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Final report for Research Grant:

Testing for threshold-crossing behaviour in millennial-scale climate variability during Plio-Pleistocene intensification of Northern Hemisphere Glaciation – new insights from North Atlantic IODP Site U1313

1. Introduction

Millennial-scale climate fluctuations are a prominent intermittent feature during glacials of the last 2.5 Myr. It is suggested that high-amplitude suborbital ice-rafting and climate fluctuations occur when a specific benthic oxygen-isotope ($\delta^{18}O_b$) threshold value[1] (4.14‰[1]) or sea-level (-45 m below present[2]) is passed, and that these high-amplitude changes were introduced as the climate system entered the Mid-Pleistocene Transition (MPT). Several studies suggest, however, that above-mentioned thresholds were passed ~1.3 Myr before the MPT during the intensification of Northern Hemisphere Glaciation (iNHG; ~2.5 to 2.9 Ma)[3],[4],[5],[6]. Whether the proposed late Pleistocene threshold values are also valid for triggering late Pliocene/early Pleistocene climate amplification is a controversial issue: While planktic foraminiferal $\delta^{18}O$ records from North Atlantic ODP Site 984 point to Dansgaard-Oeschger-like climate variability during glacials Marine Isotope Stages (MIS) G6 and 104[7], new late Pliocene/early Pleistocene high-resolution datasets from North Atlantic IODP Site U1313 raise concerns over the reproducibility of this finding – a sea-level record across MIS 100 indicates that the proposed sea-level threshold value[2] was clearly reached[8]. Mixed-layer $\delta^{18}O$-values and sea-surface temperatures (SST) on the same samples, however, only indicate small-amplitude variability at millennial-scale periodicities across iNHG (MIS 103 to 95) that prevail regardless of the glacial state[5],[9] (Figure 1a–f). These new findings indicate that either the amplification of millennial-scale climate fluctuations across iNHG required a significantly higher ice-volume threshold than its late and middle Pleistocene counterparts, that ice volume had no significant effect on the amplitude of these climate fluctuations, and/or that the majority of available sea-level estimates that record glacial lowstands during iNHG of -60 to -110 m below present[4],[5],[10] are inaccurate, and instead much lower sea-level lowstand estimates of -20 m[11] are valid.

In this study, a high-resolution bottom-water record from North Atlantic Site U1313 (based on the benthic foraminifera *Oridorsalis umbonatus*) undertaken for MIS 100[8] is expanded by investigating glacial-interglacial (G-IG) cycles MIS G6 to 95 (~2.75–2.4 Ma). The target interval includes the first three large-amplitude (~1‰ in $\delta^{18}O_b$[12]) G-IG cycles MIS 100–96 representing the culmination of iNHG. Marine Isotope Stage G6 is often said to mark the onset of NHG and is characterized by the first ice rafting events in the Northern Hemisphere and the occurrence of high-amplitude climate fluctuations[7] while MIS 100 marks the first glacial during which the Laurentide Ice Sheet advanced into the mid-latitudes[3],[13] and ice rafting became widespread across the North Atlantic Ocean[14]. Combined benthic foraminiferal (*O. umbonatus*) high-resolution Mg/Ca and $\delta^{18}O$ records will help to quantify sea-level change, and thus the possibility of threshold-crossing behaviour in millennial-scale climate variability, across this critical time period.

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[1] Please note that $\delta^{18}O_b$ values reported herein are adjusted to equilibrium calcite.

2. Material and methods

As study area for this project, the North Atlantic has been selected because of its proximity to the large, dynamic Northern Hemisphere ice sheets and its fundamental role in deep-water formation; both these characteristics make the North Atlantic one of the climatically most relevant region on Earth.

North Atlantic IODP Site U1313 (reoccupation of DSDP Site 607, Leg 94[15]), which was drilled within the framework of IODP Expedition 306 in 2005[16], provides the opportunity to work at high resolution and on the basis of maximum stratigraphic precision: A robust age model is already available for the time interval focused upon in this study and is based on a high quality benthic foraminiferal oxygen-isotope stratigraphy[5] tuned to the LR04 stack[12]. Site U1313 is located in the subpolar North Atlantic 400 km northwest of the Azores (41°N, 32.5°W) at the base of the upper western flank of the Mid-Atlantic Ridge at the southernmost end of the “ice-rafted debris belt” in a water depth of 3426 m[16].

