Subject: Resubmission of minor revisions to *Climate of the Past*

Dear Pierre,

We hereby submit the revision for our manuscript entitled ‘Reinforcing the North Atlantic backbone: revision and extension of the composite splice at ODP Site 982’ for publication in *Climates of the Past*. An additional supplementary information file is provided, including supplementary figures 1-4 and tables 2 and 6. All data produced in this manuscript is also provided in an excel file (supplementary tables 1-7). These tables, together with a full Site 982 CODD experiment and the composite core photos as IGOR binary files and PDFs will be available from the open access PANGAEA database at DOI https://doi.org/10.1594/PANGAEA.884300. This DOI will become active once the accompanying manuscript is officially published. Until that time, the data is available at https://doi.pangaea.de/10.1594/PANGAEA.884300, although the datasets themselves remain password protected.

Thank you very much for your constructive feedback in the last review. The comments and suggestions were helpful and helped to improve the manuscript further (please see our detailed response below). We are additionally very happy to hear that the content of the manuscript was well-received. We hope that the manuscript in its present form provides a well-illustrated example for researchers utilising high-resolution palaeoceanographical records that it is crucial to verify shipboard splices from legacy ocean drilling sites to ensure stratigraphic completeness of their records. We additionally hope that the new stratigraphies presented here prove useful for future palaeoceanographic research in the North Atlantic.

All authors agree to manuscript submission. Thank you again for your helpful review.

I look forward to hearing from you.

Many thanks and kind regards,

Anna Joy Drury
Corresponding author, MARUM, University of Bremen
Point by point overview of minor revisions to “Reinforcing the North Atlantic backbone: revision and extension of the composite splice at ODP Site 982”

We thank Pierre for his helpful suggestions. We have implemented almost all requested changes, or explained otherwise in our more detailed response (in blue) to each comment (in black) below.

Response to editor comments in online review:
One thing that needs to be addressed is the reference style, that is not following the format required by Clim. Past. Please also see our response below, we have corrected this.

I noted that I cannot access the data in Pangaea following the reference given. Maybe it is because you have not made the data available yet, or maybe the ling/doi ref. is wrong. Please check this.

The DOI is not currently active, as it requires the dataset to be fully published before the DOI is activated. The unpublished dataset is currently available (password protected I think) at this temporary DOI: https://doi.pangaea.de/10.1594/PANGAEA.884300. We did not include this in the revised submission as it will become defunct once the dataset is published and the DOI in the manuscript becomes active. The DOI link in the manuscript will provide an open access link to the dataset once the accompanying paper is published.

Finally, the Figure/Table numbering is not identical from one figure to another, including in the supplement. Please try having the same labelling, in the caption and in the figure itself (you often mix "a" and "A"). Please also see our response below, we have corrected this.

Response to editor comments on PDF:

Pg 1 – Ln 13: insert “that was filled with in with 263 new isotope analyses” and replace “Our” with “This”

We have made the suggested revisions, and additionally added “benthic foraminiferal” to line 11 to clarify that we are generating a benthic foraminiferal stable isotope stratigraphy (as opposed to a planktic foraminiferal or bulk stable isotope stratigraphy).

Pg 3 – Lns 2-4: I suggest to move this information to the Date availability section to avoid unnecessary repetition.
We have deleted this information here, and additionally added the reference to the JANUS database in the Data availability section.

Pg 3 – Lns 15-16: Why do you want to compare with these records. Because they are the nearest available records of the same resolution. If it is the case, please write it. (although I acknowledge you explain it in the discussion section).

Thank you for this suggestion. We have firstly elaborated that we assess the new Site 982 stratigraphy using the stable isotope stratigraphies from ODP Site 926 and Ain el Beida, which indeed are the nearest records with comparable resolution and robust astrochronologies. Additionally, we have included a sentence to explain that these records have additionally been instrumental in initially highlighting that there were stratigraphic issues with the shipboard splice at Site 982.
Please add or delete a parenthesis
We have made the suggested revisions.

Please add the link
We have made the suggested revisions.

These photos are barely visible. I understand that you do not want to make them too visible to obliterate the plots, but is it possible to do something better? At least explain why they look black & white (are they originally or did you transformed them in B&W, and if you did, please explain how)
The composite core photos are the original colour of the sediment, which are in full colour. Due to the high carbonate content, the original sediment colour is simply that light and hard to resolve against any background. Nothing was done to artificially lighten the sediments, and they appear in the figures and supplement/PANGAEA in their original colour. We have added a sentence at this location to report that the low ln(Si) values coincide with the lighter, whiter layers.
The CODD functions for Core_Table_Photos includes a lighting correction to solely removes artificial shadows due to the use of a single point lighting source on ODP core table top photos, which would otherwise imprint a ~1.5 m artificial cyclicity into the composite core photos. We have added a reference to the Wilkens et al., 2017 in Section 2.3 to indicate where the reader can find further information on the Lighting Correction function.

In the figures you use A, B, C,... Might be good to do the same in the text instead of using lowercase letters
We have made the suggested revisions.

This is barely seen in Figure 5. I would not qualify this as "Strong"
We have removed both uses of “strong” in this sentence, and replaced the first mention with “distinct” and the second mention with “visible”. We

Delete “.”
We have made the suggested revisions.

Again please put that information only in the data availability section.
We have removed this information. It is currently only referenced in the data availability section. We have additionally extended the acknowledgements to include the reviewers and editor for their constructive feedback.

References: Years of publication should be at the end of the reference (I know, this is strange). Please format the references according to the instructions. Journal titles should be abbreviated according to ISI Journal title abbreviation. Also see this document: https://www.climate-of-the-past.net/Copernicus_Publications_Reference_Types.pdf
Thank you for pointing this out, we have put the references in the correct format.

