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Final Report for Research Grant:

Temperature and stratification evolution across the Oligocene/Miocene transition in the western North Atlantic (IODP Expedition 342)

1. Introduction

After the abrupt cooling and the establishment of a large ice-sheet on Antarctica at the Eocene/Oligocene Boundary (Oi-1) (Katz et al., 2008; Lear et al., 2004; Miller et al., 1991), the middle-late Oligocene and early Miocene periods were characterized by relative warmth with a superimposed large climate variability (e.g. Freeman and Hayes, 1992; Pagani et al., 1999; Pälike et al., 2006). Stable oxygen and carbon isotope records from benthic foraminifera reveal changes that are attributed to waxing and waning of Southern Hemisphere ice-sheets that followed the trends and rhythms of orbital cyclicity (e.g. Miller et al., 1991; Pälike et al., 2006; Zachos et al., 1997). A significantly larger positive oxygen isotope excursion of 1‰ occurred immediately after the Oligocene/Miocene boundary at ~23 Ma. This event is termed Mi-1 and has a total duration of ~400 kyr (Miller et al., 1991; Paul et al., 2000; Zachos et al., 1997). The deep-sea temperature evolution is fairly well constrained (e.g. Mawbey and Lear, 2013; Paul et al., 2000; Zachos et al., 1997), with temperatures dropping by a maximum of 2-2.5°C across the Mi-1 (Lear et al., 2004; Mawbey and Lear, 2013). Surprisingly, however, only few planktic foraminiferal records exist so far (Paul et al., 2000; Pearson et al., 1997), and the sea surface temperature (SST) evolution across the Mi-1 is essentially unknown. Moreover, records are currently limited to the Southern Hemisphere and equatorial Atlantic. Consequently, the extent to which the Northern Hemisphere oceans reacted to the cooling is currently unknown. Here, we address this gap of knowledge through Mg/Ca measurements on pristinely preserved planktic foraminifera, spanning the interval from 23.3 to 21.6 Ma, including the Mi-1 event. The approach enables us to establish the first semi-high SST record from this time period. Additionally, the comparison of a mixed layer and a thermocline-dwelling species allows evaluation of upper water column stratification.

2. Material and Methods

International Ocean Drilling Program (IODP) Site U1405 (40°8.2995'N, 51°49.1845'W) was drilled during Expedition 342, recovering sediments along a depth-transect of the continental margin off the Grand Banks shelf region. The studied Site U1405 is located on J-Anomaly Ridge with a modern water depth of 4280 m (Expedition 342 Scientists, 2012). A splice of three holes was drilled at Site U1405, which provides a continuous sequence of an expanded Oligo-Miocene succession with sedimentation rates of 4 – 10 cm/kyr. Foraminifers are present and pristinely preserved ("glassy" preservation, cf. Sexton et al., 2006), providing ideal conditions for geochemical analyses.

A total of 153 samples have been taken between 118 and 252 meters composite depth (CCSF) with a sample spacing of between 0.5m and 1 m. Samples were dried and weighed before being disaggregated and washed through a 63-µm-sieve with distilled water. Two planktic foraminiferal species, *Globigerinoides primordius* and *Catapsydrax dissimilis* were picked from the > 125 µm size fraction of all samples. 40 and 48 samples provided enough tests of *G. primordius* and *C. dissimilis,* respectively, to conduct Mg/Ca measurements (10 – 40 specimens, depending on size and weight of the tests).

The foraminiferal tests of these samples were cracked with a pin and subsequently cleaned following the cleaning protocol of Boyle and Keigwin (1985), including the reductive step to remove oxidative coatings. This step was omitted for *C. dissimilis* because preliminary measurements had shown that this species does not feature such coatings. The trace element spectrum was measured at the National Oceanographic Centre Southampton (UK) with a Perkin Elmer Optima 4300DV Inductively Coupled Plasma-Optical Emission Spectrometer. Mg/Ca ratios are given in mmol/mol. Standards measured alongside our samples show a reproducibility better than 0.034 Mg/Ca mmol/mol.

