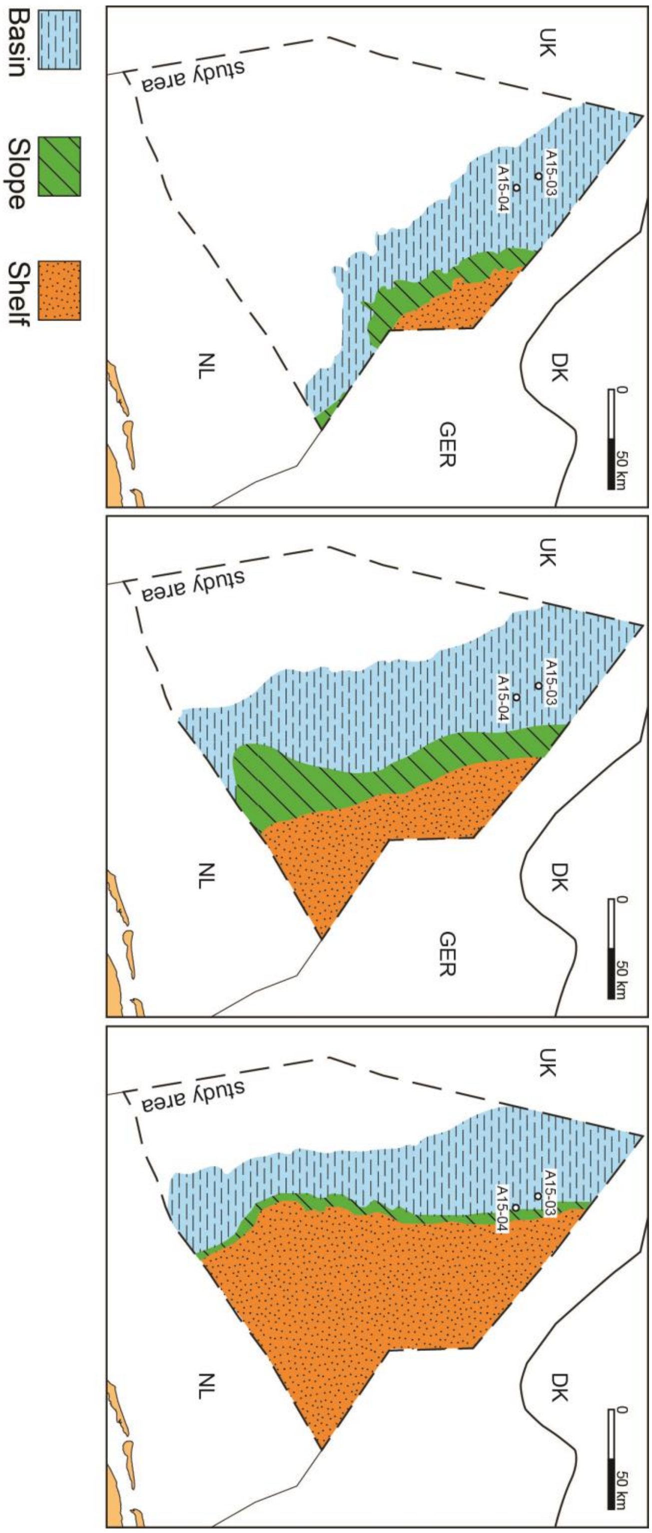
Zöllmer, V. and Irion, G., 1996. Tonminerale des Nordseeraumes ihr Verteilungsmuster in kreidezeitlichen bis pleistozänen Sedimentabfolgen und in den Oberflächensedimenten der heutigen Nordsee: Courier Forschungsinstitut Senckenberg, 190. Frankfurt am Mainz, 72 p.

Zonneveld, K.A.F., Marret, F., Versteegh, G.J.M., Bogus, K., Bonnet, S., Bouimetarhan, I., Crouch, E., de Vernal, A., Elshanawany, R., Edwards, L., Esper, O., Forke, S., Grøsfjeld, K., Henry, M., Holzwarth, U., Kielt, J.-F., Kim, S.-Y., Ladouceur, S., Ledu, D., Chen, L., Limoges, A., Londeix, L., Lu, S.-H., Mahmoud, M.S., Marino, G., Matsouka, K., Matthiessen, J., Mildenhal, D.C., Mudie, P., Neil, H.L., Pospelova, V., Qi, Y., Radi, T., Richerol, T., Rochon, A., Sangiorgi, F., Solignac, S., Turon, J.-L., Verleye, T., Wang, Y. & Young, M., 2013. Atlas of modern dinoflagellate cyst distribution based on 2405 data points. Review of Palaeobotany and Palynology 191: 1-197. https://doi.org/10.1016/j.revpalbo.2012.08.003.