There is no image in there, only plots.
We used “image” here as interchangeable with “figure”, not specifically to indicate the inclusion of composite core images. We have however replaced “images” with “plots”. 
Pg 22 – Figure 5: The depth and the time interval on which these analyses have been performed is not specified. I presume it is on the whole interval, but please indicated it here in the caption. We have noted in the caption that the spectra are of the entire stable isotope stratigraphies (8.0-4.5 Ma).

Pg 24 – Ln 7: please correct the reference style for Grinsted et al., 2004. We have made the suggested revisions.
Reinforcing the North Atlantic backbone: revision and extension of the composite splice at ODP Site 982

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Abstract. Ocean Drilling Programme (ODP) Site 982 represents a key location for understanding the evolution of climate in the North Atlantic over the past 12 Ma. However, concerns exist about the validity and robustness of the underlying stratigraphy and astrochronology, which currently limits the adequacy of this site for high-resolution climate studies. To resolve this uncertainty, we verify and extend the early Pliocene to late Miocene shipboard composite splice at Site 982 using high-resolution XRF core scanning data and establish a robust high-resolution benthic foraminiferal stable isotope stratigraphy and astrochronology between 4.5 and 8.0 Ma. Splice revisions and verifications resulted in ~11 m of gaps in the original Site 982 isotope stratigraphy, which were filled with 263 new isotope analyses. This new stratigraphy reveals previously unseen benthic δ18O excursions, particularly prior to 6.65 Ma. The benthic δ18O record displays distinct, asymmetric cycles between 7.7 and 6.65 Ma, confirming that high-latitude climate is a prevalent forcing during this interval. An intensification of the 41-kyr beat in both the benthic δ13C and δ18O is also observed ~6.4 Ma, marking a strengthening in the cryosphere-carbon cycle coupling. A large ~0.7‰ double excursion is revealed ~6.4-6.3 Ma, which also marks the onset of an interval of average higher δ18O and large precession and obliquity-dominated δ18O excursions between 6.4-5.4 Ma, coincident with the culmination of the late Miocene cooling. The two largest benthic δ18O excursions ~6.4-6.3 Ma and TG20/22 coincide with the coolest alkenone-derived SST estimates from Site 982, suggesting a strong connection between the late Miocene global cooling and deep-sea cooling and dynamic ice sheet expansion. The splice revisions and revised astrochronology resolve key stratigraphic issues that have hampered correlation between Site 982, the equatorial Atlantic and the Mediterranean. Comparisons of the revised Site 982 stratigraphy to high-resolution astronomically tuned benthic δ18O stratigraphies from ODP Site 926 (equatorial Atlantic) and Ain el Beida (north western Morocco) show that prior inconsistencies in short-term excursions are now resolved. The identification of key new cycles at Site 982 further highlights the requirement for the current scheme for late Miocene marine isotope stages to be redefined. Our new integrated deep-sea benthic stable isotope stratigraphy and astrochronology from Site 982 will facilitate future high-resolution late Miocene to early Pliocene climate research.
1 Introduction

The North Atlantic remains a crucial location for understanding past climate change. It has been a prime region of deep water formation since at least the middle Miocene (Woodruff and Savin, 1989) and a key location for correlating between the progressively enclosed Mediterranean basin and the major oceanic basins (Andersson and Jansen, 2003; Hodell et al., 2001). North Atlantic Ocean Drilling Programme (ODP) Site 982, situated on the Rockall Plateau, was recovered to document the evolution of intermediate water circulation in the North Atlantic Basin (Shipboard Scientific Party Leg 162, 1996). Palaeoclimate records generated at this location have been fundamental to improving our understanding of climate for the past 12 Ma (Bolton et al., 2011; Herbert et al., 2016; Hodell et al., 2001; Hodell and Venz-Curtis, 2006; Khelifi et al., 2014; Lawrence et al., 2009; Lisiecki and Raymo, 2005; Venz et al., 1999; Venz and Hodell, 2002). In particular, the late Miocene benthic stable isotope stratigraphy and astrochronology (Hodell et al., 2001) has been used as the basic stratigraphy and/or age model for a wide range of studies (Bickert et al., 2004; Drury et al., 2016; Herbert et al., 2016; Hodell and Venz-Curtis, 2006; Kontakiotis et al., 2016; De Vleeschouwer et al., 2017). However, there is an ongoing debate about the presence of potential stratigraphic issues in the Pliocene successions of Site 982 (Khelifi et al., 2012; Lawrence et al., 2013) and concerns exist that individual cycles may be missing from the late Miocene isotope stratigraphy (Bickert et al., 2004; van der Laan et al., 2005, 2012); however, these concerns have not yet been resolved.

Site 982 is characterised by high carbonate content, which is above 90% for most of the Pliocene and Miocene (Hodell et al., 2001; Shipboard Scientific Party Leg 162, 1996). The standard shipboard physical properties measurements, such as spectral reflectance, gamma ray attenuation (GRA) bulk density, magnetic susceptibility and natural gamma radiation are difficult to use for stratigraphic correlation in such high carbonate settings. At Site 982, the early Pliocene to late Miocene composite splice was constructed using solely GRA bulk density and spectral reflectance in the 650-700-nm band; however, the shipboard composite record for this interval has never been independently verified. The stratigraphic discrepancies between Site 982 and other deep-sea and Mediterranean sites could originate from errors in the shipboard composite record and verification of the shipboard composite splice is essential to resolve these issues. Non-destructive X-ray Fluorescence (XRF) core scanning is an ideal technique for recovering the high quality and high-resolution data that are required for composite splice verification.

