Late Pliocene onset of millennial climate variability during the intensification of Northern Hemisphere Glaciation

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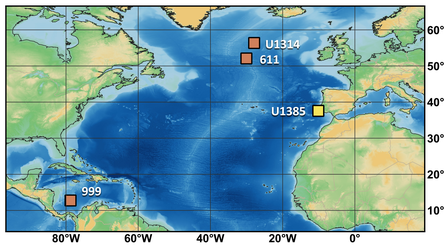
1. Research questions

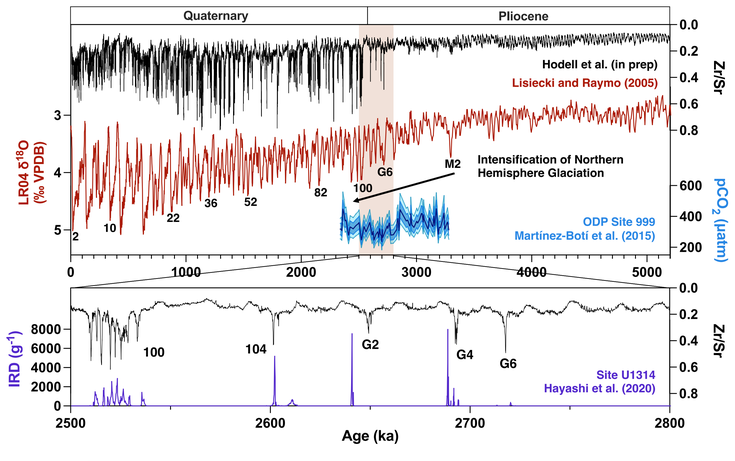
- How did millennial climate variability (MCV) evolve during the Plio-Pleistocene?
- How did MCV respond to changing orbital configuration and climate background state during the intensification of Northern Hemisphere Glaciation (iNHG) in the late Pliocene?
- Is there a benthic $\delta^{18}O$ threshold for MCV? Is it stationary or changing through the Quaternary? What are the implications for the relationship between MCV and ice-sheet size/volume/height?

2. Study site: IODP Site U1385

- Marine sediment cores from Site U1385, Iberian Margin (IODP Expedition 397)
- High sedimentation rates (averaging 9-11 cm/kyr)
- Extending back to the base of Pliocene

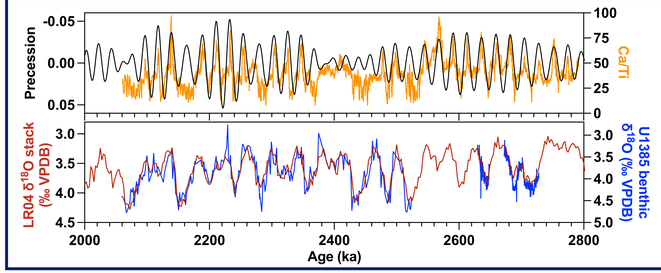


3. Studied interval in broader context



- XRF Zr/Sr shows four distinct peaks representing millennial cooling events (stadial events) in MIS G6, G4, G2 and 104. These 'precursor events' precede the onset of pronounced MCV marked by multiple stadial events beginning with MIS 100.
- Stadial events recorded at Site U1385 appear to correlate with North Atlantic ice-rafted debris (IRD) peaks at Site U1314 (Hayashi et al. 2020).

4. Precession-tuned age model



- Sediment compositional changes at Site U1385 contain strong precession signals (Hodell et al. 2013).
- We tuned Ca/Ti maxima to precession minima using QAnalyseries (Kotov and Pälike 2018) and applied a 3-kyr lag (Ziegler et al. 2010).
- Benthic $\delta^{18}O$ on the precession-tuned age model of Site U1385 shows good agreement with the LR04 timescale (Lisiecki & Raymo 2005).