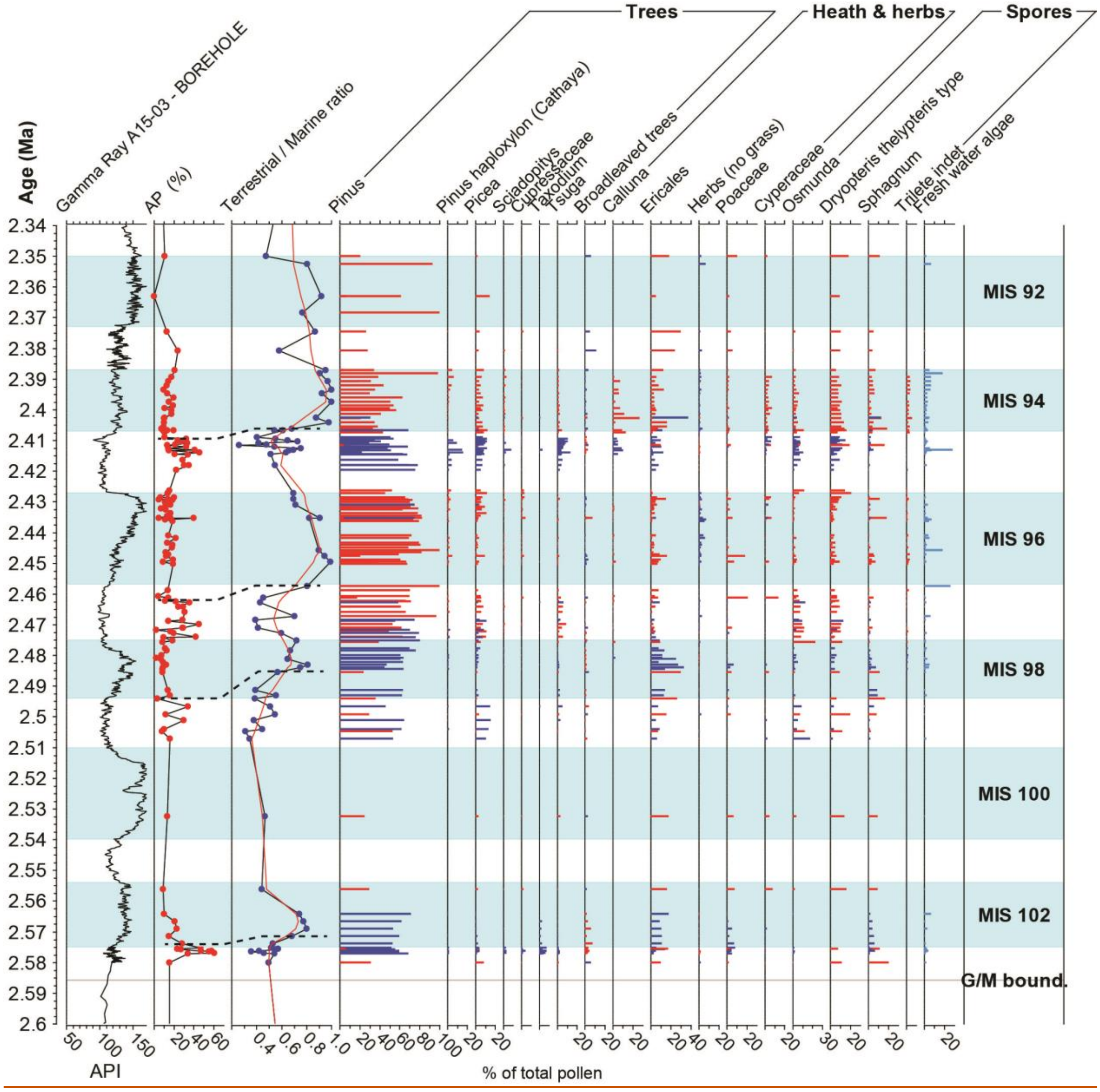
Formatted: English (U.S.)