Here, we aim to verify and establish a robust high-resolution stable isotope stratigraphy and astrochronology at Site 982 that can continue as a reference section for North Atlantic climate change. Firstly, we use XRF core scanning to successfully test and extend the early Pliocene to late Miocene shipboard splice at Site 982. Following splice revision, we generate new benthic stable isotope data to fill gaps in the existing stable isotope stratigraphy at Site 982. Using the new complete benthic $\delta^{18}O$ and $\delta^{13}C$ stratigraphy, we generate a new astrochronology for Site 982 between 4.5 and 8.0 Ma. Finally, comparing the new stable isotope stratigraphy to stable stratigraphies from ODP Site 926 (equatorial Atlantic) and Ain El Beida (northwest Morocco) allows us to assess whether previous stratigraphic issues are resolved. This study intends to reinforce Site 982, and the climate records generated there, as a backbone for palaeoceanographic research in the North Atlantic.
2 Materials and Methods

2.1 ODP Site 982

This study utilises early Pliocene to late Miocene sediments recovered from ODP Site 982 (Figure 1; 57°30.992’N, 15°52.001’W; 1134 m water depth) drilled on the Rockall Plateau in the North Atlantic during ODP Expedition 162 (Shipboard Scientific Party Leg 162, 1996). Site 982 was cored to reconstruct Neogene intermediate-water circulation in the North Atlantic. A continuous shipboard composite section was developed until approximately 248 metres composite depth (mcd) back to the late Miocene. The late Miocene through early Pliocene sediments predominantly consist of biogenic carbonate (nannofossil ooze), with minor amounts of clay and biogenic silica, interspersed with occasional ash layers (Shipboard Scientific Party Leg 162, 1996; Wallrabe-Adams and Werner, 1999). Carbonate content is high, averaging 90.8% in the late Miocene to early Pliocene sequences. A high-resolution, astronomically-tuned, benthic stable isotope record (temporal sampling ~2.5 kyr) from this location was published between 4.6 and 8.9 Ma (Hodell et al., 2001). Considering the site’s location in the North Atlantic, this isotope record is important for comparing to isotopic records from the Mediterranean basin in order to provide regional records from the enclosed Mediterranean basin with the global context preserved more strongly at deep-sea locations like Site 982 (Hodell et al., 2001; van der Laan et al., 2005). We assess the new benthic foraminiferal stable isotope stratigraphy developed here by comparing it to similarly high-resolution, astronomically-tuned, benthic stable isotope stratigraphies from proximal locations in the equatorial Atlantic (ODP Site 926) and Mediterranean basin (Ain el Beida) (Figure 1). These records have additionally been instrumental in initially highlighting that stratigraphic issues with the shipboard splice may affect the original Site 982 isotope stratigraphy (Bickert et al., 2004; Drury et al., 2017; van der Laan et al., 2005).

2.2 X-Ray fluorescence core scanning

XRF Core Scanner data were collected every 2 cm down-core over a 1 cm² area with down-core slit size of 12 mm (Run 1: 50 kV, 1.0 mA, 15 s count time; Run 2: 10 kV, 0.2 mA, 15 s count time) directly at the split core surface of the ODP 982 archive halves with XRF Core Scanner II (AVAATECH Serial No. 2) at the MARUM - University of Bremen. The split core surface was covered with a 4 µm thick SPEXCert Prep Ultraflane1 foil to avoid contamination of the XRF measurement unit and desiccation of the sediment. The reported data were acquired by a Canberra X-PIPS Silicon Drift Detector (SDD; Model SXD 15C-150-500) with 150eV X-ray resolution, the Canberra Digital Spectrum Analyzer DAS 1000, and an Oxford Instruments 50W XTF5011 X-Ray tube with rhodium (Rh) target material. Raw X-ray spectra were processed using Iterative Least square software (WIN AXIL) package from Canberra Eurisys. The data was collected between April 2014 and June 2016, during which time the X-Ray tube was replaced. To account for differences in measurement intensity, a number of sections were re-measured and a linear regression between the two datasets was used to calibrate the data collected in 2014 to the data collected in 2015-2016 (see Supplementary Information and Supplementary Figure 1). The shipboard composite
depth section (in mcd) was scanned between 120.13 to 271.58 mcd (Shipboard Scientific Party Leg 162, 1996). All XRF core scanning Si and Zr intensity data are reported in Supplementary Table 1.

2.3 CODD image processing and core composite image generation

To assist with splice verification and data interpretation, core composite images for Site 982 were compiled from core table photos using Code for Ocean Drilling Data (CODD – www.codd-home.net; Wilkens et al., 2017). For each hole, every section from the individual core table images (downloaded from the JANUS database – http://www.odp.tamu.edu/database) were cut, compiled and scaled to mcd using the Includes_Core_Table_Photos functions within CODD. A lighting correction was also applied to account for the single point lighting source used in core table photos (see Wilkens et al., 2017 and the CODD user guide for further information).

2.4 Stable isotope analyses

To fill the observed gaps in the original Hodell et al. (2001) stable isotope stratigraphy and re-establish a robust stratigraphy for the North Atlantic, an additional 263 samples were taken for isotope analysis between 200 and 280 revised m composite depth (rmcd). These samples were selected to fill the 11 m of missing sections in the original stable isotope stratigraphy, as well as overlapping with the original data to ensure the two datasets could be integrated. Each measurement consisted of 1-6 translucent specimens of Cibicidoides (C.) mundulus or C. wuellerstorfi (250-500 µm), which were analysed for carbon (δ¹³C) and oxygen (δ¹⁸O) isotopes using a Kiel I carbonate preparation device attached to a Finnigan MAT 251 at MARUM (University of Bremen, Germany), with an analytical precision of 0.03‰ for δ¹³C and 0.06‰ for δ¹⁸O. All results are reported against Vienna Peedee Belemnite (VPDB) using the standard δ notation (per mil ‰), determined using calibrated in-house standards and NBS-19. All data were corrected to equilibrium using the species-specific constants listed in Supplementary Table 2 (Shackleton et al., 1984, 1995). No offsets were found between the new δ¹³C and δ¹⁸O measurements and the existing records at Sites 982. In graphic representation, only δ¹³C data obtained on C. wuellerstorfi was used because Hodell et al. (2001) found that δ¹³C values from C. mundulus become more negative than paired δ¹³C values of C. wuellerstorfi during intervals of lower δ¹³C. All raw and corrected isotope data are provided in Supplementary Table 3.