Mg/Ca-based temperatures were estimated using the multi-species calibration of Anand et al. (2003). In order to apply this (or any other calibration), knowledge about the Mg/Ca ratio of the seawater is required. This ratio may have changed through earth history (Stanley and Hardie, 1998; Wilkinson and Algeo, 1989), although it has been suggested that the seawater Mg/Ca variability was negligible during the Cenozoic (Lear et al., 2004; Rowley, 2002). Additionally, Lear et al. (2004) measured Sr/Ca ratios on benthic foraminifera from samples between 19 and 35 Ma. It shows little systematic trend, suggesting that Mg/Ca were fairly constant through their study interval (see Lear et al., 2004 for details). We thus argue that this also applies to our record, which spans a much shorter interval (< 2 Myr) within their study interval, and therefore apply modern Mg/Ca seawater values for the temperature estimation. Absolute temperatures might be slighty underestimated with the approach, but short-term variations and relative temperature variations will be unaffected by this (Lear et al., 2004).

The age model used in this study is based on shipboard magnetostratigraphy, which provided good age control for the study interval. Linear sedimentation is assumed between magnetochron datums, resulting in sedimentation rates of 4 – 10 cm/kyr. Because of the great variability of the sedimentation rates, the resolution of our record is equally variable, ranging from 3 kyrs to > 30 kyrs.

3. Results

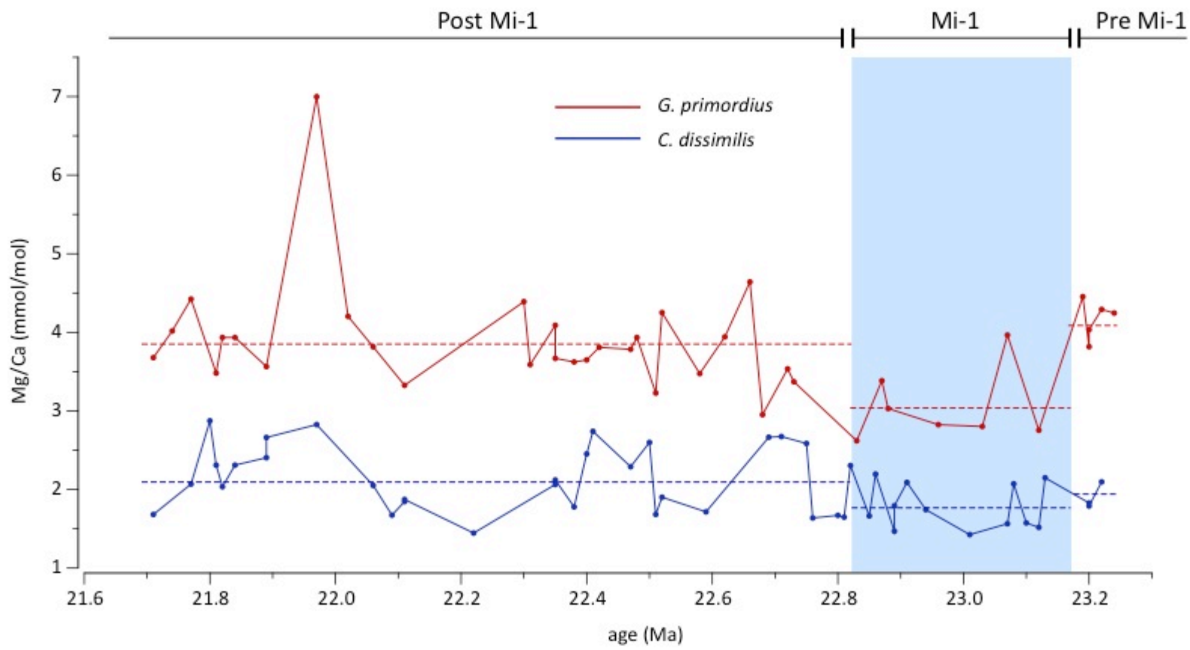

Figure 1 – Mg/Ca record of *Globigerinoides primordius* (red line) and *Catapsydrax dissimilis* (blue line). The Mi-1 interval is highlighted with a light blue bar.