Supplementary figures and data descriptions

Supplementary Figure 1: sedimentary facies interpretation of high-resolution seismically mapped surfaces S4-6 (see Fig. 2 for stratigraphical position) in relation to the wells.

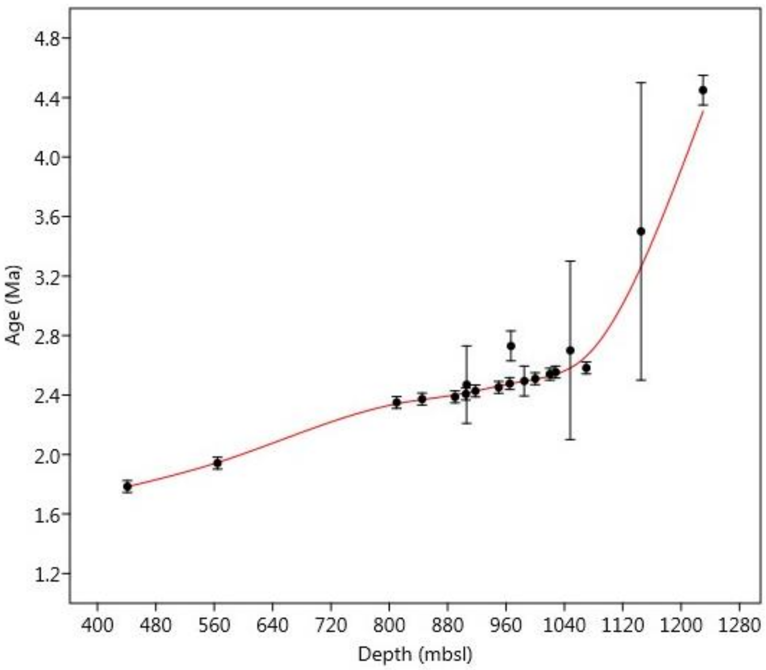


Supplementary Figure 2: Main pollen types in the spliced record of A15-3 (blue) and A15-4 (red) expressed as percentages of the total pollen. Dashed lines between AP % and T/M ratio indicate the observed lags of 3-8 kyr between (terrestrial) cooling and sea level decreases.



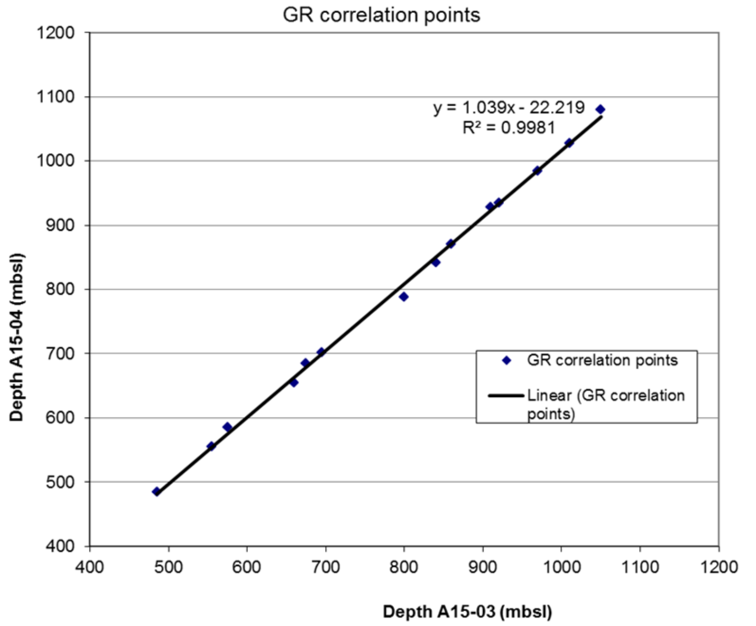
Supplementary Figure 3:

Age-depth model of the spliced A15-3 and A15-4 sections based on a smoothing spline interpolation (optimised range set to 1.65) of tie age points in Table S1 taken from Kuhlmann et al. (2006ab). The tie points where updated to recent range calibrations where necessary.