3 Results

3.1 XRF core scanning data and splice revision

The natural logarithm of the Si intensity data (ln(Si)) shows significant variability on both ~0.8 and ~1.6 m scale, which coincides well with darker sedimentary layers, as seen on the composite core photos, whilst the low ln(Si) values coincide with the lighter, whiter layers (Figure 2A; Supplementary Figure 2). Among Holes 982A, 982B and 982C, the cycles visible
in the ln(Si) and core photos are remarkably consistent (Figure 2A), which shows these are ideal for verifying the shipboard composite splice.

The XRF ln(Si) records and core photos reveal mismatches, overlaps and gaps in the shipboard composite section (Figure 2A and 3A; Supplementary Figure 2 and 3). Following splice revision, the agreement of the composite core photos and ln(Si) is remarkable between the three holes (Figure 2B and 3A; Supplementary Figure 2 and 3). The shipboard composite splice is altered and verified between 120.13 to 271.58 mcd (rmcd) and additionally extended to 280.23 mcd (Supplementary Figure 2; Tables 1 and 2). The splice revisions resulted in ~11 m of gaps in the published isotope data (Hodell et al., 2001), predominantly in the late Miocene (Figure 3B; Supplementary Figure 3). Some individual gaps and overlaps are as large as ~2-3 meters, which is equivalent to ~40-50 kyr on the original Hodell et al. (2001) age model (Figure 3B; Supplementary Figure 3). The revised offset and splice tables are presented in Tables 1 and 2, and are digitally available on PANGAEA and in Supplementary Tables 4 and 5.

On the revised composite splice, the ln(Si) data shows strong ~1.6 m cyclicity throughout the record, which is particularly strong between 180 and 240 mcd (Figure 4A; Figure 5A). Additionally, distinct ~0.8 m cyclicity is visible between 140 and 220 mcd (Figure 4C). In addition to strong ~0.8 and ~1.6 m cyclicity, some ln(Si) peaks coincide with high Zr peaks, and darker sedimentary layers, reflecting the presence of ash layers at Site 982 (pink bars - Figure 4B, D and E).

### 3.2 Revised Site 982 stable isotope stratigraphy

Using the new isotope data produced here (Figure 3B), the resulting Site 982 benthic δ¹⁸O stratigraphy display little long-term variation (0.2-0.3‰), which is characteristic of this late Miocene interval (Figure 4D). Throughout the record ~1.6 m cycles of ~0.5-0.6‰ are observed, in particular between 270 and 235 mcd and again between 215 to 160 mcd (Figure 4E; Figure 5A). Between 210 and 160 mcd ~0.8 m cycles are particularly strong in the 982 benthic δ¹⁸O record (Figure 4E; Figure 5A). The complete Site 982 δ¹³C stratigraphy displays greater long-term variability, most notably with the negative ~1‰ shift between 265 and 220 mcd (Figure 4C). The δ¹³C record displays strong ~1.6 m cycles of ~0.5‰, although longer 3.8-5.0 m cycles also appear in the upper section above ~170 mcd (Figure 4C; Figure 5A and B). The δ¹⁸O and δ¹³C records generally display an antiphase relationship on the scale of ~1.6 m cycles (Figure 4A and B). A comparison of the 982 stable isotope stratigraphy with the XRF Zr record shows that there is no effect of the ash layers on the isotope record (Figure 4).

### 4 Astrochronology

The original astrochronology presented in Hodell et al. (2001) was constructed by respectively tuning the benthic δ¹³C record filtered at 41 kyr to obliquity and the GRA bulk density record filtered at 21 kyr to summer insolation at 65°N. The obliquity and 65°N summer insolation tuning targets were taken from the La90(1,1) astronomical solution (Laskar et al.,...
Constructing an astrochronology at Site 982 was an iterative process. To establish whether the strong cyclicity observed in the benthic δ¹⁸O and δ¹³C records in the depth domain related to orbital forcing, first-order age control was provided by a 5th order polynomial fit through 13 shipboard nannofossil and planktonic foraminiferal datums (Supplementary Table 6). The initial age control shows that the ~0.8 m cycles observed in the ln(Si) and benthic δ¹³C record are consistent with precession forcing and the more dominant ~1.6 m cycles observed throughout the δ¹⁸O and δ¹³C records are consistent with obliquity forcing (Figure 5A). Additionally, the 3.8-5.0 m cycles observed in the upper part of the δ¹³C record correspond to eccentricity forcing (Figure 5B and C). The presence of these orbitally-forced cyclicities supports that the δ¹⁸O and δ¹³C records are suitable for astronomical tuning.

To construct the astrochronology for Site 982, we correlated the benthic δ¹⁸O series on depth to computed variations in the Earth’s orbit on age, since the benthic δ¹⁸O in particular showed strong variability at precession and obliquity timescales. Due to the presence of both strong obliquity and precession driven cycles, we chose a tuning target composed of equally weighted eccentricity, tilt and Northern Hemisphere precession (E+T-P, from Laskar et al., 2004). No phase shift was applied to account for possible lags between δ¹⁸O and insolation forcing due to the response time of ice sheets, as this response time is unknown for the Miocene (Holbourn et al., 2007).

