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Marine Isotope Substage 5e and the Eemian Interglacial

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Abstract

The subdivision of Marine Isotope Stage 5 (MIS5) into five substages is robustly applicable to benthic oxygen isotope records from almost all areas of the ocean. The association of the Eemian Interglacial (in the sense that this concept is utilized by palynologists) with MIS 5e is widely agreed on the basis of a diversity of evidence. Here we present the first direct evidence regarding the relationships between the boundaries of these two stratigraphic entities. The base of the Eemian as recognized here is significantly younger than the base of MIS 5, and indeed falls within the isotopic "plateau" of MIS 5e during which global sea-level is thought to have been a few meters higher than at present. The termination of the Eemian Interglacial in Portugal as recognized in the palynological record in this core off southern Portugal is well within MIS 5d.

Keywords: Marine Isotope Stage 5 (MIS5); Eemian Interglacial; oxygen isotope

1. Introduction

Oxygen isotope records obtained by analysis of planktonic foraminifers from deep-sea cores in the Caribbean were divided by Emiliani (1955) into stages numbered from the top downwards. Shackleton (1967) provided evidence that the $\delta^{18}O$ record is dominated by the effect of changes in the oxygen isotopic composition of the global ocean and therefore that the isotope stages (now widely referred to by Marine Isotope Stage, (MIS1...) numbers) could be used as a means to create a global stratigraphic framework for marine sediment. Shackleton and Opdyke (1973) proposed that the boundaries could be regarded as defined at their levels in Pacific core V28-238 which they analysed. For the description of Quaternary marine sediments this scheme is almost universally applied, although the means by which it is applied varies; Prell et al. (1986) recommend the use of "events" (isotopic extremes) rather than boundaries (transitions between isotope stages) for applying the formal oxygen isotope stratigraphy (and associ-

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ated timescale) to a core. This approach is useful for some purposes but departs from general stratigraphic practise and is not recommended here.

Shackleton (1969) recognized that in an informal sense, the marine oxygen isotope record is useful in relation to Quaternary stratigraphy in general, rather than purely to the marine record. He proposed an informal division of MIS 5 into five sub-stages, having demonstrated that the Eemian Interglacial (as this concept was understood by palynologists at that time) is equivalent to only a small part of MIS 5. It is now widely agreed that in most parts of the Earth major climatic and palaeoenvironmental units typically have a duration of the order of half a precession cycle (around 10 ka) rather than half an eccentricity cycle (around 50 ka) so that the level of stratigraphic resolution provided by the Middle Pleistocene MIS (typical duration 50 ka) is not sufficiently fine to constitute a universal stratigraphic template.

It is generally understood that the Eemian may be recognized in a vegetational sequence as the interval dominated by forest elements, preceded by the open vegetation of the previous glacial, and succeeded by the open vegetation of the last glacial complex (Turner and West, 1968). It has already been demonstrated by Sánchez-Goñi et al. (1999) that the Eemian so recognised does not have the precise relationship to MIS 5e anticipated by Shackleton (1969). The purpose of this paper is to clarify this relationship in the light of additional data, and in particular in the light of a high resolution benthic $\delta^{18}O$ record for core MD95-2042 that was investigated by Sánchez-Goñi et al. (1999), as well as a new sea-surface temperature record for the same core.

2. Methods

Core MD95-2042 was collected using the CALYPSO Kullenberg corer aboard Marion Dufresne at 37°48′ N, 10°10′ W in a water depth of 3146 m (Bassinot et al., 1996). The working half was sliced into pieces 1 cm thick. For this study stable isotopes and pollen were analysed with a 4-cm resolution and alkenones with a 10-cm resolution. Pollen analysis and stable isotope analyses were carried out on the same slices, and approximately 50% of the samples for alkenone analysis were also taken from these same samples. The methods for pollen analysis are reported by Sánchez-Goñi et al. (1999) where the data are discussed in detail. For benthic $\delta^{18}O$ analysis samples were disaggregated in deionised water and washed over a 63-μm sieve. Benthic specimens were picked from the fraction greater than 212 μm; in the interval discussed here over 50% of the analyses were of *Cibicidoides wuellerstorfi* and the remainder were *Uvigerina peregrina* or *Globobulimina affinis*. Oxygen isotope values for *Cibicidoides wuellerstorfi* were adjusted by 0.64‰ to take account of its departure from isotopic equilibrium (Shackleton and Opdyke, 1973). Oxygen isotope values for *Globobulimina affinis* were adjusted by −0.3‰ (Shackleton et al., 2000) to take account of the departure from isotopic equilibrium of this species (this figure is based on comparison with *Cibicidoides wuellerstorfi* in samples containing specimens of both these species). In order to minimise the analytical variability on the "plateau" of MIS 5e, only *Cibicidoides wuellerstorfi* specimens were analysed over this interval. The majority of measurements on this species combined three specimens.