5. Site U1385 paleo-records

a) Site U1385 benthic $\delta^{13}C$ of *C.wuellerstorfi;*

b) IRD from IODP Site U1314 (Hayashi et al. 2020) and DSDP Site 611 (Bailey et al. 2013);

c) Site U1385 Ca/Ti (Hodell et al. in prep);

d) Site U1385 planktic $\delta^{18}O$ of *G. bulloides*;

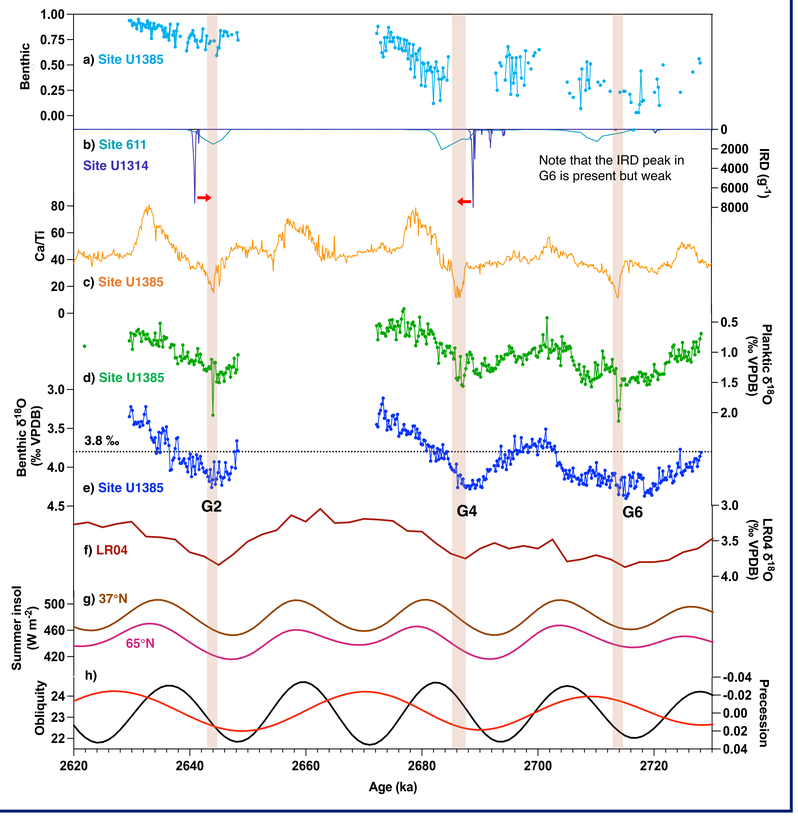
e) Site U1385 mixed benthic (*C. wuellerstorfi* and *U. peregrina*) $\delta^{18}O$. *C. wuellerstorfi* $\delta^{18}O$ has been corrected by 0.64‰. Dotted line show the MCV threshold at 3.8‰ (Hodell et al. 2023);

f) LR04 benthic stack (Lisiecki & Raymo 2005);

g) 65°N and 37°N summer (JJA) insolation (Laskar et al. 2004);

h) Precession (black) and obliquity (red) (Laskar et al. 2004).

Orange shadings highlight the timing of the stadial events.



6. MCV increased with the iNHG

- The first significant millennial cooling event (stadial event) occurred during MIS G6 at 2.72 Ma. The next three glacial stages (G4, G2 and 104) are also marked by single stadial events. The onset of multiple stadial events began with MIS 100 at 2.54 Ma.
- Stadial events during MIS G2 and G4 occurred late in the glacial cycle near the onset of termination (i.e. terminal stadial events). In contrast, the stadial event during MIS G6 occurred in the middle of the glacial stage.
- Each stadial event just followed the summer insolation minima.
- All stadial events occurred when benthic $\delta^{18}O$ had exceeded the 3.8‰ threshold – the same value as identified for the last 1.45 Ma at Site U1385 (Hodell et al. 2023), suggesting no change in the threshold.
- Peaks in North Atlantic IRD appear to be correlative with stadial events on the Iberian margin within the error of the respective age models, indicating a link with iceberg calving and freshwater forcing at high latitude.
- Ice sheets had grown large enough during the glacials MIS G6, G4, G2 and 104 to induce a significant response to freshwater forcing upon deglaciation.

7. Future work

- Extend the high-resolution benthic and planktic $\delta^{18}O$ records over the entire interval of iNHG to determine phase relations and the nature of MCV.
- Analyse Mg/Ca on benthic foraminifera to deconvolve the combined effects of deep-water temperature and ice volume on benthic $\delta^{18}O$ values.
- Apply Empirical Nonlinear Orbital Fitting (ENOF) analysis (Liautaud et al. 2020) to estimate the relative importance of obliquity and precession in proxy records.

References and acknowledgements

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Funding for this work was provided by the C-CLEAR NERC DTP. Sincere thanks to members of the Godwin Laboratory for their contribution and support: Jeannie Booth, Sean (Xi) Chen and James Rolfe. Additional appreciation is extended to Kejia Ji for his advice on poster design.

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