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Paleogene calcite compensation depth in the eastern subtropical Pacific: Answers and questions

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[1] Ocean Drilling Program Leg 199 drilled a north-south transect across the Eocene paleoequator in the eastern Pacific, permitting reconstruction the calcite compensation depth (CCD) since earliest Eocene time. The CCD was relatively shallow near the early Eocene Pacific equator, 3200 m, and unlike modern latitudinal CCD gradients deepened to the north (to ~3600 m; paleolatitude ~10°N). At 41 Ma the CCD underwent a brief, sharp, transient deepening of 700 m, then remained shallow until the Eocene/Oligocene boundary. At the E/O boundary, the CCD deepened by 1200 m in less than 300 kyr. This rapid deepening served to more than double the area of seafloor subject to $CaCO_3$ deposition. Sea level fall associated with ice volume buildup, and ensuing shelf-basin fractionation, is unlikely to be the sole cause of the increased deep-ocean $CaCO_3$ burial; rather, a sudden, rapid increase in the amount of Ca entering the ocean appears necessary to explain the observations.

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1. Introduction

[2] Calcite is produced by plankton in ocean surface waters and dissolves at depth. Dissolution increases with depth, usually in a nonlinear manner, so we commonly find that carbonates accumulate at shallower sites but not in the deep ocean basins. For any time and place, the depth where the calcite supply from the surface is matched by the dissolution at depth defines the calcite compensation depth or CCD; at greater depths dissolution rates exceed supply rates and no $CaCO_3$ accumulates. Because rates of both carbonate production and dissolution may change, the CCD also varies throughout the oceans and with time. Furthermore, because marine $CaCO_3$ formation releases CO_2 to the ocean-atmosphere system (essentially: $Ca^{++} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$) the history of calcite deposition is very important to studies of carbon cycling and paleoclimate.

[3] Calcite dissolution in the deep sea has been recognized since the days of the *Challenger* Expedition [*Murray and Renard*, 1891; *Bramlette*, 1961]. However, it was not until oceanic crustal subsidence curves [*Sclater et al.*, 1971] were incorporated into studies of carbonate sedimentation [*Berger*, 1973; *Berger and Winterer*, 1974] that a modern picture of the history of the CCD began to emerge. Since the first oceanwide and global CCD compilations [*van Andel and Bukry*, 1973; *van Andel and Moore*, 1974; *van Andel et al.*, 1975; *Heath et al.*, 1977] much of the research on Cenozoic carbonate accumulation histories has been focused on depth transects set in regions generally above the CCD, such as those on the Ontong-Java Plateau, Shatsky Rise, Ceara Rise, Demerara Rise and Walvis Ridge. In the more recent past, the only attempts to reconstruct regionwide behavior of the CCD have been undertaken in the Pacific (southeast Pacific [*Rea and Leinen*, 1985]; North Pacific [*Rea et al.*, 1995]; basinwide [*Lyle*, 2003]; and in the Indian Ocean [*Peterson et al.*, 1992]).

[4] ODP Leg 199, the Paleogene Equatorial Transect, drilled a series of sites located in a north-south array across the Eocene paleoequator (Figure 1). Most of these sites (all except 1218) targeted 56 m.y. old crust with the objective of capturing the Paleocene-Eocene boundary event and the paleoceanographic record of the Eocene, Oligocene and early Neogene equatorial and subtropical region [*Lyle et al.*, 2002]. One of the significant findings of Leg 199 was the quantification of the timing and vertical extent of the rapid fall of the calcite compensation depth that characterizes the Eocene/Oligocene boundary.

2. Prior Investigations

[5] The work of reference for the eastern tropical and subtropical Pacific is the monograph by *van Andel et al.* [1975], who examined all the Deep Sea Drilling Project cores in the region then available and determined the geologic history of calcium carbonate deposition. Results of this work included the effects on the geometry of sediment accumulation in response to the northward drift of the Pacific plate as it moved beneath the equatorial high-productivity zone. *van Andel et al.* [1975] defined a shallow Eocene CCD of 3400 m in the equatorial Pacific, and of about 3200 m north and south of 4° latitude. Further, they reported a sudden deepening of the CCD at the time of the