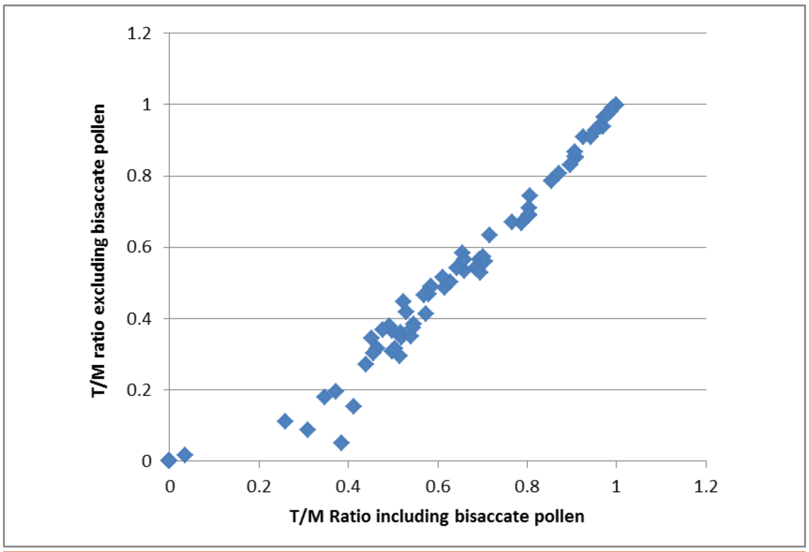
Supplementary Figure 4:

Well tie correlation points between A15-3 and A15-4 are based on the Gamma Ray correlation displayed in Fig. 2. The high R^2 of the linear relation between the well tie points confirms that the proxy records from both wells can by spliced confidently into a single record.



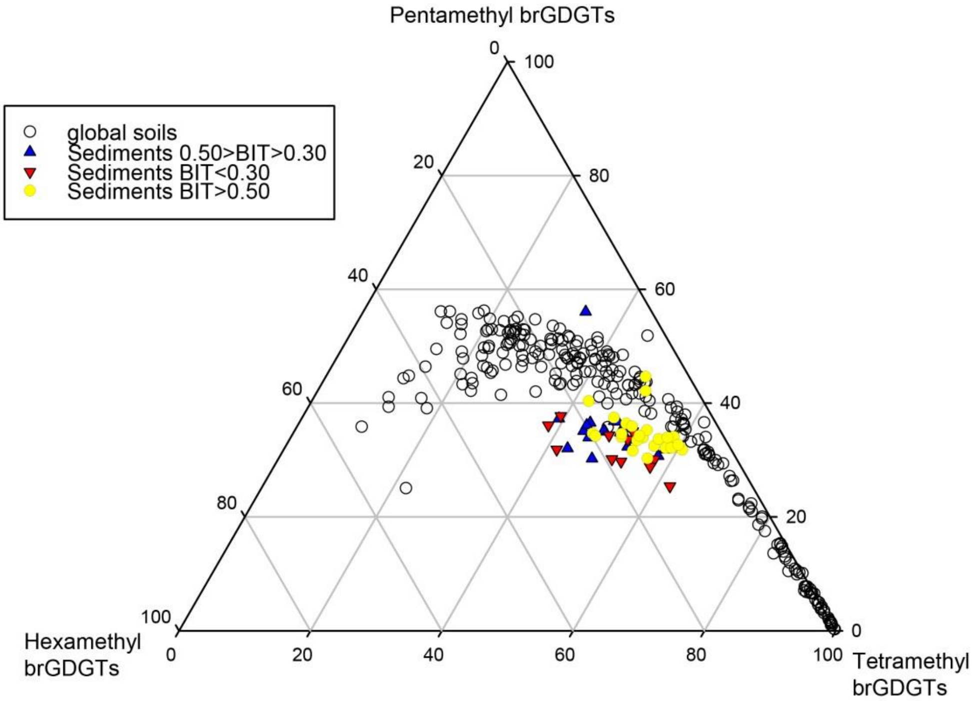
Supplementary Figure 5:

The terrestrial to marine palynomorph (T/M) ratio with in- and exclusion of bisaccate pollen show minimal offset, indicating a low influence of differential transport processes.



Supplementary Figure 6:

Ternary diagram based on the brGDGT analyses showing values close but not identical to the soil calibration. Samples with higher BIT (>0.5) show a greater correspondence to the soil calibration, which indicates some contribution of in-situ produced (aquatic) brGDGTs.



