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Research paper

Radiolarian stratigraphy near the Eocene–Oligocene boundary

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A R T I C L E I N F O

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A B S T R A C T

Three sites from the equatorial Pacific (ODP 1218, IODP U1333, and U1334) are judged to have a complete stratigraphic sequence across the Eocene–Oligocene boundary. The sections of all three sites from ~40 Ma to ~30 Ma have been sampled and the samples merged into a single composite section with an average sample spacing <20 kyr. A total of 76 radiolarian species, species groups, and specific variant forms provide a detailed radiolarian stratigraphy across this climatically important boundary. Altogether 47 Eocene radiolarian species had their last appearance between ~40 Ma and the end of the final step of the Eocene–Oligocene climate transition, many of them in discreet episodes of extinction that grew in magnitude as the transition was approached. First appearance datums appear to cluster at the base of the cool-down from the middle Eocene climate optimum and near the base of the Oligocene, following a maximum in radiolarian last appearances and coincident with relatively abundant diatoms. There appears to be little relationship between paleoproductivity as measured by barite accumulation rates and both first and last appearances of radiolarians. Diatoms are not common in the Eocene and their blossoming in the Oligocene is preceded by the major episodes of radiolarian extinctions. In the Oligocene radiolarian extinctions appear to be associated with low to moderate diatom abundance, whereas species first appearances seem to be associated with moderate to high diatom abundance. Neither paleoproductivity nor a competition for the dissolved silica (a resource necessary for diatom frustule and radiolarian test construction) appears to control the episodic extinction of radiolarians in the Eocene or the more dispersed loss of species in the Oligocene.

1. Introduction

Nigrini et al. (2006) developed the radiolarian stratigraphy for three Ocean Drilling Program (ODP) sites in the tropical Pacific: Sites 1218, 1219, and 1220 and tied it to the paleomagnetic time scale, giving a comprehensive tabulation of radiolarian datums in the tropical Pacific. In their work, 12 new species were defined that added to the resolution of the stratigraphy, particularly in the upper Eocene and lower Oligocene. However, near the Eocene–Oligocene (E/O) boundary, defining the First and Last Appearance Datums (FADs, LADs) is made difficult by the presence of hiatuses and the reworking of older species into the younger levels.

Coxall et al. (2005) determined that Site 1218 shows a characteristic “two-step” shift in all major lithostratigraphic and isotopic variables across the E/O boundary, which they linked to a two-phase development of the Antarctic ice sheets (DeConto and Pollard, 2003); but, of the three sites studied by Nigrini et al. (2006), only Site 1218 is regarded as having a complete section. The other two sites studied have short hiatuses across the E/O boundary, and all three sites show a substantial amount of reworked radiolarians in samples near this boundary, especially in the latest Eocene (Nigrini et al., 2006; Moore and Kamikuri, 2012; Moore, 2013). This made the definition of the LADs particularly difficult for many Eocene species that became extinct near the E/O boundary.

Nigrini et al. (2006) averaged the age estimates obtained from the three, paleomagnetically dated sites to provide a conservative estimate of the age of datums identified in their study. The presence of hiatuses and the reworking of Eocene species introduced substantial error into these averages for datums near the E/O boundary. In this paper we return to Site 1218 with a more detailed sampling scheme for the interval from ~40 Ma to 30 Ma. We also have taken samples with a similar spacing in Integrated Ocean Drilling Program (IODP) Sites U1333 and U1334 (Fig. 1), the only other sites in the tropical Pacific having the two-step shift in lithologic properties (Pälike et al., 2009) at the Eocene–Oligocene transition (EOT) that indicates the completeness of the boundary section. Using these three sample sets we are able to better identify the radiolarian first and last appearances and more precisely define the age of these datums. Because of the relatively close sample spacing, we are also able to suggest some of the evolutionary connections between species and to relate first and last appearances to changing environmental conditions.

This dramatic turnover in the radiolarian fauna near the Eocene–Oligocene boundary has been associated with a marked loss in average test weight between ~35 Ma and ~33 Ma (Lazarus et al., 2009), a loss in weight that continued at a more gradual pace in the tropics during the Cenozoic. Both Harper and Knoll (1975) and Lazarus et al. (2009) allude to the possibility that the rise of diatoms in the tropics, very efficient

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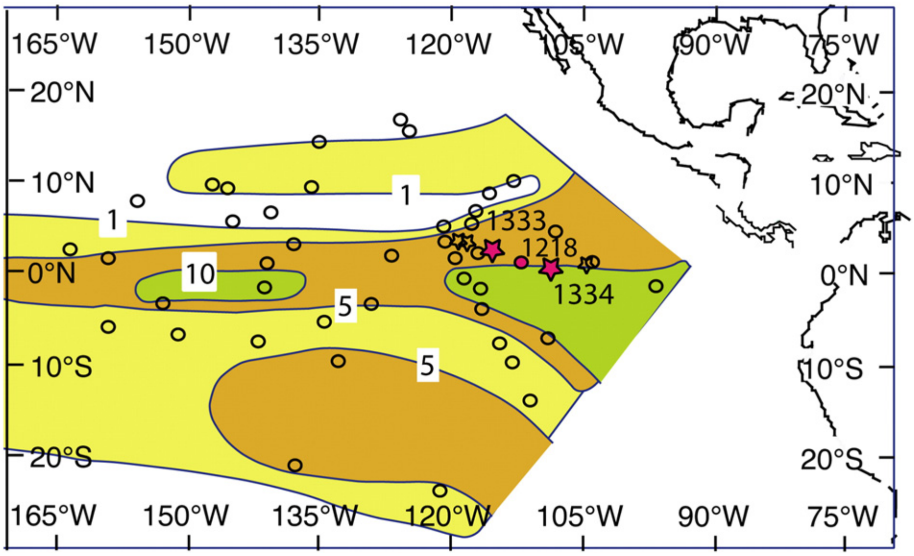