A total of 189 samples were examined on 8-cm intervals (equals ~1550 years[5]), with a higher, 4-cm resolution (equals ~775 years[5]) during glacial terminations, along the primary shipboard splice from 114.12 to 130.56 meters composite depth, representing 2.75–2.41 Ma (MIS G6–95) (cores 1313C-12H-3-112 cm to 1313C-12H-5-56 cm, 1313B-12H-2-118 cm to 1313B-12H-6-124 cm, 1313C-13H-3-2 cm to 1313C-13H-4-26 cm, and 1313B-13H-1-74 cm to 1313B-13H-5-57 cm). On average, 10 individuals of the benthic foraminiferal species *Oridorsalis umbonatus* (>150 µm) were picked from these samples. Foraminiferal tests were crushed, homogenously mixed, and separated into two fractions to allow for paired stable-isotope and Mg/Ca analysis on the same biotic carrier. Picking of foraminiferal tests was carried out at Heidelberg University between February and October 2016. Samples for Mg/Ca measurement were cleaned at Heidelberg University, following the protocol of [17] but omitting the reductive cleaning step[18], prior to the research visit for Mg/Ca analysis at the National Oceanography Centre Southampton (NOCS), UK.

Mg/Ca analyses were carried out at NOCS using a Thermo Fischer Element High-resolution Inductively Coupled Plasma Mass Spectrometer (HR-ICP-MS) during 17th and 25th November 2016. Stable isotopes were analysed at Goethe-University Frankfurt between August and October 2016 using a ThermoFinnigan MAT253 gas source mass spectrometer equipped with a Gas Bench II for automated analyses (financed by my current Ph.D. project).

Oridorsalis umbonatus Mg/Ca ratios were converted into bottom-water temperature (BWT) estimates following a species-specific equation for *O. umbonatus* ($\mathrm{BWT} = \ln[\mathrm{Mg/Ca}/1.008] \times [1/0.114]$)[19]. Because the applied equation is based on oxidative and reductive cleaning of foraminiferal tests, while only oxidative cleaning was applied for Site U1313 samples, measured Mg/Ca values were adjusted by reducing each value by 10%[18]. The oxygen-isotope composition of seawater was than calculated using *O. umbonatus*-based $\delta^{18}O$ and BWT estimates ($\delta^{18}O_{sw,\,SMOW} = [(\mathrm{BWT} - 16.9)/4.0] + \delta^{18}O_b + 0.27‰$)[20],[21]. Finally, $\delta^{18}O_{sw}$ was converted to sea-level assuming that 0.11‰ change in $\delta^{18}O_{sw}$ is equivalent to a 10 m change in sea-level[22] (thereby the influence of different water masses at Site U1313 on G-IG timescales [Antarctic Bottom Water and North Atlantic Deep Water[23],[24]] was incorporated).

3. Results

Deep-sea $\delta^{18}O$

The new high-resolution $\delta^{18}O$ record of *O. umbonatus* from Site U1313 varies between 2.62‰ and 4.60‰ across the interval of study (~2.75–2.4 Ma) with lower values during interglacial periods compared to higher values during glacial periods (Figure 1g). Overall, the $\delta^{18}O$ record of *O. umbonatus* follows the obliquity-related G-IG cyclicity given by the *Cibicidoides wuellerstorfi* $\delta^{18}O$ record from that site[5] (Figure 1b). Glacial-interglacial amplitudes became stronger across prominent iNHG glacials (>1‰) compared to the time period prior to MIS 100 (<1‰). Interestingly, the final ~10 kyr of MIS 100 are characterized by an additional increase in $\delta^{18}O$ before $\delta^{18}O$ rapidly decreased during the following termination.

