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Erosion and reworking of Pacific sediments near the Eocene-Oligocene boundary

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[1] The Eocene-Oligocene (E/O) boundary interval marks one of the largest and most rapid changes in climate during the last 50 Myr. Because of a very shallow calcium carbonate compensation depth in the Eocene, as well as the reworking of sediments and hiatuses in the boundary zone, it has also been one of the most difficult stratigraphic boundaries to study in deep water marine sections, especially in the Pacific Ocean. Recently, three drill sites have recovered complete sections of the E/O boundary interval in the tropical Pacific. A detailed study of these sections shows a series of pulses of reworked older radiolarians in the upper Eocene and lowermost Oligocene. The two largest pulses are coincident with the two sharp steps in carbon and oxygen isotope values that bracket the E/O boundary. Several smaller peaks in reworked material precede these two maxima. It is proposed that immixing of the older radiolarian species results from erosion and redeposition, possibly linked to pulses of new bottom water formation and the formation of a deep pycnocline.

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1. Introduction

[2] There is a distinct maximum in hiatuses in the deep-sea sedimentary record within the upper Eocene-lower Oligocene interval [*Moore et al.*, 1978]. This is one of several breaks in the stratigraphic record of deep-sea sediments. The presence of these hiatuses has generally been attributed to the dissolution rate of the carbonate and siliceous microfossils in deep-sea pelagic sediments being greater than their supply rate to the seafloor; thus, temporal variation in the presence of hiatuses was caused by variations in these two rates. In some sites, erosion/nondeposition near boundary currents and flow around large bathymetric features may have also played a role. As recovery of sediments has improved and the stratigraphy of Paleogene sections have become more finely resolved during the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program (IODP), this peak in a missing section has been narrowed down to the Eocene-Oligocene (E/O) boundary region itself, the boundary that marks the rather abrupt shift from the "hothouse" world to the "icehouse" world. Of the 127 sites drilled in the Pacific basin proper, sites that penetrated below the E/O boundary and contained fossiliferous sediments, only 25 actually captured the upper Eocene-lower Oligocene boundary in a core (Table S1 in the Auxiliary Material). The boundary appeared to be between cores in 40 of these sites [*Moore*, 1972]. The 62 remaining sites contained a hiatus at the E/O boundary, sometimes representing a lacuna of millions of years or more and sometimes only a few hundred thousand years. Only where detailed sampling and high-resolution lithostratigraphy or isotope stratigraphy were performed (e.g., ODP Site 1219) could these rather small hiatuses be detected. Thus, there are likely to be small breaks in the stratigraphic record in at least some of the 22 cores that captured the E/O boundary but for which such detailed stratigraphy is not available.

[3] There have been only three tropical Pacific sites in which a complete section across the E/O boundary appears to have been recovered (Table S1 in the Auxiliary Material). The first site, ODP Site 1218, shows the characteristic "two-step" shift in all major lithostratigraphic and isotopic changes across the boundary [*Coxall et al.*, 2005; *Coxall and Pearson*, 2007; *Dunkley Jones et al.*, 2008; *Lear et al.*, 2008], which was linked to a two-phase development of the Antarctic ice sheets [*DeConto and Pollard*, 2003]. More recently, two more sites that recovered very similar sections in the near-equatorial region of the tropical Pacific have been cored: IODP Sites U1333 and U1334 [*Pälike et al.*, 2010] (Figure 1).

[4] Work on these three sites has revealed the multifaceted problems in resolving the E/O boundary, even when using paleomagnetic stratigraphy, as well as the more highly resolved biostratigraphies now available. First, the paleomagnetic stratigraphy indicates that the E/O boundary lies just below the base of Chron C13n, which coincides with the base of the second (youngest) step in lithologic and isotopic changes [*Dunkley Jones et al.*, 2008; *Coxall and Wilson*, 2011]. The boundary itself is contained within

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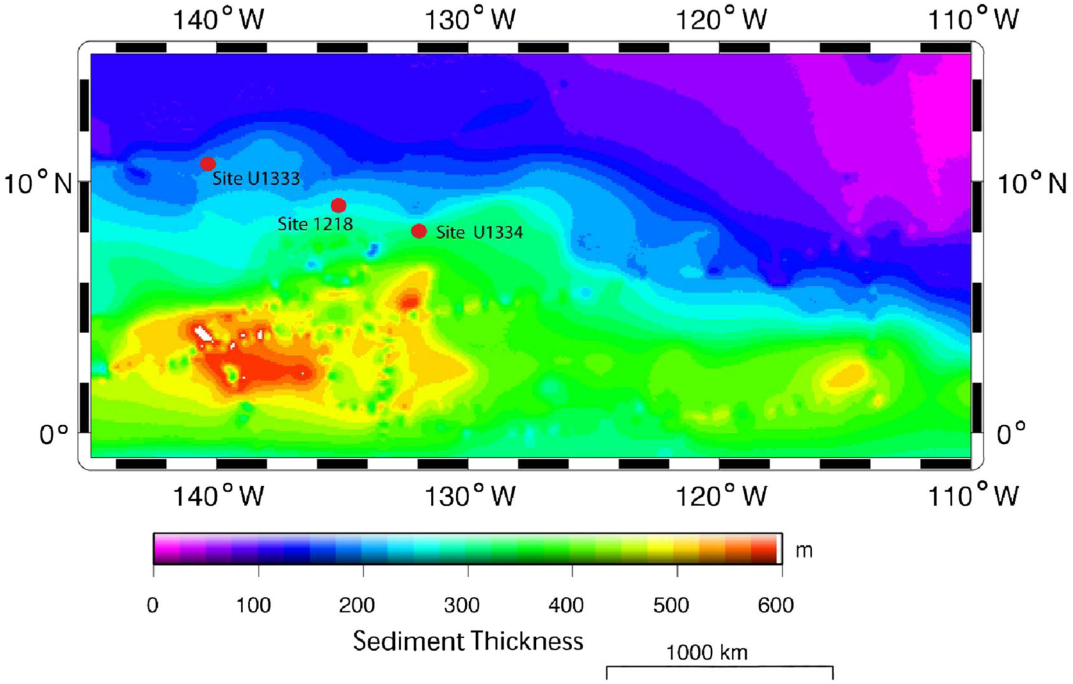

Figure 1. Locations of studied sites on a map of sediment thickness in the tropical Pacific biogenic sediment mound (sediment thickness in the equatorial Pacific; in part from D. L. Divins, NGDC Total Sediment Thickness of the World's Oceans and Marginal Seas, http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html) [see also *Mitchell*, 1998].

the uppermost part of Chron C13r [*Coxall et al*., 2005]. There are marked changes in the microfossil assemblages across the E/O boundary [*Funakawa et al*., 2006; *Dunkley Jones et al*., 2008; *Wade and Pearson*, 2008], so it should be easy to precisely locate this boundary. But here we run into some difficulty. Preservation of carbonate is generally poor in the Eocene deep-sea sediments of the Pacific, so Eocene carbonate microfossils are generally rare, poorly preserved, or absent altogether. In the deep Pacific basin, you are just as safe assuming that if the sediments are carbonate rich, they are Oligocene; if they are siliceous clays, they are Eocene. But exactly where in the Eocene?