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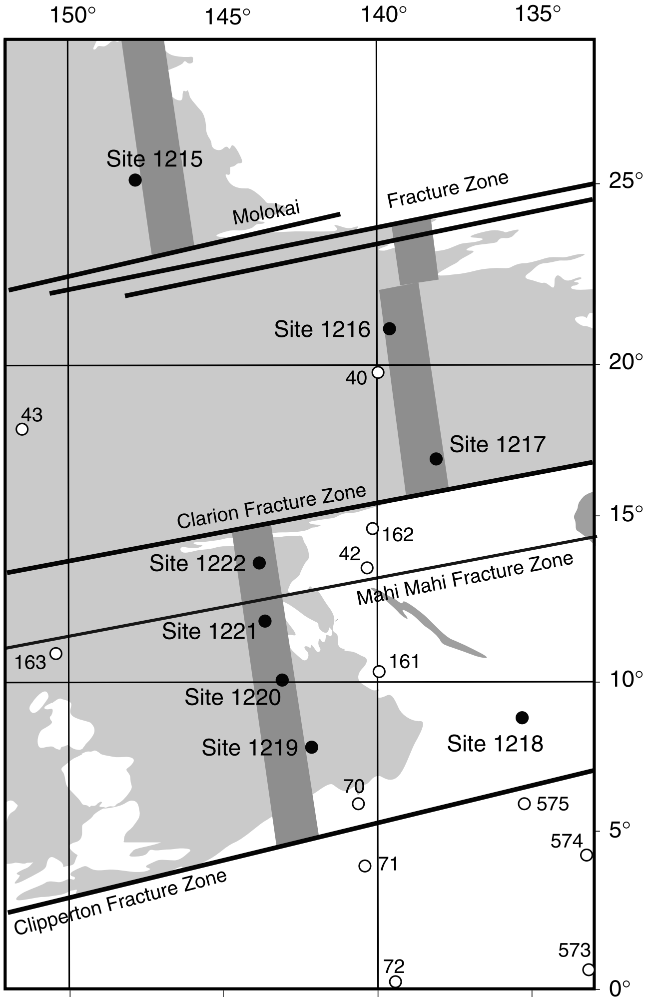

Figure 1. Map of the eastern subtropical Pacific showing the Leg 199 (solid dots) and other (open circles) drill sites [after *Lyle et al.*, 2002]. Solid lines are fracture zones and the shaded bar represents crust of 56 m.y. age.

Eocene-Oligocene boundary, of 1600–2000 m to about 5000 m in the equatorial region and of about 1000 m to approximately 4200 m in the extra-equatorial region [*van Andel et al.*, 1975; *Heath et al.*, 1977]. The off-equatorial CCD was deep in the Oligocene and shoaled a few hundred meters by the middle to late Miocene, then deepened to its current depths [*van Andel et al.*, 1975; *Heath et al.*, 1977]. Addition of the later DSDP and ODP cores has shown that the shoaling occurred in the early Miocene, and is the only basinwide carbonate event in the Neogene [*Lyle*, 2003].

[6] The pattern observed in the tropical Pacific is mimicked in the southeastern Pacific where the present CCD is located at 4100 m [*Rea and Leinen*, 1985]. In the far northwest Pacific, a region of high siliceous productivity, the CCD shoaled continuously through time from its Oligocene maximum of roughly 4000 m to a present depth of about 2400 m [*Rea et al.*, 1995]. In the central gyre region of the North Pacific the modern CCD is quite deep, perhaps 4700 m [*Lyle*, 2003], although data are sparse. Results from the eight drill sites of Leg 199 yield a several-fold increase in our information about the eastern subtropical Pacific CCD, especially for Paleogene time.

3. Depth Backtracking Methods

[7] *van Andel et al.* [1975] developed their own seafloor subsidence curve for the equatorial Pacific, derived from present age-depth settings and without accounting for sediment loading [*van Andel and Bukry*, 1973]. Their curve backtracks to an initial mid-ocean ridge axial depth of about 3000 m, while the theoretical age-depth curve of *Sclater et al.* [1971] plots back to about 2000 m initial depth. *van Andel et al.* [1975] estimate a resulting uncertainty in paleodepth of ±150 m in addition to the uncertainty in past axial depths.