Supplementary Table S1

Chronostratigraphical control points taken from Kuhlmann et al. (2006ab). The tie points where updated to recent range calibrations where necessary.

Supplementary Table ~~S1~~S2

Palynological abundance data of A15-3 and A15-4 by taxon and composite indices as displayed in Fig. 3. Percent data are based on a separate marine and terrestrial total.

Supplementary Table ~~S2~~S3

Borehole Gamma Ray data (A15-3) and geochemical data of A15-3 and A15-4 (O and C stable isotope ratios, TOC, Alkane ratios, brGDGTs).

Chronostratigraphic control points		Depth A15-3	Age	Max. age (	Min. age	Range	
1st order	**2nd order**	mbsl	Ma	Ma	Ma	Ma	**Reference calibration**
Top Olduvai	FOD *Azolla filicoides*	441	1.785	1.795	1.775	0.02	(Kuhlmann et al., 2006a; Kasse, 1996)
base Olduvai		564.5	1.942	1.952	1.932	0.02	(Kuhlmann et al., 2006a)
	top MIS 92 (GR*)	810	2.35	2.36	2.34	0.02	(Noorbergen et al., 2015)
	top MIS 93 (GR*)	845	2.373	2.383	2.363	0.02	(Noorbergen et al., 2015)
	top MIS 94 (GR*)	890	2.387	2.397	2.377	0.02	(Noorbergen et al., 2015)
	top MIS 95 (GR*)	905	2.407	2.417	2.397	0.02	(Noorbergen et al., 2015)
	LOD *Operculodinium erikianum* (A15-4)	906	2.47	2.6	2.34	0.13	(De Schepper et al. 2008; De Schepper et al., 2015).
X-event	top MIS 96 (GR*)	918	2.427	2.437	2.417	0.02	(Noorbergen et al., 2015; Kuhlmann et al., 2006a)
	top MIS 97 (GR*)	950	2.452	2.462	2.442	0.02	(Noorbergen et al., 2015)
	top MIS 98 (GR*)	965	2.477	2.487	2.467	0.02	(Noorbergen et al., 2015)
	LOD *Invetrocysta lacrymosa* (A15-4), scattered	966.8	2.73	2.74	2.72	0.5 **	(Hennissen et al., 2014; De Schepper and Head, 2008).
	top MIS 99 (GR*)	985	2.494	2.504	2.484	0.05	(Noorbergen et al., 2015)
	LOD *Melitasphaeridium choanophorum*, scattered	990	3	3.3	2.7	0.3	(De Schepper et al., 2017; diachronous excl. in model)
	top MIS 100 (GR*)	1000	2.51	2.52	2.5	0.02	(Noorbergen et al., 2015)
	top MIS 101 (GR*)	1020	2.54	2.55	2.53	0.02	(Noorbergen et al., 2015)
	top MIS 102 (GR*)	1028	2.554	2.564	2.544	0.02	(Noorbergen et al., 2015)
	LCO *Neogloboquadrina atlantica* (s)	1048	2.7	3	2.4	0.3	(Weaver and Clement, 1986; Spiegler and Jansen, 1989
G/M boundary	LOD *Barssidinium* (calibrated at A15-3)	1070	2.582	2.592	2.572	0.02	(Kuhlmann et al., 2006a; De Schepper & Head, 2009)
	FOD *Elphidiella hannai*, base FA zone	1145	3.5	4	3	0.5	(Doppert, 1980; King, 1983)
	LOD *Reticulosphaera actinocoronata*	1230	4.45	4.5	4.4	0.05	De Schepper et al., 2015; 2017
	Uvigerina macrocarinata and *Bolboforma fragoris*	1243	11.15	11.7	10.6	0.55	(Von Daniels, 1986; Spiegler and von Daniels, 1991; Spiegler, 1999)
	Unipontidinium aquaeductum, *Apteodinium spiridoides*, *Palaeocystodinium ventricosum*	1280	14.1	15.2	13	1.1	(De Verteuil and Norris, 1996, updated to Ogg et al., 2016)

LOD= Last occurrence datum, FOD= First occurrence datum, LCO= Last Common Occurrence

* GR events are correlated to Noordwijk well where they are tuned by high resolution δ18O to LR04 (Noorbergen et al., 2015)

** Increased range represents disjunct record in A15-4