3. Oxygen isotope stratigraphy and time scale

In this paper we have attempted to present the data for core MD95-2042 on a time scale that is entirely constrained by radiometric age determinations. Fig. 1 shows the benthic $\delta^{18}O$ data versus depth in core. The data can be described as an interval of transition from MIS 6 to MIS 5e, a "plateau", and an interval of transition from MIS 5e to MIS 5d. This "plateau" may be informally defined as that interval beyond which values become significantly more positive. We also recognise other intervals of constant value that may be denoted as "stillstands"; for each stillstand we give a mean, a standard deviation and the number of analyses contained. Between 24.92 and 25.76 m the mean value is 3.15 ± 0.11‰ (n = 26); at 24.88 m the value is 3.45‰ and at 25.80 m, 3.37‰, above which values become much isotopically heavier again, so that the length of the MIS 5e plateau is easily defined. Despite the small standard deviation over the "plateau" there is a clear trend with the lightest values at the base of the "plateau".

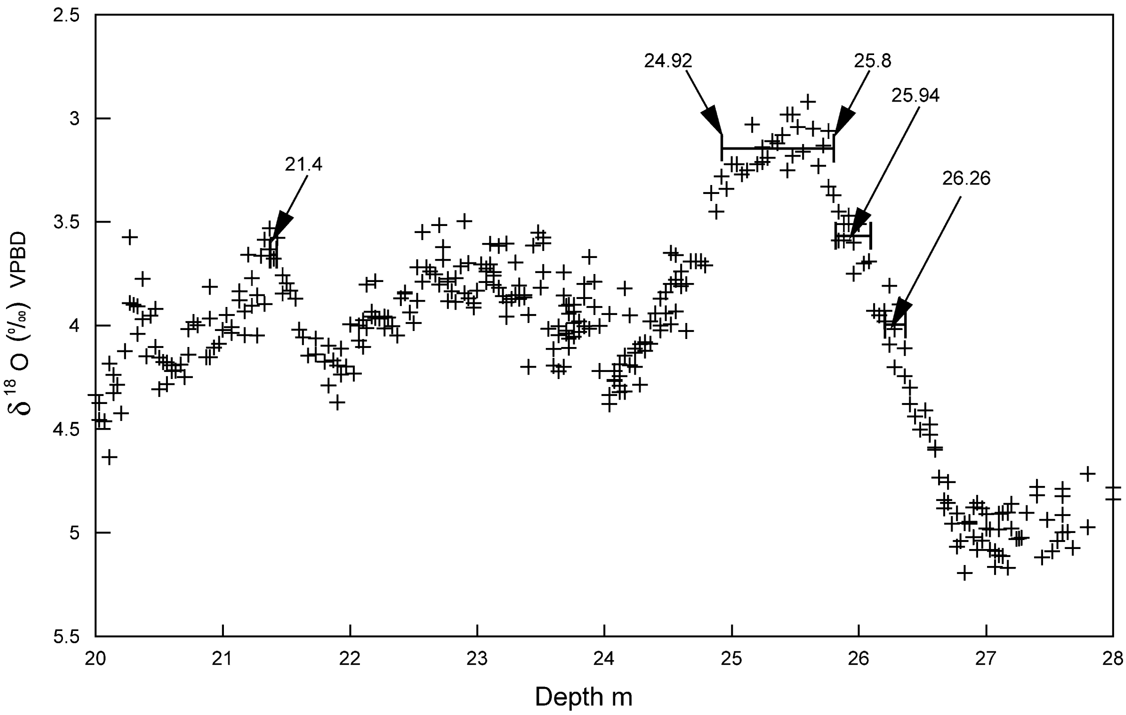

Fig. 1. Benthic δ^{18}O record (individual analyses) for MIS5 and MIS6 in core MD95-2042. Depths used for age controls are indicated by arrows, with bars showing the depth interval over which values are averaged to indicate the MIS 5e plateau and the stillstands (see text).