[5] This problem could be resolved with the radiolarian microfossils as their stratigraphy in the E/O boundary region has been greatly improved by the work of *Nigrini et al*. [2006] using material from ODP Leg 199. The material studied by *Nigrini et al*. [2006] included Site 1218 as well as Sites 1219 and 1220. These latter sites unfortunately do not have complete E/O boundary sections. This causes some uncertainty in the placement of datum levels, which in turn causes some uncertainty in defining the E/O boundary with radiolarian stratigraphy. This uncertainty is exacerbated by the apparent reworking of older radiolarian species, many of which became extinct somewhere near the E/O boundary [*Funakawa et al*., 2006; *Moore and Kamikuri*, 2012]. The plethora of reworked radiolarians found near the E/O boundary is an almost unique event in the Cenozoic stratigraphy of the tropical Pacific. The only other interval in which such extensive reworking is commonly found is the uppermost part of the section on the northern flank of the equatorial Pacific biogenic sediment mound [*Moore et al*., 2012].

[6] The pervasive reworking of the upper Eocene radiolarians was investigated by *Moore and Kamikuri* [2012] in a detailed sampling of ODP Site 1218 as well as IODP Sites U1333 and U1334 (Figure 1 and Table 1), which also recovered stratigraphically complete E/O boundary sections. In their study, they identified Site U1334 as generally having the deepest (oldest) last appearance datums (LAD) for most of the stratigraphically important Eocene species. Furthermore, the older reworked radiolarians in the upper Eocene section were usually lower in abundance in U1334 than in either 1218 or U1333. Using Site U1334 as a guide and looking for discontinuous appearances of the older Eocene radiolarians that became extinct near the E/O boundary, *Moore and Kamikuri* were able to quantify the number of older reworked radiolarians in samples from all three sites.

[7] In this paper, we look at the record of reworked older radiolarians in Sites 1218, U1333, and U1334 and compare their changes in abundance through the interval from ~30 to ~40 Ma (i.e., the E/O boundary interval as used herein). We then try to relate these changes to possible paleoceanographic changes that might have led to this reworking as well as to the widespread presence of hiatuses within this boundary interval. As used herein, the E/O boundary zone spans the two-step change seen in isotopic and lithologic data.

2. Materials and Methods

2.1. Cores and Samples

[8] Based on the correlation of multisensor track data and paleomagnetic stratigraphy, 1 cm samples (one quarter core) were taken over the stratigraphic interval spanning from ~40 to ~30 Ma. Samples were taken from cores in individual holes

Table 1. Location and Characteristics of Drill Sites Studied

Site	Latitude	Longitude	Water Depth (m)	Section Thickness Pre-E/O (m)	Basement Relief (m)	Basement Age (Ma)	Oldest Reworked Radiolarian LAD (Ma)
1218	8°53.378′N	135°22′W	4828	58	370	42.3	*P. trachoides* (41.23)
U1333	10°30.996′N	138°25.159′W	4853	66	360	45.8	*E. lagena* (43.05)
U1334	7°59.998′N	131°58.408′W	4799	36	395	~38	*P. chalara* (38.74)

at each site 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 ~20 and ~50 cm. A total of 641 samples was examined in the three sites used in this study (see *Moore and Kamikuri*, 2012, for data tables). The average sample spacing in the sites is ~35 cm.

[9] The work of *Westerhold et al.* [2012] greatly facilitated this study by providing a revised depth scale for all holes at a group of tropical Pacific sites, including IODP Sites U1331, U1332, U1333, and U1334 as well as ODP Sites 1218, 1219, and 1220. This allowed samples from any given hole to be placed in relative stratigraphic order with respect to samples from all other holes at each site. This depth adjustment was based on a decimeter-scale correlation using multisensor track data from all cores at each of the sites covered in their study. In a further refinement that is critical to sites used in this study, Sites U1333 and U1334 were correlated with Site 1218 using the same correlation techniques. This allowed the placement of all samples used in this study on a common (Site 1218) depth scale, thus greatly enhancing our ability to refine the stratigraphy in these three sites and to correlate accurately data from all sites studied [*Westerhold et al.*, 2012].

[10] Samples were prepared following procedures similar to those described by *Sanfilippo et al.* [1985]. Details of the sample preparation and counting procedures are given in the work of *Moore and Kamikuri* [2012]. The area of each slide scanned was adjusted to ensure that between ~5000 and 10,000 specimens were examined. In these slides, 76 species, species groups, and specific variant forms were counted [see Taxonomic Notes in *Moore and Kamikuri*, 2012].

2.2. Time Scale

[11] The time scale used in this study is based on the orbitally tuned age calibrations for the reversal boundaries of Subchrons C12n and C13n derived from Sites 1218 and 1219 [*Pälike et al.*, 2006]. Below the base of C13n, the paleomagnetic time scale of *Cande and Kent* [1995] was applied to the paleomagnetic stratigraphy of Site U1333 and through correlations in depth [*Westerhold et al.*, 2012] applied to both Sites U1334 and 1218.

2.3. Defining Reworking

[12] Although the sections studied are judged to be complete, the sediments of all three sites appear to contain varying amounts of reworked older radiolarians. Many radiolarian species become extinct near the close of the Eocene, but radiolarian stratigraphy of the uppermost Eocene has always been plagued by the fact that the reworking of older radiolarians makes the exact level of extinction of these species suspect. *Nigrini et al.* [2006] acknowledged this problem and indicated both the "last occurrence" and the "last continuous occurrence" of several upper Eocene species whose last occurrence in the samples may have been affected by reworking and immixing. Of the 47 Eocene species that had their LAD between ~40 Ma and the E/O boundary zone (~33.7 Ma), 13 had their LAD within the boundary zone and 34 below this zone. These 34 species, along with 4 other species, whose LAD occur before ~40 Ma (*Lithochytris vespertillio*, *Podocyrtis* (*Lampterium*) *mitra*, *Podocyrtis* (*Lampterium*) *trachodes*, and *Sethochytris triconiscus*), generally make up the "reworked assemblage" found in the upper Eocene samples of this study [*Moore and Kamikuri*, 2012]. All 47 species may contribute to reworked assemblages found in the lower Oligocene.

[13] Of the sites studied here, Site U1334 appears, on average, to have the fewest immixed older radiolarians (Figure 2). Here we take the last continuous occurrence of a species to be its LAD, relying on the last continuous occurrence of the species in Site U1334 as a guide. Because we can accurately relate this depth to equivalent depths in all three sites through the correlations established by *Westerhold et al.* [2012] to Site 1218, we can evaluate the LAD, as well as first appearance datums, as a composite of all three sites studied [Table 5 in *Moore and Kamikuri*, 2012]. This, plus the relatively dense sampling in the sites studied, aided in determining the continuous versus discontinuous presence of a species. However, there are two exceptions to this general guideline. First, if a species is very rare throughout its range, there may be samples within its range in which it is not found. Because such very rare species are statistically less likely to be reworked into younger sediments, the upper limit of their stratigraphic range can usually be determined unambiguously. The second exception is where the last continuous occurrence in one site is above that in the other sites (18 of 47 LADs). Usually, in such cases, data from Site U1334 help define the lowest last continuous occurrence when one of the other or (in 5 of 47 cases) both sites have continuous occurrences of the species above that level. For the purposes of defining the amount of reworked material in each sample, the lowest last continuous occurrence found in the three sites is taken to be the correct level of the LAD of the species and samples in other sites containing specimens of this species above the equivalent depth of the lowest LAD are assumed to have been reworked.