Initially, a minimal tuning strategy was applied (see also Holbourn et al., 2007; Drury et al., 2017), where distinctive δ¹⁸O minima were visually correlated to E+T-P maxima using 20 tie points (purple lines - Figure 6; Supplementary Figure 4 and Table 7), facilitated by the tuning functions available in CO3D (Wilkens et al., 2017). The shipboard biostratigraphic datums (Supplementary Table 6) were used to initially guide the minimal tuning process, but were not included as fixed tie points. Although the shipboard datum ages were updated to the astronomically tuned Neogene timescale (GTS2012; Hilgen et al., 2012), the Site 982 minimal tuning is negligibly influenced by the GTS2012 calibration, as the shipboard datums have large depth errors (±0.25-2.5m; Supplementary Table 6) and were not used as definitive tie points. The exact minimal tuning tie points were selected to align δ¹³C minima-E-T-P maxima as best as possible between individual ties. Additionally, consecutive ties were ideally placed at least ~100 kyr apart (actual range 90-377 kyr), as recommended by Zeeden et al. (2015) to avoid the introduction of frequency modulation through the astronomical tuning process. Finally, a fine-tuning strategy was applied (see also Drury et al., 2017), where an additional 41 tie points were added to correlate the remaining distinctive δ¹⁸O minima to E+T-P maxima (grey lines - Figure 6; Supplementary Table 7). This fine-tuning age model provides higher-resolution age control and removes remaining δ¹³O minima-E-T-P maxima misalignments in between the initial minimal tuning tie points (Figure 6).

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5 Discussion

5.1 New excursions and deep-sea cooling: insights from benthic isotope stratigraphy at Site 982

Surprisingly, following splice revision, the new, complete, high-resolution (~2.5 kyr) benthic δ¹⁸O and δ¹³C records from Site 982 show a number of large excursions that have not been observed previously (Figure 7 D) Spectral analyses of both records confirm that obliquity is the dominant forcing across the entire interval, although precession is additionally present (Figure 5, Figure 7 D and E). Many of the new excursions occur between 7.7 and 6.65 Ma, when the benthic δ¹⁸O record shows a strong response to obliquity forcing (Figure 7 C and D), confirmed by the strength of the obliquity spectral peak (Figure 5 D). The timing and shape of the δ¹⁸O cycles in particular coincides with the distinctive saw-tooth obliquity-driven cycles observed between 7.7-6.9 Ma at eastern equatorial Pacific IODP Site U1337 (Drury et al., 2017). The asymmetry of the δ¹⁸O cycles seen at Site U1337, coincident with antiphase obliquity cycles in δ¹³C and δ¹⁸O, were associated with high-latitude climate forcing, although the asymmetry could partly also result from the interference pattern between strong obliquity forcing and the influence of minor precession (Drury et al., 2017). The distinct cycles at Site 982 between 7.7 and 6.65 Ma also display asymmetry and coincide with a strong antiphase relationship between the Site 982 δ¹³C and δ¹⁸O records (Figure 7 D, E), supporting that high-latitude climate forcing is strong during this interval of the late Miocene. However, the precessional influence observed at Site U1337 is not as developed in the Site 982 δ¹³C records during the 7.7-6.9 Ma interval (Figure 5 D, Figure 7 C and D). In addition to the dominance of obliquity over precession forcing (Figure 5 D), the obliquity-driven δ¹³C cycles at Site 982 continue until 6.65 Ma, indicating an extended influence of high-latitude processes until 6.65 Ma. Between ~6.7 and 6.7 Ma, the Site 982 benthic δ¹³C record is characterised by the Late Miocene Carbon Isotope Shift (LMCIS) (Figure 7 D), a globally expressed negative ~1‰ shift that is thought to reflect a global change in the δ¹³C of the oceanic reservoir (Haq et al., 1980; Hodell and Venz-Curtis, 2006; Keigwin, 1979). When compared to the high-resolution δ¹³C stratigraphy from ODP Site 926 (equatorial Atlantic), this confirms that the timing of the onset and termination of the LMCIS was globally synchronous within a few kyr (Figure 8 D), as shown between Site 926 and Site U1337 (equatorial Pacific) (Drury et al., 2017).

The Site 982 δ¹³C and δ¹⁸O records show minimal variability between 6.65 and 6.5 Ma during a long-term obliquity node; however, obliquity forcing strongly manifests itself again ~6.5 Ma in the δ¹³C record. This is shortly followed by a remarkably large double excursion in the Site 982 benthic δ¹³C spanning two obliquity cycles between ~6.3-6.4 Ma (~210-214 mcd), which marks a rapid increase of ~0.7‰ (black arrow - Figure 7 C; Figure 4 B). This excursion coincides with the first occurrence of strong obliquity forcing in the δ¹³C record as well as the δ¹³C record (Figure 5 E and F, Figure 7 B), confirming a strengthening of the antiphase cryosphere-carbon cycle coupling and an intensification of the 41-kyr beat indicated at Site U1337 after 6.4 Ma (Drury et al., 2017). The large δ¹³C excursion marks the onset of a strong response to both obliquity and northern hemisphere precession in particular the Site 982 δ¹³C record between 6.4 and 5.4 Ma, with strong obliquity forcing continuing until at least 4.6 Ma (Figure 7 D). The interplay between precession and obliquity forcing
on the δ¹⁸O record between 6.4 and 5.4 Ma could account for the presence of well-expressed power in the 24, 22 and 19-kyr bandwidth seen in the MTM power spectra (Figure 5 D).