A stillstand for the glacial extreme of MIS 5d may be defined between 24.04 and 24.16 m with values of 4.24 ± 0.11 ‰ (n = 10). The isotopically lightest peak in MIS 5c is a short stillstand represented between 23.44 and 23.52 m with values of 3.65 ± 0.09 ‰ (n = 5). The stillstand for the glacial maximum in the upper part of MIS 6 may be defined for comparison with MIS 5e by the 26 values immediately below 26.73 m with values of 5.00 ± 0.09 ‰ (n = 26). The transition from MIS 6 to MIS 5 is fairly smooth; the best candidates for stillstands are between 25.80 and 26.08 m with values of 3.56 ± 0.11 ‰ (n = 10) and between 26.20 and 26.36 m with values of 4.00 ± 0.12 ‰ (n = 8).

For all the values quoted here the 1-sigma variability is a little larger than that observed for replicate analyses of small samples of standard marble (typical 1-sigma about 0.08 ‰), but is nevertheless small enough to support the hypothesis that sea-level was more or less stationary (it must be borne in mind that "more or less stationary" permits a range in excess of 10 m, which is enormous in terms of the geomorphic identity of a high-stand). In particular the measurements over what we have designated the MIS 5e plateau are certainly not consistent with the occurrence during this interval of a low-stand at between − 60 and − 80 m, such as is apparently documented in "Aladdin's Cave" (Esat et al., 1999), being within this interval. Even a single specimen that lived during such an episode would probably have been detected by our measurements, and it seems inconceivable that sea-level could have dropped so far and returned to its interglacial level in such a short interval that it would go undetected in our study. However, the apparent low stillstand between 26.20 and 26.36 m is a reasonable candidate for the correlative of this event, with benthic δ^{18}O values 0.85 ‰ heavier than those of the MIS 5e plateau. Cutler et al. (1999) report on a sudden rise in sea level by about 25 m, culminating at the level of the interglacial high stand, with a date of 129.1 ± 0.8 ka for coral living during a stillstand of the sea preceding this final rise (Edwards et al., 1997); the stillstand immediately preceding the MIS 5e plateau, 0.31 ‰ heavier than the values for the MIS 5e plateau, is consistent with this event. This is in agreement with the date of 128 ± 1 ka given by Stirling et al. (1998) for the oldest coral at the altitude of the MIS 5e highstand. If this interpretation is correct, an age of 132 ± 2 ka for the "Aladdin's Cave" (Esat et al., 1999) is reasonable although it does imply a more rapid deglaciation than at the end of the last glacial. It should be noted that the actual Aladdin's Cave radiometric measurements cover a range in age estimates that is an order of magnitude greater than the analytical uncertainty, yet the true age span can hardly exceed 1 ka. The age obtained by Henderson and Slowey (2000) of 135 ± 2 ka for the mid-point of the