[14] Although some degree of diachrony in radiolarian data has been observed in the tropical Pacific [*Moore et al.*, 1993], this was generally thought to range up to ~100 Kyr and to be associated with site positions within and outside the equatorial high productivity zone. The three sites studied here were all positioned to be within the zone of equatorial upwelling during the Late Eocene [*Pälike et al.*, 2010] and thus are less likely to show diachrony in their LAD. *Nigrini et al.* [2006] noted that the disappearance and reappearance of species could conceivably be caused by temporarily shifting environmental conditions for sites on the edge of the South Equatorial

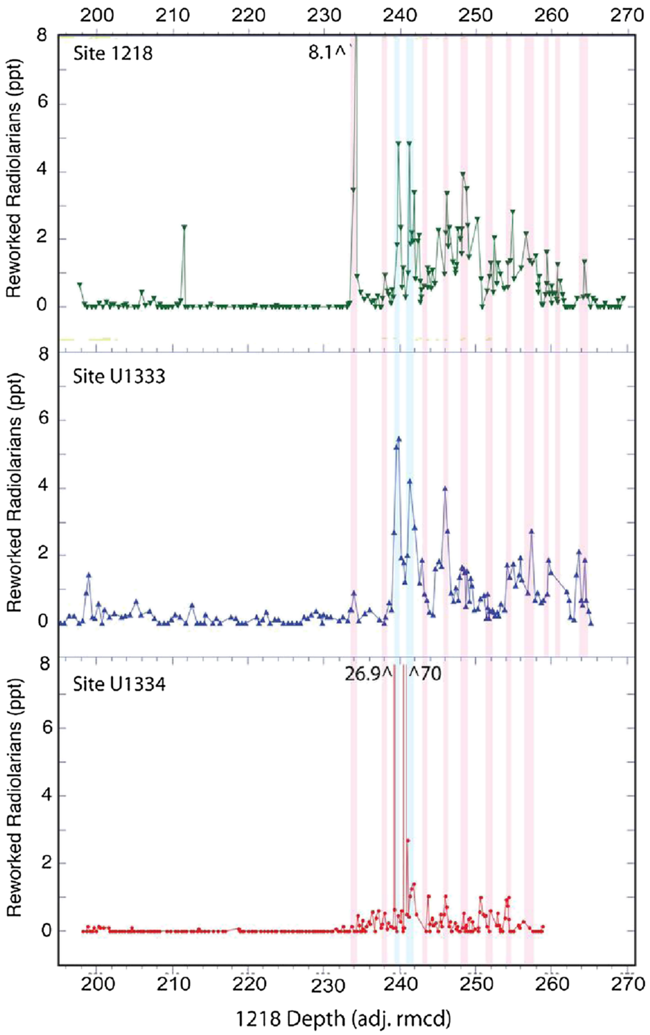

Figure 2. Abundance of reworked older radiolarians in the three sites studied. Blue bars denote major peaks in reworked radiolarian abundances associated with steps 1 and 2 in the E/O boundary zone (cf. Figure 4). Pink bars denote lesser peaks in reworked radiolarian abundances. Data are plotted on corrected and adjusted revised meters composite depth in Site 1218, with which Sites U1333 and U1334 have been correlated [*Westerhold et al.*, 2012].

Current (Sites 1218, 1219, and 1220), resulting in apparent discontinuous occurrences of some species with stratigraphic gaps ranging up to several million years. They referred specifically to four Oligocene-Miocene species. Such apparent discontinuous occurrences could also be a result of difficulties in the taxonomic definition of these species (almost certainly true for at least two of the four noted species). This is a fairly rare problem not noted in Eocene species. Certainly there are large environmental changes associated with the E/O boundary interval and there may be a few species from the upper Eocene assemblages of the Pacific equatorial zone that briefly disappear and then reappear; however, as the climate cooled in the Late Eocene, the dominant pattern of radiolarian assemblage change is extinction. It marks the largest turnover of radiolarian species in the entire Cenozoic [*Funakawa et al.*, 2006].

[15] There are at least eight distinct peaks in the amount of reworking as defined herein (Figures 2 and 3). These peaks are numbered in Figure 3. The immixed species were examined in two samples from each site at these maxima in reworked material. These data (Table 2) show that from 4 to 34 species are associated with these maxima in reworking, usually with more reworked species in the younger maxima. In most cases, a particular reworked species is found in only one or two of the three sites studied. There are 12 species found at all three sites in at least one of the reworking maxima (*Calocyclas turris*, *Calocycletta* (*Calocycletta*) *anekathen*, *Cryptocarpium ornatum*, *Lithocyclia aristotelis gr*., *Lithocyclia ocellus gr*., *Lychnocanoma babylonis*, *Lychnocanoma turgidum*, *Thyrsocyrtis* (*Pentalacorys*) *krooni, Thyrsocyrtis* (*Pentalacorys*) *lochites*, *Thyrsocyrtis* (*Pentalacorys*) *triacantha*, *Thyrsocyrtis* (*Thyrsocyrtis*) *bromia*, and *Thyrsocyrtis* (*Thyrsocyrtis*) *rhizodon*). These tend to be the more common and/or more robust constituents of the Eocene assemblage studied.

[16] The apparent displacement of the reworked species above their LAD ranges from 5 to over 50 m (measured in corrected revised meters composite depth (rmcd) Site 1218 depths; Table 2), with an average displacement of

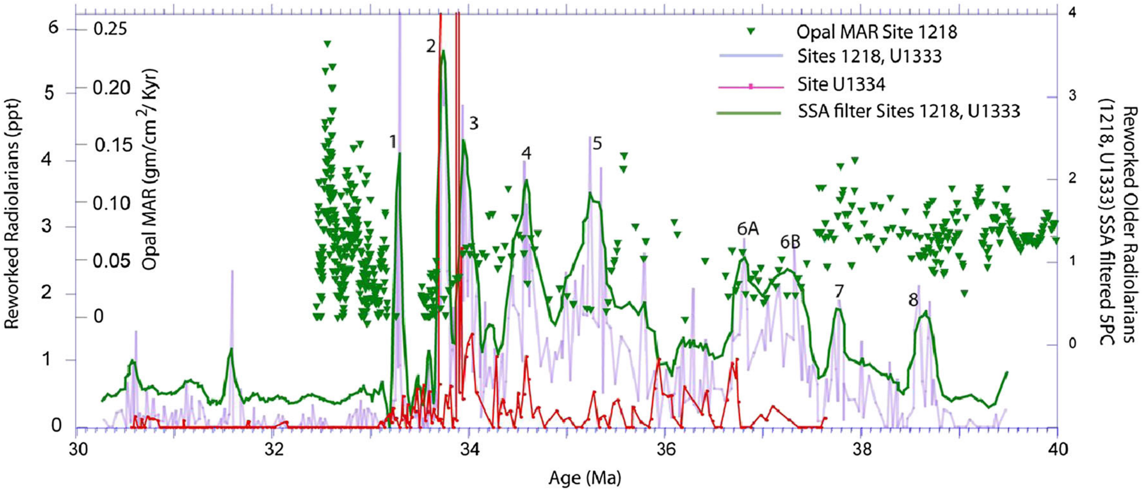

Figure 3. Singular spectrum analysis [5 PC; *Paillard et al*., 1996] of reworked radiolarian abundance in Sites 1218 and U1333 (cf. Figure 2) plotted in green. Merged raw data from Sites 1218 and U1333 are plotted in light purple. Reworked radiolarian abundance in Site U1334 is plotted in red. Opal mass accumulation rates in Site 1218 are plotted as solid green triangles [after *Moore et al*., 2008].

the reworked species of ~5 to ~15 m. The average accumulation rate of upper Eocene sediments in Site 1218 is 5 m/Myr [*Lyle et al*., 2002]; thus, this depth difference is equivalent to an average time gap of 1 to 3 Myr.