Between 6.4 and 5.4 Ma, the δ¹⁸O stratigraphy is characterised by average higher δ¹⁸O, and the greatest variability seen throughout the record. This interval at Site 982 was associated with the latest Miocene glaciation by Hodell et al. (2001). In addition to the new excursion ~6.4-6.3 Ma, marine isotope stages TG12/14 (~5.5-5.6 Ma) and TG20/22 (~5.7-5.8 Ma) are also clearly expressed at Site 982 (Figure 7 D). This high-δ¹⁸O, high-variability interval coincides with end of the late Miocene cooling interval associated with declining atmospheric CO₂ concentrations identified by Herbert et al. (2016).

Notably, the two biggest drops in alkenone-derived sea surface temperatures (SSTs) from Site 982, when surface waters were only ~12-13°C, coincide with the two largest excursions in benthic δ¹⁸O, namely the new excursion revealed ~6.4-6.3 Ma and TG20/22. The previous absence of the 6.4-6.3 Ma excursion in benthic δ¹⁸O record of Site 982 is attributed to missing section in the shipboard splice, which accounts for why the late Miocene global cooling observed by Herbert et al. (2016) did not seem to be associated with any response in deep-sea temperatures or global ice volume expansion. However, the synchronicity between the 6.4 Ma intensification of the 41-kyr beat in both the δ¹³C and δ¹⁸O records, the new 6.4-6.3 Ma δ¹⁸O excursion, the greatest cooling in the alkenone SST records (Figure 7), suggests that the late Miocene cooling seen in the high-latitudes lead to a combination of deep-sea cooling, dynamic ice sheet expansion and a stronger coupling between the cryosphere and the carbon cycle.

5.2 Integrating the Mediterranean and North Atlantic

Site 982 is a key reference section for palaeoceanographic and palaeoclimate study, as it is the only deep-sea location in the North Atlantic with high-resolution benthic oxygen isotope stratigraphies for the late Miocene to early Pliocene. As such, it is frequently used as a North Atlantic end member to investigate past deep-sea circulation (Bickert et al., 2004; Drury et al., 2016; Hodell et al., 2001; Hodell and Venz-Curtis, 2006; Khélifi et al., 2014). Additionally it reflects a crucial link to tie regional records of the enclosed Mediterranean basin, such as those from Ain el Beida and Salé Briqueterie, to the global signal preserved more strongly in deep-sea sediments (Hodell et al., 1994, 2001; Kontakiotis et al., 2016; van der Laan et al., 2005, 2012). However, although the long-term trends at Site 982 remained useful for investigating long-term, million-year changes in deep-water circulation patterns, on inspection at higher-resolution, misalignments between distinct excursions become apparent (Bickert et al., 2004; van der Laan et al., 2005). Bickert et al. (2004) constructed their ODP Site 999 age model by correlating their isotope data to the isotope stratigraphy from Site 982; however, to account for obvious mismatches between Site 999 and nearby ODP Site 926, they had to adjust the original Site 982 astrochronology to account for some inconsistencies with respect to obliquity. The isotope stratigraphy at 926 has recently been extended back to ~8.0 Ma, following splice verification and revision and validation of the original Shackleton and Hall (1997) astrochronology (Drury et al., 2017; Wilkens et al., 2017; Zeeden et al., 2013). Although there is overall agreement in long-term trends and the onset of the LMGS, inconsistencies between distinctive short-term events in the original Site 982 shipboard stratigraphy...
and the updated Site 926 stratigraphy are evident (Figure 8A). Disagreement between the δ¹³C records from Sites 926 and 982 is particularly pronounced before 7.3 Ma, between 6.3-6.9 Ma (the termination of the LMCIS) and between 5.9-5.1 Ma (Figure 8A). Following splice revision and the new astronomical calibration, the new Site 982 stratigraphy shows far better agreement throughout, both in terms of the long-term trends, the onset and termination of the LMCIS, and especially with respect to individual excursions (Figure 8B). This considerable improvement between these two Atlantic deep-sea benthic stratigraphies strongly supports the revised astrochronologies at both sites.

Comparisons between late Miocene Mediterranean records and Site 982 also raised concerns about the validity of the original astrochronology and splice. A high-resolution comparison between stable isotope data from Ain el Beida (AEB; northwest Morocco) and Site 982 indicated that there were both mismatches in the number of cycles present at both locations, as well as inconsistencies between the age models with respect to the age of clearly identical cycles (Figure 8C; van der Laan et al., 2005). Again, following the splice revisions and new orbital tuning, the agreement between these two records is radically improved (Figure 8D). The misalignment in age between TG12/14 (~5.5-5.6 Ma) at Site 982 highlighted by van der Laan et al. (2005) (Figure 8C) has been resolved when using the new benthic stratigraphy (Figure 8D).

Furthermore, by the addition of an extra cycle through the revision of the splice at Site 982, the agreement between AEB and Site 982 is improved between TG34 and C3An.δ¹⁸O14/16 (**14/16 in Figure 8C and D). Older than stage C3An.δ¹⁸O16, between 6.5 and 6.3 Ma, correlation between Site 982 and AEB was difficult based on the original stratigraphies, with the identification of the large new double excursion in benthic δ¹⁸O at Site 982 between ~6.3-6.4 Ma (Figure 7D), the benthic δ¹⁸O records from AEB and Site 982 now show remarkable agreement in this interval (Figure 8D). This is further indication that this event marks a major global event, preceding the coolest temperatures as identified by Herbert et al. (2016).