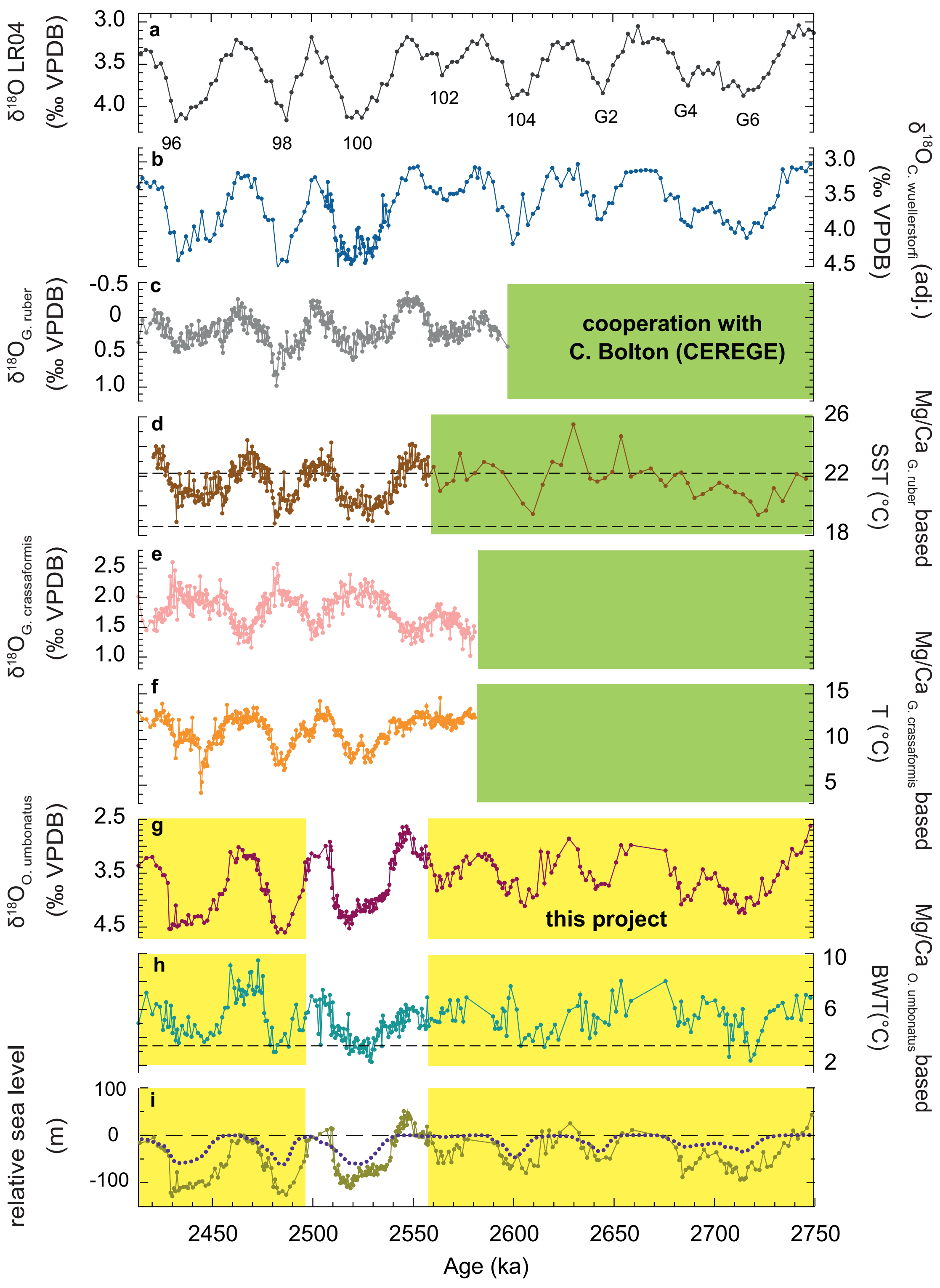

Figure 1: High-resolution proxy records from IODP Site U1313 for MIS G6 to 95, tuned to the LR04 stack. Yellow boxes: This study. Green boxes: Records provided by C. Bolton. **(a)** LR04 stack[12]. **(b)** $\delta^{18}O_{C. wuellerstorfi}$[5],[8]. **(c)** $\delta^{18}O_{G. ruber}$[5]. **(d)** *G. ruber* Mg/Ca-based SST estimates[9]; upper line: Modern mean summer SST; lower line: Modern mean annual SST[25]. **(e)** $\delta^{18}O_{G. crassaformis}$[29]. **(f)** *G. crassaformis* Mg/Ca-based thermocline temperature estimates[29]. **(g)** $\delta^{18}O_{O. umbonatus}$ ([8] and this study). **(h)** *O. umbonatus* Mg/Ca-based BWT estimates ([8] and this study); black line: Modern mean annual BWT[25]. **(i)** Sea-level estimates relative to present ([8] and this study); blue dotted line: Modelled global sea-level relative to present[4]; black dashed line: Modern sea-level.