[17] Given the wide prevalence of a stratigraphic gap at the E/O boundary in the Pacific basin sediments, it is logical to expect a high degree of sediment (and microfossil) reworking near the E/O boundary, and certainly the largest maxima in reworking presented here are near this boundary (peaks 2 and 3 in Figure 3). The youngest maximum (peak 1 in Figure 3) is within the lowermost Oligocene, above the level of extinction of most species that appear in the Eocene [*Nigrini et al*., 2006]. The older maxima in reworking (peaks 4–8) gradually diminish in size down section but retain a statistical similarity to the younger maxima (Table 2). The observations and data presented here suggest that the great majority (if not all) of the immixed specimens identified by *Moore and Kamikuri* [2012] have been reworked by erosion and redeposition.

[18] Maxima in the abundance of reworked older radiolarians generally ranged from 2‰ to 6‰ of the specimens scanned in a slide, with rare cases where there were 8 to 70 reworked specimens per 1000 scanned (Figure 2). With 5000 specimens scanned, a count of 30 reworked specimens, giving a proportion of 6‰, would have a 95% confidence interval of between 4.1‰ and 8.6‰ (sampling error). For a proportion of 2‰, the 95% confidence interval would be between 1‰ and 3.7‰. With larger numbers of specimens scanned, the confidence interval would be slightly smaller.

[19] The error associated with each LAD location [*Moore and Kamikuri*, 2012] includes the full range of last continuous occurrences in all sites. Given the average error bars assigned to each Eocene LAD [Table 5 in *Moore and Kamikuri*, 2012] of ±25 cm (depth in 1218 rmcd) and given the average upper Eocene accumulation rate in Site 1218 of ~5 m/my [*Lyle et al*., 2002], this average depth error in LAD location represents ±50 Kyr.

[20] The abundance of reworked radiolarians is based only on the species recognized as being of stratigraphic importance [*Nigrini et al*., 2006; *Moore and Kamikuri*, 2012]. It should be emphasized that this estimate of the amount of reworked material is only an index of the amount of actual reworked material that was contributed to the sediment [*Moore et al*., 2012]. The sum of the species composing this index probably never exceeds 20% of the assemblage in which they are normally found [*Kamikuri et al*., 2012;

Table 2. Reworked Species in Sites 1218, U1333, and U1334

Reworking Peak	No. of Species in One Site Only	No. of Species in Two Sites	No. of Species in Three Sites	Total Reworked Species	Mean Offset From LAD*	Standard Deviation Offset	Maximum Offset	Minimum Offset
1	19	4	2	25	13.62	15.65	32.32	4.45
2	13	18	3	34	10.08	8.93	31.99	0.44
3	11	14	8	33	12.26	9.63	50.70	0.05
4	11	7	6	24	7.30	6.32	25.89	1.27
5	11	9	1	21	7.59	5.86	23.72	0.30
6A	6	6	0	12	7.35	6.94	37.05	0.17
6B	5	5	2	12	5.32	3.86	13.36	1.01
7	8	5	-	13	4.92	6.48	32.73	0.07
8	2	2	-	4	14.85	11.69	28.66	1.91

*Offset is the average distance of reworked species from their LAD in corrected revised meters composite depth in Site 1218 from *Westerhold et al*. [2012]. Standard deviation of offset, maximum offset, and minimum offset are also expressed in revised meters composite depth.

Moore and Kamikuri, 2012]. This index is expressed as the ratio (X1000) of reworked older radiolarians to the total number of radiolarians counted [*Moore and Kamikuri*, 2012; Figure 2].

3. Results

3.1. Comparison of Sites

[21] The maximum age of the reworked radiolarians in a given site is based on the oldest LAD of the species identified as part of the reworked assemblage (Table 1). In each case, this age is <3 Myr younger than the age of the basement at the site location (based on calcareous nannofossil stratigraphy) [*Pälike et al.*, 2010]. Thus, the reworked material is not likely to have been transported from great distances.

[22] Data from all samples on the revised 1218 depth scale (rmcd) established by *Westerhold et al.* [2012] are plotted in Figure 2. A comparison of the varying amounts of reworked material in each site shows that the variations in reworked material in Sites 1218 and U1333 are very similar. Based on the similarity in these latter two sites, their reworking data have been merged and a filtering of the merged data set (singular spectrum analysis) is used to produce a smoothed record of variation in reworking [*Paillard et al.*, 1996] (Figure 3). The reworking in Site U1334 is in general less common, but it shows some minor peaks that appear to coincide with those in Sites 1218 and U1333 (Figure 2). It has only two short intervals of major reworking. These two intervals occur within the E/O boundary zone and just above each of the two largest peaks in the smoothed record of reworking in Sites 1218 and U1333 (Figure 3). The similarity in the position and relative magnitude of the peaks in reworked radiolarian abundance lends credence to a consistent and widespread pattern of episodic reworking.

3.2. Comparison With Benthic Isotopes

[23] For Sites 1218 and U1333, the two major peaks in reworking (blue shading in Figure 2; peaks 2 and 3 in Figure 3) occur at the two major shifts in the isotopic data that mark the E/O boundary zone (steps 1 and 2 in Figure 4). The two maxima in reworking in Site U1334 occur at the base of steps 1 and 2 (cf. Figure 3). The youngest large peak in reworking occurs within the lowermost Oligocene at the maximum in oxygen isotopes associated with the Oi-1b event (Figure 4a) [*Coxall and Wilson*, 2011]. Although Site U1334 does not show a comparable peak at Oi-1b time, it does mark the end of a consistent presence of reworked material in the U1334 samples.

[24] In the interpretation of the benthic oxygen isotope record, we must deal with the effects of global ice volume and salinity, as well as temperature of the waters; however, in general, benthic oxygen isotopes in the deep sea can be used as an index of climate, with the larger (heavier) values indicating cooler conditions. It seems clear from Mg/Ca studies [e.g., *Lear et al.*, 2008] and modeling efforts [e.g., *DeConto and Pollard*, 2003] that the Late Eocene through early Oligocene was a time of ice sheet growth in Antarctica. Thus, both ice volume effects as well as salinity and temperature changes in the waters around Antarctica are likely to have affected the climate "signal" of the benthic oxygen isotopes. In the older part of the Late Eocene, isotope data from Site 1218 are very sparse [*Coxall et al.*, 2005; *Coxall and Wilson*, 2011] (Figures 4a and 4b) as a result of the shallow calcium carbonate compensation depth (CCD) and generally poor preservation of carbonate. Thus, these records do not have the detail that can be found in the carbonate-rich Oligocene section. However, as the oxygen isotopic values become heavier from 40 through ~37 Ma, the amount of reworking and the peak height of the reworking maxima tend to increase (Figure 4a). The maxima in reworking seem to appear at times near local maxima in benthic carbon isotopes (Figure 4b); however, this relationship can only be seen as tentative given the sparseness of isotopic data. In the simplest of cases, we usually think of deep waters having a relatively high $\delta^{13}C$ value as being chemically "younger" than those with a relatively low $\delta^{13}C$ value. This view is undoubtedly oversimplified, especially at the E/O boundary interval, where the effects of carbon burial and the extraction of "labile carbon" from the deep ocean waters are likely to have affected $\delta^{13}C$ values in benthic foraminifera [*Salamy and Zachos*, 1999; *Pälike et al.*, 2012].