The new stratigraphy does not resolve all misalignments between Site 982 and AEB. Between TG12/14 and TG20/22, van der Laan et al. (2005) identified an additional cycle at Site 982 that was not visible in AEB (Figure 8C). In the new stratigraphy, the agreement between Site 982 and AEB is still not perfect, with Site 982 displaying 1-2 cycles more than AEB (Figure 8D). Low sedimentation rates at AEB in this interval (van der Laan et al., 2005), as well as lower sampling resolution, could indicate cycles may be missing at this location. Splice uncertainty at Site 982 is unlikely to be the cause of this discrepancy, as the XRF core scanning splice verifications show that the splice is robust in this interval. Also the interval where Site 982 shows additional cycles compared to AEB occurs within a single core. Although sedimentary disturbances cannot be excluded and are difficult to identify in low-contrast deep-sea pelagic sediments with high carbonate content, the stable isotope and XRF core scanning datasets support that the sedimentary succession at Site 982 in this interval is undisturbed.

Our study has resolved many of the issues surrounding the stratigraphy and astrochronology at Site 982. New cycles were identified, which correlate well with isotope records from the Mediterranean and equatorial Atlantic. Past attempts have been made to extend the Marine Isotope Stage (MIS) identification scheme first developed by Shackleton et al. (1995) into the late Miocene (Drury et al., 2016; van der Laan et al., 2005). The identification of the new cycles at Site 982 highlights
the need for a redefinition of the current MIS scheme for this interval. Considering the number of high-resolution, robust benthic foraminiferal stratigraphies that now exist for the latest Miocene (Bickert et al., 2004; Drury et al., 2016, 2017; Vidal et al., 2002; Westerhold et al., 2005), a redefinition of late Miocene MIS should soon be attempted, following the global approach applied for the Pliocene by Lisiecki and Raymo (2005).

6 Conclusions

Here, we present a new high-resolution benthic stable isotope stratigraphy and astrochronology for ODP Site 982. Splice revisions using XRF core scanning data resulted in ~11 m of gaps in the original Site 982 isotope stratigraphy, with some gaps/overlaps as large as ~2-3 meters, equivalent to ~40-50 kyr on the original age model. Our complete stratigraphy reveals previously unseen benthic δ¹⁸O excursions, particularly in the late Miocene section. The benthic δ¹⁸O record displays distinct, asymmetric cycles between 7.7 and 6.65 Ma, supporting evidence from the Pacific that high-latitude climate forcing is strong during this interval. Additionally, the intensification of the 41-kyr beat in both the benthic Site 982 δ¹⁸O and δ¹³C records confirm that a strengthening of the cryosphere–carbon cycle coupling occurred ~6.4 Ma.

Around 6.4-6.3 Ma, the splice revisions also reveal a significant ~0.7‰ double excursion in the Site 982 δ¹³C stratigraphy covering two obliquity cycles. This excursion marks the onset of the 6.4-5.4 Ma interval characterised by average higher δ¹³C and greater short-term variability dominated by obliquity and minor precessional influence. This long-term δ¹³C maximum and associated high short-term variability strongly coincides with the maximum of late Miocene cooling associated with declining CO₂ (Herbert et al., 2016). In particular, the two largest benthic δ¹³C excursions ~6.4-6.3 Ma and TG20/22 coincide with the coolest alkenone-derived SST estimates from Site 982. This suggests that the late Miocene global cooling coincided with deep-sea cooling and dynamic ice sheet expansion. At 6.4 Ma, the intensification of the 41-kyr beat, the onset of high benthic δ¹³C variability and greatest alkenone SST cooling at Site 982, strongly supports that the hypothesised decline in atmospheric CO₂ concentrations and late Miocene cooling led to deep-sea cooling, dynamic ice sheet expansion and a stronger coupling between the cryosphere and the carbon cycle.

The revised splice and astrochronology resolve key stratigraphic issues that have hampered correlation between Site 982 and other locations. Comparisons of the revised Site 982 δ¹³C stratigraphy to benthic δ¹³C stratigraphies from ODP Site 926 and Ain el Beida show that prior inconsistencies in short-term excursions are now resolved. Individual excursions show remarkable agreement between the north and equatorial Atlantic Ocean, as well as the north Atlantic and the Mediterranean basin, thereby strongly supporting the revised astrochronology. The identification of new cycles at Site 982 also highlights the need for a redefinition and extension of the current late Miocene MIS scheme. Finally, our new deep-sea stratigraphy will enable Site 982 to continue as a key North Atlantic sequence for high-resolution study of the palaeoceanography of the late Miocene to early Pliocene.
Data Availability and Code

All data, including a Site 982 CODD experiment and all composite core images, are available on the open access PANGAEA database at https://doi.org/10.1594/PANGAEA.884300. The supplementary data tables are also available from the supplementary information at Climate of the Past. CODD functions for IGOR Pro™ used in this paper (Wilkens et al., 2017) are available for download from https://www.codd-home.net and the shipboard physical property data from ODP Site 982 is available online from the JANUS database (http://www.odp.tamu.edu/database/).

Author Contributions

The project was designed by AJD, TW and DH. AJD, TW and UR contributed to the XRF dataset, AJD and TW generated the stable isotope record and AJD cut the core images from the core box photos. All authors contributed to data collection, quality control and analysis. All authors were involved in scientific discussions. AJD and TW wrote the manuscript with additional contributions from all authors.