Fig. 1. Map of sediment accumulation rates (m/Myr) in the tropical Pacific at 32 Ma (averaged from 30 Ma to 34 Ma; after Moore et al., 2004). Site locations from original map adjusted according to Parés and Moore (2005). Circles denote site locations used in original work; stars indicate sites from IODP Expedition 320. Filled symbols and labels denote the three sites used in this study.

cyclers of silica in the modern world ocean, may have driven a co-evolution with the radiolarians based on their mutual use of silica for frustule and test construction. This idea was supported by the work of Cervato and Burckle (2003), which showed that diatoms did not become a major part of the fossil record in the tropics until near the Eocene–Oligocene boundary.

This blossoming of the diatoms in the tropical oceans during the Oligocene led Cervato and Burckle (2003) to believe that productivity in the Oligocene tropics was high relative to the Eocene. However, more recent studies (Erhardt et al., 2013; Moore et al. 2014) indicate that in spite of the diatom abundance in the Oligocene, paleoproductivity (export productivity) in the Oligocene was on average only half that of the Eocene (Erhardt et al., 2013). This decrease in estimated export productivity was accompanied initially by a marked cooling of the deeper waters (Liu et al., 2009), a deepening of the tropical thermocline (Sijp et al., 2011; Moore et al., 2014 and references therein), and a marked depletion of the nutrient content of the deep waters (Pälike et al., 2012). Lazarus et al. (2009) proposed that the decreased availability of dissolved silica in the upper ocean could have been at least one of the drivers for the decrease in radiolarian test weight. A drop in the availability of dissolved silica near the Eocene–Oligocene transition (EOT) is consistent with the ocean modeling work of Pälike et al. (2012).

But did the competition for dissolved silica between the rapidly reproducing diatom flora of the tropics and the radiolarian fauna play a role in either the reduction in radiolarian test weight or in the episodes of radiolarian extinctions? In this paper we will address this question using the detailed record of radiolarian first and last appearances to compare with other records of changing environmental conditions in the same sections.

2. Methods and materials

2.1. Samples

The three sites studied have been correlated by Westerhold et al. (2012) using multisensory track data (primarily GRAPE density and magnetic susceptibility) and digital color scans. This detailed correlation resolved variations in the data down to the decimeter scale, with the result that sample depths in Sites U1333 and U1334 can be expressed as equivalent depths in Site 1218. Based on the correlation of multisensor track data and paleomagnetic stratigraphy (Pälike et al., 2009), one cm samples (one quarter core) were taken for radiolarian study over the stratigraphic interval spanning from ~40 Ma to 30 Ma. Samples were taken from cores in individual holes that showed relatively complete and undisturbed recovery. There was some stratigraphic overlap of sampling when shifting from one hole to another in the sampling scheme. Sample spacing varied between about 20 cm and 50 cm. The average sample spacing in the sites is ~35 cm. A total of 641 samples were examined in the three sites used in this study (see Moore and Kamikuri, 2012 for data tables).

Samples were prepared following procedures similar to those described in Sanfilippo et al. (1985). Sediment samples were placed in a beaker with 15% H_2O_2 to remove organic material and a 15% HCl solution to remove the calcareous fraction from the sediment. Samples were washed and sieved through a 63-μm sieve. If upon visual inspection, the coarse residue was found to contain clumps of cemented clays and radiolarian fragments, the sample was treated for up to one minute in a concentrated solution of NaOH (pH ~ 11), immersed briefly (~15 s) in an ultrasonic bath, and then resieved. This usually disaggregated the cemented clumps and cleaned the radiolarian skeletons so that they could be more easily identified. Residues were randomly settled onto a slide (Moore, 1973) and then a 22 × 40 mm cover slip was mounted on top using Norland Optical Adhesive #61 as a mounting medium.

Slides were studied under a transmitted light microscope at x100 magnification. An estimate of the number of radiolarian specimens on each slide was made by counting the number of specimens in one vertical traverse of the slide (one column, 1.4 mm wide) and in one horizontal traverse (one row, 1.5 mm wide). These values were multiplied by the number of rows and number of columns scanned and averaged to estimate the total number of specimens examined on the slide. The number of columns scanned was adjusted to assure that between ~5000 and 10,000 specimens were examined.

2.2. Species used

In these slides a total of 76 species, species groups, and specific variant forms considered to be stratigraphically useful were counted and are given in the Supplementary Taxonomic List (see also the Taxonomic Notes, Tables, and plates in Moore and Kamikuri, 2012). Of these, four species only occurred as reworked, older specimens in some of the sites (*Lithochytris vespertillo*, *Podocyrtis* (*Lampterium*) *mitra*, *Podocyrtis* (*Lampterium*) *trachoides*, *Sethochytris triconiscus*). *Pteropilium sp.* aff.