4. Discussion

4.1. Reworking in the E/O Boundary Interval

[25] The robust tests of Eocene radiolarians are fairly resistant to dissolution on the seafloor, especially when dissolved nutrient levels in deep waters were likely to have been high in the Eocene [*Pälike et al.*, 2012]. The tests produced by radiolarians only gradually became more delicate in the upper Eocene of tropical oceans, with the most abrupt change in robustness occurring across the E/O boundary (between two samples at ~36 and 33 Ma in the work of *Lazarus et al.* [2009]). Thus, Eocene radiolarians are often preserved in sediments on the northern flank of the equatorial Pacific sediment mound when most younger radiolarians have been dissolved. The stratigraphic pattern of reworked radiolarians as defined by *Moore and Kamikuri* [2012] and used herein bears little resemblance to the discontinuous occurrence of Oligocene-Miocene species described by *Nigrini et al.* [2006]. Instead of being rare, there are numerous reworked radiolarian species in the upper Eocene and their number grows as more Eocene species become extinct (Table 2). They appear sporadically in the section after their LAD, and the more common reworked species are also among the more common and/or robust species where they occur in situ. However, their stratigraphic pattern does closely resemble the scattered occurrence of Eocene species above their LAD as noted in the work of *Nigrini et al.* [2006] by "+" marks in the range charts of the different sites.

[26] Evidence for the reworking of carbonate microfossils in the upper Eocene is practically nonexistent. It appears that even if some Eocene carbonate is originally preserved in the sediment, it usually gets dissolved in the reworking process. In Sites 1218 and U1333, calcareous nannofossils and planktic foraminifera in the upper Eocene are generally poorly preserved or absent altogether [*Lyle et al.*, 2002; *Bown and Dunkley Jones*, 2012; *Blaj et al.*, 2009; *I. Raffi*, pers. com., 2012]. In the upper Eocene of Site U1334, where the preservation of calcareous nannofossils ranges from poor to good, 2 of the 10 samples examined showed the appearance of a few specimens that might have been reworked [Chart 4 in *Bown and Dunkley Jones*, 2012]. With the very shallow CCD of the Eocene, it may be very difficult to document the presence of carbonate reworking, except in very shallow sites.

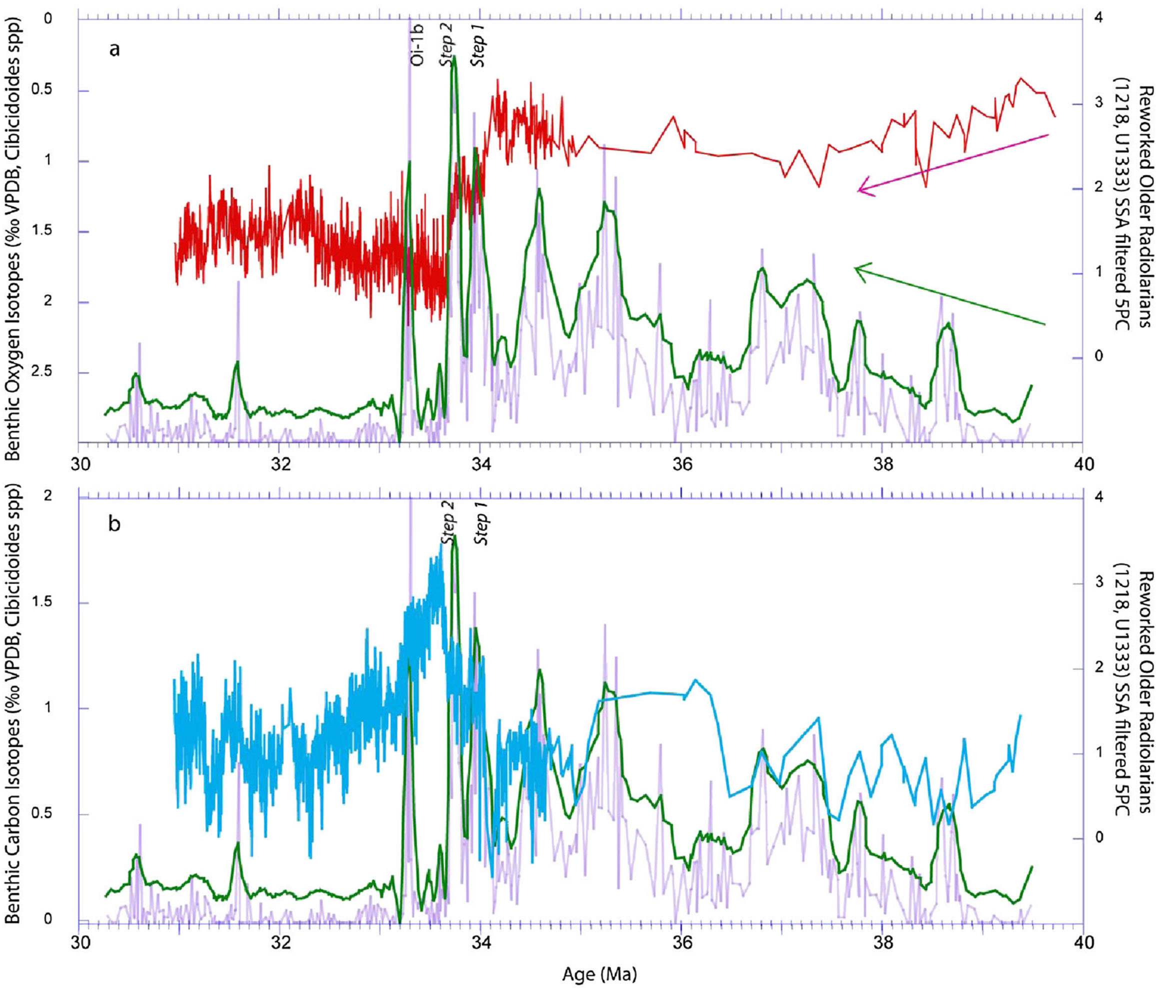

Figure 4. Singular spectrum analysis filtering [5 PC; *Paillard et al.*, 1996] of reworked radiolarian abundance for Sites 1218 and U1333 (cf. Figure 2). Merged raw data from Sites 1218 and U1333 are plotted in light purple. (a) Benthic oxygen isotope data [*Coxall et al.*, 2005; *Coxall and Wilson*, 2011] from ODP Site 1218 are plotted in red compared to abundance of reworked older radiolarians in Sites 1218 and U1333. The red arrow denotes the trend in oxygen isotope data. The green arrow denotes the trend in reworked radiolarian data. (b) Benthic carbon isotope data [*Coxall et al.*, 2005; *Coxall and Wilson*, 2011] from ODP Site 1218 plotted in blue compared to abundance of reworked older radiolarians in Sites 1218 and U1333.

[27] The oldest reworked material found in the E/O boundary interval is the same age as the basement at the drill site or only a few million years younger (Table 1). The (compacted) thickness of the section beneath the E/O boundary at the drill sites studied here is <70 m (Table 1). Because of this relatively thin Eocene sediment cover around the three sites studied, it seems very unlikely that the reworking is associated with local hydrothermal "springs" [*Moore et al.*, 2007, 2012]. The fact that the oldest reworked species found in Site U1334 (*Podocyrtis chalara*, a robust and relatively common Eocene species) (Table 1) was not found at this site in the deepest samples that contained preserved radiolarians [*Pälike et al.*, 2010] suggests that dissolution in the basal section of U1334 postdated reworking during the Late Eocene.

[28] If the mechanism for redeposition of older reworked radiolarians is different in the E/O boundary interval from that in the near-surface sediment, what is that mechanism? *Mayer* [1981], in his search for the mechanism of formation of the first well-surveyed pit in tropical Pacific sediments, ruled out formation by simple scour and erosion by bottom currents. The currents measured in the region, generally related to tidal motions, were just too low for erosion (~10 cm/s). Work by *Lonsdale and Southard* [1974] and that by *McCave* [1984] indicate that to erode siliceous red clays similar to the upper Eocene section at the sites studied here would require bottom current velocities in the order of ≥30 cm/s.