Mg/Ca data are plotted in Figure 1; estimated temperatures are shown in Figure 2. Background Mg/Ca values from the latest Oligocene were ~4.1 mmol/mol in the mixed surface layer (*G. primordius*), corresponding to an estimated temperature of ~27°C. With the onset of the Mi-1 at 23.20 Ma, temperatures dropped by 4°C (to Mg/Ca values of 3.1 mmol/mol). Throughout the ~400 kyr-long Mi-1 interval temperatures remained lower on average, but high-amplitude variability is also visible. At 22.80 Ma, the Mg/Ca values increased to 3.8 mmol/mol (temperatures increase of ~3°C), not quite recovering to pre-event values, and remained relatively constant through the rest of the study interval. Mg/Ca values of *C. dissimilis* were significantly lower, averaging 1.9 mmol/mol (Pre Mi-1), 1.8 mmol/mol (Mi-1) and 2.1 mmol/mol (Post Mi-1), respectively. Correspondingly, thermocline temperatures were around 6-7°C colder throughout the study interval, and the Mi-1 only caused a transient ~1°C cooling. Mixed layer and thermocline temperatures were variable throughout the study interval, but contrary to the stable isotope records, the depth gradient is not significantly affected by the Mi-1 and remained fairly constant throughout the study interval.

Temperature calibration

The basis of the Mg/Ca paleothermometry is that the ratio at which Mg is incorporated into the calcareous shell of the foraminifera as a substitute of Ca is a direct function of temperature (Barker et al., 2005 and citations within; Blackmon and Todd, 1959; Chave, 1954). This ratio is, however, also dependent on species-specific vital effects, so that single-species calibrations are usually required to reconstruct absolute temperatures. Unfortunately, such calibrations do not exist for either *G. primordius* or *C. dissimilis.* It has, however, been suggested that the temperature sensitivity for Mg/Ca is rather similar for almost all planktic foraminiferal species (~10 ‰ per 1°C temperature change) (Anand et al., 2003; Elderfield and Ganssen, 2000; Lea et al., 1999), and multispecies calibrations have been developed (e.g. Anand et al., 2003; Cléroux et al., 2008; Regenberg et al., 2007). Such calibrations will provide fairly robust relative temperature changes even though they