Deep-sea temperatures

The new *O. umbonatus* Mg/Ca-based BWT record from Site U1313 fluctuates between a maximum value of 9.5°C and a minimum value of 2.2°C between ~2.75 and 2.4 Ma (Figure 1h). Interglacial BWTs are in the order of ~6 to 7°C with exception of MIS 97, which documents the by far warmest temperatures (>7°C, up to 9.5°C) across the entire record. Glacial temperatures (except for MIS G4 and 102) approximate modern mean annual BWT values of 3.4°C[25] at that site. Warmer than glacial standard BWTs during MIS G4 and 102 suggest that these modest glacials as evidenced in benthic foraminiferal $\delta^{18}O$ (Figure 1a,b,g) were too subtle to induce larger-scale changes in deep-ocean temperature. Average BWTs across the studied time interval of ~5.2°C indicate slightly warmer (~1.8°C) than present-day values. This supports the overall notion of a warmer-than-modern global climate during the late Pliocene and early Pleistocene.

Sea-level estimates

The new *O. umbonatus* Mg/Ca- and $\delta^{18}O$-based sea-level record from Site U1313 indicates a clear G-IG cyclicity especially from MIS 100 onward (Figure 1i). Prior to MIS 100, interglacial sea-level highstand estimates tend to significantly exceed present-day sea-level values (this is not documented during MIS 103 and G3 which is a matter of low sample resolution during that interval), while glacial sea-level lowstand estimates remain below modern values. Raw data produce peak sea-level lowstand values (relative to present) of approximately -80 m for MIS 104, -60 m for MIS 102, -55 m for MIS G2, -90 m for MIS G4 and -95 m for MIS G6. From MIS 100 onward, mean sea-level highstand estimates during interglacials approximate modern values. Sea-level lowstand estimates (relative to present) during prominent iNHG glacials are -110 m, -125 m and -130 m for MIS 100, 98, and 96, respectively.

Sea-level estimates from Site U1313 point to a drop in sea level during both glacial and interglacial intervals of ~50 m and ~25 m, respectively, contemporaneously with the onset of prominent G-IG cycles MIS 100–96. This dictates larger-scale G-IG amplitudes from MIS 100 onward compared to the time interval before. This pattern is similar to that observed at Site 607 during the late Pliocene cooling[26], and also reproduces findings from east Pacific Site 849 for the same time interval[27].

The overall G-IG variability in sea level evolution of MIS 100 and 96 determined for the North Atlantic resembles the asymmetric "sawtooth" pattern of late Pleistocene G-IG cycles, with a gradual sea-level drop into glacial periods followed by an abrupt sea-level rise (~1.3 m per century) during the termination. Identical to observations made for the Site U1313 benthic $\delta^{18}O$ record (Figure 1g), the high-resolution sea-level record for MIS 100 at Site U1313 demonstrates that the final ~10 kyr of this glacial is characterized by an additional drop in sea level before sea level rose rapidly during the following termination. A comparable, but more subdued pattern emerges for MIS 96. Hence, the overall internal structure of MIS 100 and 96 appears to be strikingly similar to late Pleistocene glacials.

Testing of the hypothesis of an ice-volume threshold for millennial-scale climate amplification during the early Pleistocene – preliminary conclusions

Reconstructed BWT (this study) (Figure 1h) and SST[9] (Figure 1d) estimates from Site U1313 show no evidence for amplification during glacials MIS 100, 98 and 96. However, these glacials reach the thresholds of either a benthic $\delta^{18}O$ value of 4.14 ‰ as proposed for the late Pleistocene[1] (Figure 1a,b,g) or a sea-level drop of ~45-50 m below present[2] (Figure 1i). These results support findings from Eastern Equatorial Pacific Site 849[27],[28] that question the existence of such a threshold. Possibly the proposed thresholds were only barely reached (as opposed to not clearly surpassed) for a time interval too short to trigger the amplification of millennial-scale climate fluctuations. Alternative explanations could be (1) that a higher ice-volume threshold than proposed might be required to amplify millennial-scale climate fluctuations during the early Pleistocene or (2) that factors other than ice volume might exist that triggered higher amplitudes of millennial-scale climate fluctuations.

4. Publication of results

Results will be published in peer-reviewed journals; a manuscript (Jakob et al. [in prep.]) is close to submission.

5. Accounting of expenditures

Mg/Ca measurements at NOCS	1,900 EUR
Travel expenses	
Flight and train ticket (Heidelberg - Southampton - Heidelberg)	450.20 EUR
Public transport	40.59 EUR
Accommodation expenses for 9 nights	270.00 EUR
Daily allowance	355.20 EUR
Total expenses	**3015.99 EUR**

6. Acknowledgements

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8. List of appendices

Accounting of expenditures and receipts