[29] It is conceivable that pulsed variations in the flux rates of radiolarians from near-surface waters to the seafloor might have affected the ratio of reworked to in situ radiolarians found in the sediment; however, the accumulation rate of opal (primarily radiolarians in the Eocene; Figure 3) shows no consistent relationship with the relative amount of reworked material. All sites studied here were in the zone of equatorial high productivity near the E/O boundary, and yet the closest two sites with very similar sediment accumulation rates [1218 and U1334; *Lyle et al.*, 2002; *Pälike et al.*, 2010] have

very different ratios of reworked material. This also argues against temporal variations in the flux of radiolarians from near-surface waters being the primary factor controlling the relative amount of reworked material. This is especially true since Site U1333, the site farthest from 1218 and from the equator [Table 1 in *Moore and Kamikuri*, 2012], has concentrations of reworked material very similar to those of Site 1218. Something other than the flux of radiolarians from the upper ocean must be the primary control.

[30] Although the close correspondence in age between the basement age at the sites and the age of the reworked material argues for erosion and reworking that are local in nature, the widespread presence of a missing section near the E/O boundary (Table S1 in the Auxiliary Material) [*Moore et al*., 1978] argues for the process causing such erosion and reposition to be basin-wide in nature. In addition, the timing of variation in reworking of older radiolarians appears to be similar from site to site (Figure 2); thus, an explanation of the process that might be appropriate for acting at one place at one time but not at the same time in other places would not be applicable, (e.g., erosion and turbidites found at Sites U1331 and U1335) [*Pälike et al*., 2010]. It requires a more pervasive mechanism that acts over large areas of the seafloor (Figure 1).

[31] Recent work on the large shift in oxygen and carbon isotopes at the end of the Eocene that marked a relatively rapid transition from the hothouse world to the icehouse world has shown that this shift in climatic and oceanographic conditions was not a simple, single event [*Coxall et al*., 2005, *Pearson et al*., 2008; *Coxall and Wilson*, 2011]. The E/O boundary zone itself contains two steps, and records that extend further back into the Eocene show even older (albeit smaller) oscillations in the isotopic data [*Coxall et al*., 2005; *Pälike et al*., 2006; *Zachos et al*., 2008; *Coxall and Wilson*, 2011]. These records for Site 1218, when compared to the data on reworked radiolarians (Figure 4), show a fairly consistent relationship. The two largest pulses of reworked material occur in the E/O boundary zone and are coincident with the sharp drop to heavier values in both carbon and oxygen benthic isotopes. Further back, some of the peaks in reworked radiolarians are close to small peaks in the δ^{13}C record. The match with the oxygen isotope data is less clear in the older part of the record, with only a few the reworking peaks being associated with increases in δ^{18}O. However, E/O boundary zone steps 1 and 2 and the Oi-1b event in the δ^{18}O record are clearly associated with maxima in reworking. Accepting the low resolution of the older part of the isotopic records, this degree of coherence seems meaningful.

4.2. Proposed Mechanism of Reworking

[32] Whatever the cause of the reworking of older radiolarians near the E/O boundary, it must explain (a) the pulses of reworked material gradually increasing in magnitude with time and culminating very near the E/O boundary itself, (b) local erosion and redeposition acting synchronously over broad regions of the deep Pacific basin, and (c) an apparent association with the largest changes in benthic isotope stratigraphy of the upper Eocene and lowermost Oligocene. All of these observations point to an association between reworking and pulses of bottom water formation in high southern latitudes associated with climatic cooling and ice sheet development in Antarctica at the end of the Eocene.

[33] It is logical to assume, given the natural variability of climate and the pulsating nature of climate change [*Pälike et al*., 2006], that the cool down of the Pacific bottom waters was not a simple, continuous process and that it was likely to have occurred neither in a single step nor perhaps in just two steps. The pulse-like nature of the maxima in reworking suggests that they may be related to the "heartbeat of climate" demonstrated by *Pälike et al*. [2006] for the Oligocene. Sample spacing in the upper Eocene is, on average, between 20 and 50 Kyr; however, the time scale used here is based solely on linear interpolation between magnetic chron boundaries (see Methods section) and has not been orbitally tuned. Nevertheless, the spacing in time of individual reworking peaks varies between ~120 and ~420 Kyr (i.e., within the range of maxima in the eccentricity spectrum).

[34] If we take the carbon isotopic record as an indicator of when pulses of chemically "younger" bottom waters originated in high southern latitudes and swept through the Pacific basin, then we might suspect that these pulses had something to do with the maxima in reworking. The fact that the two largest changes in the isotopic composition of the bottom waters are associated with the two largest pulses in reworking in all three sites lends support to this assumption.

[35] It does not seem likely that such episodes were characterized by large advective, unidirectional flows that swept through the Pacific basin and were responsible for erosion and reworking of the deep-sea sediments during the late Eocene. The large "tongues" of deep and intermediate waters seen in meridional cross-sections of the modern ocean are thought not to be a result of strong advective flow but rather to be caused by turbulent mixing, largely on isopycnal surfaces, enhanced by movement over a rough ocean bottom [e.g., *Rudnick et al*., 2003; *Wumsch and Ferrari*, 2004].

[36] Within the water column, internal waves generated by tides and large storms can cause turbulent mixing that generates water velocities ≥30 cm/s [*Cacchione and Drake*, 1986; *Cacchione et al*., 2002], velocities that are capable of eroding deep-sea siliceous clays [*Lonsdale and Southard*, 1974]. Such internal waves form on surfaces within the ocean across which there is a strong density contrast. To use the higher velocities associated with internal waves as the cause of the erosion and reworking we see in the E/O boundary interval would then require a deep pycnocline, separating the younger, more dense, and deeper waters from the less dense and shallower waters in the deep Pacific.

[37] One could picture that with the initial formation of cooler, denser waters, they would sink to the bottom of the basin near Antarctica and through turbulent mixing spread northward through the Pacific. At first, the density contrast between the younger, denser waters and the older, lighter waters might develop a pycnocline on which internal waves could form. With time and continued turbulent mixing, the density contrast and the steepness of the deep pycnocline could be diminished, only to be reestablished with the next climatically induced pulse of cold, dense bottom waters.

[38] As the pulsed formation of such waters continues, they would gradually fill the basin. But no strong evidence for the gradual shoaling of a deep pycnocline yet exists; indeed, it may be difficult to acquire. The locations of

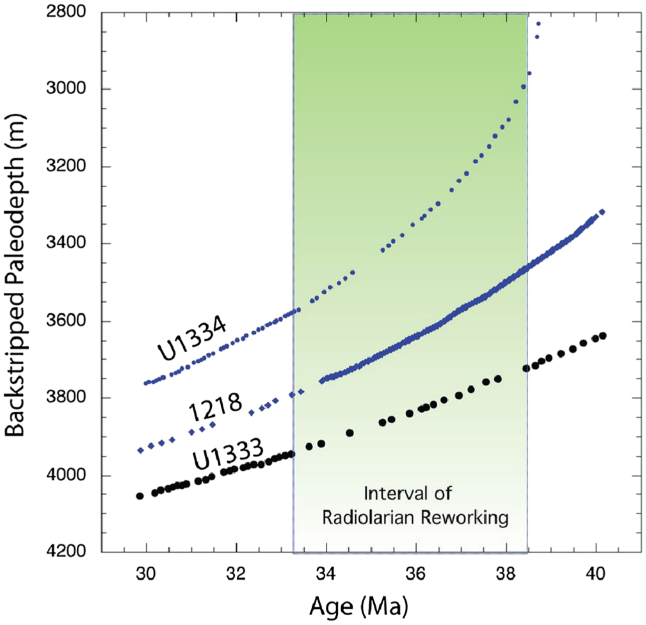

Figure 5. Backtracked paleo water depths of Sites 1218, U1333, and U1334 [*Pälike et al.*, 2010, 2012] during the interval of substantial input of older reworked radiolarians (shaded in green).

the sites studied here were selected based on their position within the paleoequatorial zone and their proximity to the Late Eocene crest of the Pacific spreading center, one of the shallowest locations in the deep basin (Figure 5). There are no deeper sites drilled that have been shown to have a complete E/O boundary interval. Other more shallow tropical Pacific locations such as aseismic oceanic plateaus and ridges exist (Table S1 in the Auxiliary Material), but their records of the upper Eocene-lower Oligocene section have yet to be studied in detail and shown to be complete. In addition, sharp changes in bathymetry on isolated bathymetric features generate their own turbulence in the deep ocean and thus make it more difficult to trace the changing vertical structure of the oceans.