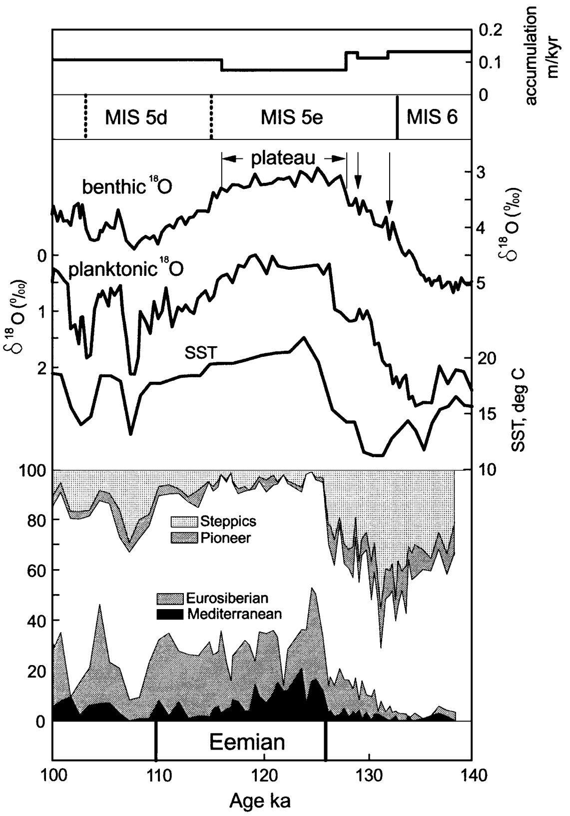

Fig. 2. Marine and continental records of the last interglacial in core MD95-2042 on a time scale based on radiometric dates for uplifted corals (see text). From the top: Sedimentation rate implied by the age controls marked; benthic δ^{18}O record (replicates averaged); planktonic δ^{18}O record (replicates averaged); sea surface temperature based on U^{k}_{37} alkenones; major groups of pollen taxa.

Stage 6–5 transition would allow a slightly less rapid deglaciation.

The termination of the MIS 5e plateau is best dated by the work of Stirling et al. (1998) at Mangrove Bay which documents the regression from the MIS 5e high stand. We assign their age of 116.1 ± 0.9 ka for the start of the marine regression to the depth in core of 24.92 m, the upper limit of our MIS 5e plateau. It is difficult to assign ages precisely in MIS 5c because the record is quite complex, but MIS 5a appears to have a clearly defined maximum (21.37 to 21.42 m, 3.66 ± 13 ‰, $n = 5$) that we assign the age of 82.9 ± 0.4 ka (Edwards et al., 1997). We use these dates to present the data for core MD95-2042 on a radiometric timescale that is independent of astronomical calibration. Fig. 2 shows benthic δ^{18}O, planktonic δ^{18}O, sea-surface temperature and the key vegetational elements for the last interglacial using these age controls.

4. Discussion

The beginning of the Eemian is identified in the vegetational sequence by a simultaneous drop in steppic elements and a rise in Eurosiberian and Mediterranean trees; there is no ambiguity in its placement. This change coincides with a 5° rise in sea-surface temperature as indicated by the alkenone measurements; the coincidence with the planktonic δ^{18}O change (also indicating a sea-surface temperature rise) is equally striking. The age of this event on our timescale is 126 ka, significantly later than the attainment of the MIS 5e plateau in benthic δ^{18}O. This implies that in contrast to the base of the Holocene, the major ice sheets had completely melted before the beginning of interglacial climatic conditions in Northwest Europe. In view of the fact that immediately prior to this transition, cold water was offshore at the latitude of southern Portugal, it is very unlikely that the beginning of the vegetation-defined interglacial was any earlier at sites further to the North.

The end of the Eemian is identified in the vegetational sequence by a simultaneous rise in steppic elements and a drop in Eurosiberian trees, and the disappearance of the Mediterranean elements. Again the placement of the boundary is relatively uncontroversial at least at a local level. This boundary is well within MIS 5d and indeed appears shortly before the most positive benthic $\delta^{18}O$ values are recorded, implying that the Laurentide ice sheet had grown considerably. It should be noticed that the local sea-surface temperature appears to have been falling gradually through the Eemian, but that a further cooling occurred very close to the end of the Eemian as identified here. There is a continual evolution of the vegetation during the Eemian and it cannot be assumed that a boundary marking the end of the interglacial would be drawn at the same age in a vegetational sequence covering the same time interval in a more northerly part of Europe.

5. Conclusions

Early in MIS 5 this part of the North Atlantic was too cold to permit the development of the tree cover on adjacent Portugal that is the basis for recognising the Eemian Interglacial. The base of the Eemian Interglacial appears to be about 6000 years younger than the base of MIS 5 (defined as the mid-point of the MIS 6–5 transition measured in benthic foraminifera) and about 2000 years younger than the attainment of interglacial sea-level close to its present altitude at the base of the "MIS 5e plateau". After the end of MIS 5e an Eemian Interglacial vegetation cover survived (at least at the latitude of Portugal) well into MIS 5d at the same time as substantial continental ice was accumulating in North America.

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