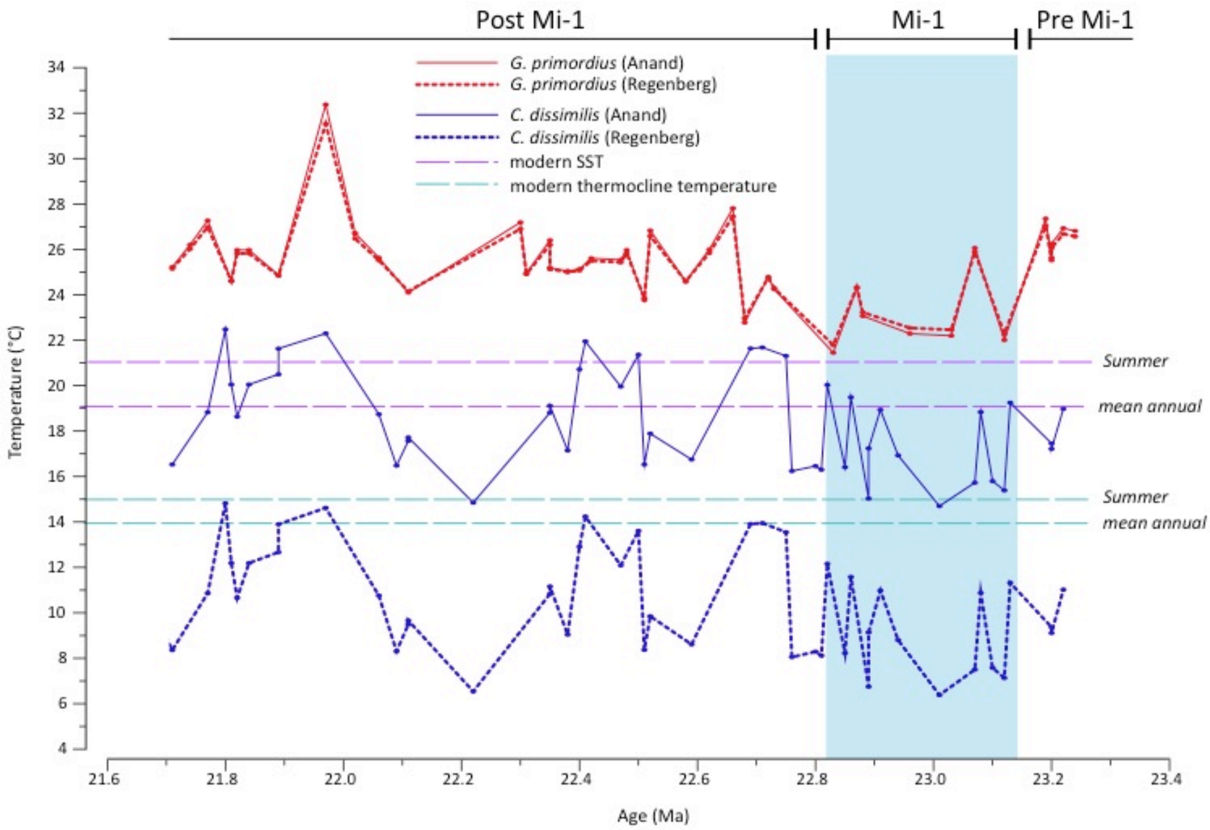

Figure 2 – Mg/Ca-temperature calibrations after Anand et al. (2003) (solid lines) and Regenberg et al. (2007) (dotted lines). The calibrations are almost identical for *Globigerinoides primordius* (red lines), but *Catapsydrax dissimilis* (blue lines) shows much colder thermocline temperatures with the Regenberg calibration, resulting in a very large vertical gradient (double of the present day value). Dashed lines indicate mean annual and average summer surface temperatures for the sea surface (purple) and for the thermocline (turquoise) (Locarnini et al., 2010).

might over- or underestimate absolute temperatures somewhat (Anand et al., 2003).

The calibrations of Cléroux et al (2008) cannot be used for our samples because the expected SSTs are too high and outside the calibration range. We applied the calibrations of Anand et al. (2003) and Regenberg et al. (2007) to our Mg/Ca data (Fig 2). The estimated temperatures are almost identical for *G. primordius*, but *C. dissimilis* temperatures are on average 8°C lower with the Regenberg calibration. This results in an average thermocline-mixed layer gradient of 6°C for the Anand calibration, and ~14°C with the Regenberg calibration. At present day, the upper water column gradient varies between ~2°C (winter) and 6°C (summer)(Locarnini et al., 2010)(Fig. 2). Therefore, we suggest that the calibration of Anand et al (2003) is more suitable for our data, because such a big gradient compared to present day values (more than double) at this site is unlikely.

Throughout the entire study interval the temperatures estimated from Anand et al. (2003) are higher than modern summer SSTs at this site (Locarnini et al., 2010)(Fig. 2). They show that even the average temperatures during the Mi-1 are ~2°C above modern average summer surface temperatures. This is, however, not surprising since the Oligo-Miocene mean state was characterized by higher global temperatures compared to today (e.g. Zachos et al., 2001) that did not yet support significant Northern Hemisphere glaciation. It is also in agreement with South Atlantic bottom water temperatures that are ~2-2.5°C warmer during the Mi-1 compared to modern temperatures (Mawbey and Lear, 2013).

Additionally, it is possible that the species might preferentially reproduce and calcify during the summer months and thus record temperatures that are biased towards summer temperatures (rather than mean annual temperatures), an effect known from observations on modern planktic foraminifer species such as *Globigerinoides ruber* (e.g. Kawahata et al., 2002; Lee and Slowey, 1999; Pujol and Grazzini, 1995; Troelstra and Kroon, 1989). This is, however, hard to assess for extinct species. Nevertheless, we suggest that the temperatures estimated from Mg/Ca with the Anand calibration are fairly reasonable, and relative temperature changes are neither effected by the calibration nor the possible bias towards summer temperatures.

4. Preliminary conclusions

- Mi-1 cooling is clearly reflected in the surface temperatures of the mid-latitude North Atlantic
- significant SST cooling of 4°C between 23.20 and 28.82 Ma
- muted 1-2°C cooling at thermocline depth
- coolest Mi-1 temperatures are ~2°C above modern average summer surface temperatures
- this might suggest that strength and/or flow patterns of surface currents (e.g. the Gulf Stream) were influenced by this event

5. Accounting of Expenditures

Mg/Ca measurements at the National Oceanographic Centre Southampton	482,87 €
Travel expanses	350 €
Hotel Costs for 6 nights	321,50 €
Daily Allowance	85,63 €
Total	**1240 €**

6. Acknowledgements

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