[39] The only hint that there may be a gradual shoaling of the pycnocline during the E/O boundary interval comes from Site U1334, the shoalest site studied here (Figure 5 and Table 1). Of the three sites, it shows the least amount of reworking, perhaps because of its thinner section (younger crust) (Table 1) or perhaps because it lay slightly above the deep pycnocline in the latest Eocene. During the interval studied here, U1334 is estimated to have been between 500 and 200 m shoaler than Site 1218 (Figure 5). In spite of the lower average amount of reworked radiolarians in the U1334 section, there are two very prominent spikes in reworking at this site, both of which are larger than the peaks in reworking at Sites 1218 and U1333. Both of these spikes occur just after steps 1 and 2 in the E/O boundary zone of the δ^{18}O record, and both come slightly after the peaks in reworking seen at Sites 1218 and U1334 (Figure 3). This may indicate a phasing in the growth of the new, colder Pacific bottom waters that raised the deep pycnocline level up to and eventually above Site U1334. Hopefully, work on the isotopes from the upper Eocene benthic foraminifera at Site U1334 and shoaler sites will shed more light on this idea.

5. Conclusions

[40] The three complete sections of the E/O boundary interval recently recovered from the tropical Pacific give us insights into the oceanographic processes by which this major change in climate occurred. The occurrence of reworked older radiolarians in all three sites, particularly below and at the steps near the E/O boundary itself, shows a spatially and temporally coherent pattern of pulses in abundance between ~39 and ~33 Ma. These intervals of reworking, taken together with the widespread hiatus near the E/O boundary itself, indicate that the cause of these pulses in reworking is repeated episodes of physical erosion and redeposition. In the modern deep ocean, we rarely see currents with sufficient velocity to erode deep-sea clays except in restricted areas of boundary current flow and flow through narrow passages. Higher bottom current velocities have been measured in areas where internal waves, interacting with the irregular seafloor, give rise to turbulent flow with sufficient velocity to erode deep-sea clays; however, these waves are associated with steep density gradients, such as the thermocline in the upper few hundred meters of the modern ocean. We propose that the cooling of deep ocean waters from Late Eocene into Oligocene times occurred in climatically driven pulses of colder, denser waters that, upon sinking and spreading into the Pacific basin, gave rise to a deep pycnocline. Internal waves that developed on this pycnocline and the associated turbulent mixing near the seafloor led to the erosion of the upper Eocene sections and redeposition of the older radiolarians in that section.

[41] The magnitude of the maxima in reworking may be related to the initial density contrast in the deep pycnocline, and its differing impact on the three sites studied may relate to the depth of that pycnocline relative to the paleodepth of the sites. With time, this turbulent mixing tended to diminish the sharp density contrast across the deep pycnocline until the next pulse of bottom water formation reestablished it.

The magnitude of the pulses gradually increased with time, and the largest two pulses of mixing occurred within the E/O boundary zone and are closely associated with two sharp, step-like increases in carbon and oxygen isotopes, the two steps that define the shift from a hothouse world to an icehouse world. The reworking of older radiolarians into the younger section above this boundary is much more rare, with only one strong peak in the lower Oligocene where another shift in benthic oxygen isotopes is seen (the Oi-1b event). Other small peaks above this level are very rare, not consistent from site to site, and likely a result of local conditions.

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References

Blaj, T., J. Backman, and I. Raffi (2009), Late Eocene to Oligocene preservation history and biostratigraphy of calcareous nannofossils from paleo-equatorial Pacific Ocean sediments, *Riviata Ital. Paleo. e Strat.*, *115*(1), 67–85.

Bown, P. R., and T. Dunkley Jones (2012), Calcareous nannofossils from the Paleogene equatorial Pacific (IODP Expedition 320 Sites U1331-1334), *J. Nannoplankton Res.*, *32*(2), 3–51.

Cacchione, D. A., and D. E. Drake (1986), Nepheloid layers and internal waves over continental shelves and slopes, *Geomarin.*, *6*, 147–152.

Cacchione, D. A., L. F. Pratson, and A. S. Ogston (2002), The shaping of continental slopes by internal tides, *Science*, *296*(5568), 724–727.

Cande, S. C., and D. V. Kent (1995), Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, *J. Geophys. Res., [Solid Earth]*, *100*(B4), 6093–6095. doi:10.1029/94JB03098.

Coxall, H. K., P. A. Wilson, H. Pälike, C. H. Lear, and J. Backman (2005), Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean, *Nature*, *433*(7021), 53–57, doi:10.1038/nature03135.

Coxall, H. K., and P. N. Pearson (2007), The Eocene-Oligocene transition, in *Deep-Time Perspectives on Climate Change: Marrying the Signal From Computer Models and Biological Proxies*, edited by M. Williams, et al., pp. 351–387, *Micropalaeontol. Soc., London*.

Coxall, H. K., and P. A. Wilson (2011), Early Oligocene glaciation and productivity in the eastern equatorial Pacific: Insights into global carbon cycling, *Paleoceanography*, *26*, PA2221, doi:10.1029/2010PA002021.

DeConto, R. M., and D. Pollard (2003), Rapid Cenozoic glaciation of Antarctica triggered by declining atmospheric CO2, *Nature*, *421*, 245–249.

Dunkley Jones, T., P. R. Bown, P. N. Pearson, B. S. Wade, H. K. Coxall, and C. H. Lear (2008), Major shifts in calcareous phytoplankton assemblages through the Eocene-Oligocene transition of Tanzania and their implications for low-latitude primary production, *Paleoceanography*, *23*, PA4204, doi:10.1029/2008PA001640.

Funakawa, S., H. Nishi, T. C. Moore, and C. A. Nigrini (2006), Radiolarian faunal turnover and paleoceanographic change around Eocene/Oligocene boundary in the central equatorial Pacific, ODP Leg 199, Holes 1218A, 1219A, and 1220A, *Palaeogeogr. Palaeoclimatol. Palaeoecol*, *230*, 183–203, doi:10.1016/j.palaeo.2005.07.014.

Kamikuri, S., T. C. Moore, K. Ogane, N. Suzuki, H. Pälike, and H. Nishi (2012), Data report: early to middle Eocene radiolarian biostratigraphy, IODP Expedition 320 Site U1331, eastern equatorial Pacific, in *Proceedings of the Integrated Ocean Drilling Program*, vol. 320/321, edited by H. Pälike, M. Lyle, H. Nishi, I. Raffi, K. Gamage, A. Klaus, and the Expedition 320/321 Scientists, Integrated Ocean Drilling Program Management International, Inc., Tokyo, doi:10.2204/iodp.proc.320321.202.2012.