Acknowledgements

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References


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**Table 1: Revised and Shipboard offsets for ODP Site 982 (Holes A-D)**

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**Key**
- **BOLD** = changes compared to shipboard splice
- Italics = shipboard splice shifted to accommodate new offsets higher in the section.
## Table 2: Revised Splice for ODP Site 982

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<th>Lower Core tie point ID</th>
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<td>(in revised CSF-4)</td>
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- Bold: new splice tie point
- Italic: old splice tie point with revised composite depth

**CSF**

- **m CSF**: mbsf
- **m revised CCSF**: mcsf
Figure 1: Map showing the location of ODP Sites 982 and 926, as well as the Ain el Beida quarry section. Red site locations indicate new data was produced, yellow site locations indicate the use of published data.
Figure 2: Panels showing A) the shipboard composite splice and B) the revised splice between 200 and 230 m composite depth. Each panel consists of the composite core images of the Site 982 splice and Holes 982A, 982B and 982C, with the shipboard GRA bulk density data and the new XRF ln(Silica counts) record. Tie point locations are shown by yellow (upper tie point within a core) and red (lower tie point within a core) lines. See Supplementary Figure 2 for images of the entire revised splice interval. We could not include the reflectance data, since it was not present in the ODP database, but instead was archived as damaged data.
Figure 3: A) XRF ln(Silica counts) for the individual holes at Site 982 on the shipboard composite depth with the corresponding age on the top axis, and on the revised composite depth on the bottom axis. B) Stable isotope δ¹³C and δ¹⁸O records for the individual holes at Site 982 published in Hodell et al. (2001) on the shipboard composite depth with the corresponding age on the top axis. On the bottom axis, the published stable isotope data is plotted on the revised composite depth, together with the new stable isotope data (black lines) produced in this study. Vertical lines show how the splice was adjusted and highlight the effect of these adjustments on the agreement between the XRF data from the three holes. See Supplementary Figure 3 for plots of the entire revised splice interval.
Figure 4: Overview of the new XRF and updated stable isotope datasets on the revised composite depth at Site 982. The complete benthic A) δ¹³C records from this study (orange) and Hodell et al. (2001) (red) and B) δ¹⁸O records from this study (light blue) and Hodell et al. (2001) (dark blue), the XRF counts for C) ln(Silica) (green) and D) Zirconium (Zr) (black), and E) the composite splice image for Site 982. Pink intervals highlight the location of ash layers, based on the presence of Zr peaks, which affect the XRF data, but show no influence on the stable isotope records.
Figure 5: Multitaper method (MTM) power spectra of the entire stable isotope stratigraphies (8.0–4.5 Ma) generated using Astrochron (Meyers, 2014; for the specific code, please see the Supplementary Information) for δ¹⁸O in A/D) and δ¹³C with a full vertical axis shown in B/E) and vertically expanded in C/F) to show the same vertical axis extent as in A/D. The red noise fit (AR1) and 90, 95 and 99% confidence limits (CL) relative to red noise are also indicated. The periods of different peaks are annotated. The MTM spectra are shown in the depth domain in A), B) and C) and in the time domain in D) E) and F).
Figure 6: Fine-tuned astrochronology for Site 982, with minimal tuning tie points indicated in purple and fine-tuning tie points indicated in grey. A) Fine-tuned benthic foraminiferal $\delta^{13}C$ (in ‰ versus VPDB). B) Fine-tuned benthic foraminiferal $\delta^{18}O$ (in ‰ versus VPDB). C) Eccentricity+Tilt-Precession tuning target (E+T-P) from Laskar et al. (2004) D) Benthic foraminiferal $\delta^{18}O$ (in ‰ versus VPDB) on depth. E) Fine-tuned sedimentation rates (in m/Myr) on depth.
Figure 7: A) Alkenone \( \Delta^{37} \) derived SSTs from Site 982 (Herbert et al., 2016). B) Fine-tuned Site 982 benthic foraminiferal \( \delta^{13} \) C (in ‰ versus VPDB). C) Fine-tuned Site 982 benthic foraminiferal \( \delta^{18} \) O (in ‰ versus VPDB) on the fine tuned astrochronology. D) Wavelet analysis of the Site 982 benthic \( \delta^{13} \) C data (in ‰ versus VPDB) on the fine tuned astrochronology. E) Wavelet analysis of the Site 982 benthic \( \delta^{18} \) O data (in ‰ versus VPDB) on the fine tuned astrochronology. F) Coherence wavelet analysis of the Site 982 benthic \( \delta^{13} \) C and \( \delta^{18} \) O, with the black arrows to the left indicating anti-phase and the black arrows to the right indicating in-phase. Prominent MIS are annotated, with ** standing for C3An.\( \delta^{18} \) O. All wavelets were generated using Grinsted et al. (2004).
Figure 8: A) The benthic $\delta^{13}$C record from ODP Site 982 published in Hodell et al. (2001) on its original age model, compared to the benthic $\delta^{13}$C record from ODP Site 926 on its astronomical age model (Drury et al., 2017; Wilkens et al., 2017; Zeeden et al., 2013).

B) The revised benthic $\delta^{13}$C record, with new data indicated in blue, on the revised age model, compared to the benthic $\delta^{13}$C record from ODP 926 on its astronomical age model (Drury et al., 2017; Wilkens et al., 2017; Zeeden et al., 2013).

C) The benthic $\delta^{18}$O record from ODP Site 982 published in Hodell et al. (2001) on its original age model, compared to the benthic $\delta^{18}$O record from Ain El Beida on its astronomical age model (van der Laan et al., 2005, 2012).

D) The revised benthic $\delta^{18}$O record, with new data indicated in blue, on the revised age model, compared to the benthic $\delta^{18}$O record from Ain El Beida on its astronomical age model (van der Laan et al., 2005, 2012). In panels C) and D), MIS are indicated as they were originally identified in by Hodell et al. (2001) in black and by van der Laan et al. (2005) in red. Where the identification of an MIS agrees, either in the original or revised chronology, the stage is indicated in two-tone red and black. The ** is short for C3An.$\delta^{18}$O (see van der Laan et al. (2005) for further details).