Lazarus, D. B., B. Kotrc, G. Wulf, and D. N. Schmidt (2009), Radiolarians decreased silicification as an evolutionary response to reduced Cenozoic ocean silica availability, *Proc. Natl. Acad. Sci. U.S.A.*, *106*(23), 9333–9338, doi:10.1073/pnas.0812979106.

Lear, C. H., T. R. Bailey, P. N. Pearson, H. K. Coxall, and Y. Rosenthal (2008), Cooling and ice growth across the Eocene-Oligocene transition, *Geology*, *36*, 251–254, doi:10.1130/G24584A.1.

Lonsdale, P., and J. B. Southard (1974), Experimental erosion of north pacific red clay, *Mar. Geol.*, *17*, M51–M60.

Lyle, M., et al. (2002), *Proceedings of the Ocean Drilling Program, Initial Reports*, vol. 199, Ocean Drilling Program, College Station, TX. doi:10.2973/odp.proc.ir.199.2002.

McCave, I. N. (1984), Erosion, transport and deposition of fine-grained marine sediments, in *Geol Soc Spec. Publ. 15*, edited by D. Stow, and D. Piper, pp. 35–69, Geological Society of London, London, UK.

Mayer, L. (1981), Erosional troughs in deep-sea carbonates and their relationship to basement structure, *Mar. Geol.*, *39*, 59–80.

Mitchell, N. C. (1998), Modeling Cenozoic sedimentation in the central equatorial Pacific and implications for true polar wander, *J. Geophys. Res.*, *103*, 17,749–17,766.

Moore, Jr., T. C. (1972), DSDP: successes, failures, proposals, *Geotimes*, *17*, 27–31.

Moore, Jr., T. C., N. G. Pisias, and N. J. Shackleton (1993), Paleoceanography and the Diachrony of Radiolarian Events in the Eastern Equatorial Pacific, *Paleoceanography*, *8*(5), 567–586.

Moore, Jr., T. C., T. H. van Andel, C. Sancetta, and N. Pisias (1978), Cenozoic hiatuses in pelagic sediments, *Micropaleontology*, *24*, pp. 113–138.

Moore, T. C., Jr., N. C. Mitchell, M. Lyle, J. Backman, H. Pälike (2007), Hydrothermal pits in the biogenic sediments of the equatorial Pacific Ocean, *Geochem. Geophys. Geosyst.*, *8*, Q03015, doi:10.1029/2006GC001501.

Moore, T. C., J. D. Jarrard, Jr., A. Olivarez Lyle, and M. Lyle (2008), Eocene biogenic silica accumulation rates at the Pacific equatorial divergence zone, *Paleoceanography*, *23*, PA2202, doi:10.1029/2007PA001514.

Moore, T. C., Jr, and S. Kamikuri (2012), Data report: radiolarian stratigraphy across the Eocene – Oligocene Boundary in the Equatorial Pacific from Sites 1218, U1333, and U1334, in *Proceedings of the Integrated Ocean Drilling Program*, vol, 320/321, edited by H. Pälike, M. Lyle, H. Nishi, I. Raffi, K. Gamage, A. Klaus, and the Expedition 320/321 Scientists, p. 37, Integrated Ocean Drilling Program Management International, Inc), College Station, TX, doi:10.2204/iodp.proc.320321.204.2012.

Moore, T. C., L. A. Mayer, and M. Lyle (2012), Sediment mixing in the tropical Pacific and radiolarian stratigraphy, *Geochem. Geophys. Geosyst.*, *13*, Q08006, doi:10.1029/2012GC004198.

Nigrini, C. A., A. Sanfilippo, and T. C. Moore Jr. (2006), Cenozoic radiolarian biostratigraphy: a magnetobiostratigraphic chronology of Cenozoic sequences from ODP Sites 1218, 1219, and 1220, equatorial Pacific, in *Proc. ODP, Sci. Results*, *199*, edited by P. A. Wilson, M. Lyle, and J. V. Firth, pp. 1–76, Ocean Drilling Program, College Station, TX, doi:10.2973/odp.proc.sr.199.225.2006.

Paillard, D., L. Labeyrie, and P. Yiou (1996), Macintosh program performs time-series analysis, *Eos Trans. AGU*, *77*, 379.

Pälike, H., R. D. Norris, J. O. Herrle, P. A. Wilson, H. K. Coxall, C. H. Lear, N. J. Shackleton, A. K. Tripati, and B. S. Wade (2006), The Heartbeat of the Oligocene Climate System, *Science*, *314*, 1894–1898.

Pälike, H., H. Nishi, M. Lyle, I. Raffi, K. Gamage, A. Klaus, and the Expedition 320/321 Scientists (2010), Expedition 320/321 summary, in *Proc. IODP* 320/321, edited by H. Pälike, M. Lyle, H. Nishi, I. Raffi, K. Gamage, A. Klaus, and the Expedition 320/321 Scientists, p. 141, Integrated Ocean Drilling Program Management International, Inc., Tokyo, doi:10.2204/iodp.proc.320321.101.2010.

Pälike, H., et al. (2012), A Cenozoic record of the equatorial Pacific carbonate compensation depth, *Nature*, *488*(7413), 609–614, doi:10.1038/nature11360.

Pearson, P. R., I. K. McMillan, B. S. Wade, T. Dunkley Jones, H. K. Coxall, P. R. Bown, and C. H. Lear (2008), Extinction and environmental change across the Eocene-Oligocene boundary in Tanzania, *Geology*, *36*, 179–182.

Rudnick, D. L., et al. (2003), From tides to mixing along the Hawaiian Ridge, *Science*, *301*(5631), 355–357.

Salamy, K. A., and J. C. Zachos (1999), Latest Eocene–Early Oligocene climate change and Southern Ocean fertility: inferences from sediment accumulation and stable isotope data, *Palaeogeog., Palaeoclim. Palaeoecol.*, *145*, 61–77.

Sanfilippo, A., M. J. Westberg-Smith, and W. R. Riedel (1985) Cenozoic Radiolaria. in *Plankton Stratigraphy*, edited by H. M. Bolli, J. B. Saunders, and K. Perch-Nielsen, pp. 631–712, Cambridge Univ. Press, Cambridge.

Wade, B. S., and P. N. Pearson (2008), Planktonic foraminiferal turnover, diversity fluctuations and geochemical signals across the

Eocene/Oligocene boundary in Tanzania, *Mar. Micropaleontol.*, *68*, 244–255.

Westerhold, T., U. Röhl, R. Wilkens, H. Pälike, M. Lyle, T. D. Jones, P. Bown, T. Moore, S. Kamikuri, G. Acton, C. Ohneiser, Y. Yamamoto, C. Richter, P. Fitch, H. Scher, D. Liebrand, and the Expedition 320/321 Scientists (2012), Revised composite depth scales and integration of IODP Sites U1331 -U1334 and ODP Sites 1218 -1220, in *Proc. IODP*, *320/321*, edited by H. Pälike, M. Lyle, H. Nishi, I. Raffi, K. Gamage, A. Klaus, and the Expedition 320/321 Scientists, Integrated Ocean Drilling Program Management International, Inc., Tokyo, doi:10.2204/iodp.proc.320321.201.2012.

Wumsch, C., and R. Ferrari (2004), Vertical mixing, energy, and the general circulation of the oceans, *Annu. Rev. Fluid Mech*, *36*, 281–314.

Zachos, J. C., G. R. Dickens, and R. E. Zeebe (2008), An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics, *Nature*, *451*, 279–283, doi:10.1038/nature06588.