[8] More recently, age-depth determinations have been based on the understanding that ocean floor crustal depth can be hindcast based upon an estimation of the initial axial depth and the determination of a subsidence parameter, k, such that the change in depth (in km) is proportional to the square root of crustal age (in m.y.) [*Davis and Lister*, 1974; *Parsons and Sclater*, 1977]:

$$\Delta Z = k(T)^{1/2}$$

and

$$Z_{\text{modern}} = Z_{\text{axis}} + \Delta Z.$$

[9] The main assumption in all this work is the initial depth of the seafloor spreading center, which we take to be 2750 m for the old Pacific-Farallon Ridge. This value is similar to depths along the modern East Pacific Rise and has been used in earlier studies by *Rea and Leinen* [1985, 1986]. Once the exact modern basement depth is discovered, and age of seafloor at any drill site is determined either from biostratigraphy of the basal sediment or from seafloor spreading magnetic anomalies, then the subsidence parameter can be calculated from the depth increase over that time. Usually, values for k are in the range of 0.32 to 0.36. Bulk density considerations show that sediment loading depresses the seafloor by an amount equal to half the sediment thickness [*Berger*, 1973], so any complete determination of age-depth histories requires that the sediments which have accumulated at any site are taken into account.

[10] In determining the history of the Paleogene CCD from the Leg 199 drill sites, we have assumed an initial ridge axial depth of 2750 m and calculated a slightly different subsidence parameter for each site on the basis of the age and unloaded basement depth (Table 1). Paleodepths for the igneous crust were calculated from the subsidence parameter, crustal age, and axial depth and then reloaded with sediment (Figure 2). The sediment accumulation history was simplified somewhat from the individual records at Sites 1215, 1217, 1218, and 1219 to reflect an older higher sedimentation rate, followed by a younger slower accumulation rate. A single loading rate was used for backtracking depths at Site 1220, and 1221. We did not

Table 1. Parameters Relating to Subsidence Calculations for the Leg 199 Drill Sites[a]

Site	Seafloor Depth, m	Sediment Thickness, m	Basement Depth, m	Unloaded Depth, m	Basement Age, Ma	Subsidence Parameter
1215	5396	70	5466	5431	56.4	0.357
1217	5342	138	5480	5411	56.5	0.354
1218	4827	274	5101	4964	42.4	0.340
1219	5063	245	5308	5185.5	55.2	0.328
1220	5218	216	5434	5324	55.5	0.346
1221	5175	156	5331	5253	56.5	0.333
1222	4990	106	5096	5043	55.0	0.309

[a] Basement ages are from shipboard biostratigraphy [*Lyle et al.*, 2002]. The subsidence parameter is calculated using the assumption of an initial ridge axis depth of 2750 m.

use information from Site 1216 because drilling did not reach basement there. Similarly, poor recovery and hiatuses at Site 1222 rendered this site less useful for our purposes. The careful determination of both subsidence history and sediment loading resulted in paleodepths that have a precision relative to the initial axial depth (thus also relative to each other) of about ±50 m. Internal consistencies within our data set provide confidence in this estimate of precision. Uncertainty in absolute values for paleodepth depends on the accuracy of the axial depth estimation, although possible errors from this parameter become increasingly smaller with increasing crustal age.

[11] Because all drill sites move with their respective plates, they must be backtracked in space as well as depth. *van Andel et al.* [1975] recognized the paramount importance of this realization with respect to the motion of the Pacific plate beneath the equatorial high productivity zone and constructed a series of backtrack paths based largely on the locus of maximum sediment thickness through time. Drill sites for Leg 199 have been backtracked geographically using the poles of rotation developed by *Gripp and Gordon* [1990] for the past 5 m.y. and by *Engebretson et al.* [1985] for older times.

4. Paleogene CCD in the Eastern Pacific Ocean

[12] The new information from Leg 199 bears upon several aspects of the Pacific CCD record: (1) its depth during the early Eocene, (2) a brief, 700+ m, deepening around 41 Ma, (3) the dramatic and sudden deepening associated with the Eocene/Oligocene transition, and (4) its early Neogene depth. All sites show a generally similar sedimentary record. Carbonate sediment deposited high on the rise flank during the early Eocene give way to siliceous deposits at roughly 52 to 53 Ma. The lower portions of these siliceous deposits contain cherts, whereas the middle to late Eocene is represented by nearly pure "brown sugar" radiolarian ooze. In most of our sites the radiolarian ooze gives way suddenly to lower Oligocene calcareous ooze, which, in turn, grade upward into upper Oligocene to lower Miocene biogenic ooze. Lithologically, the youngest 20 to 50 m.y. at each site is represented by pelagic clay, which

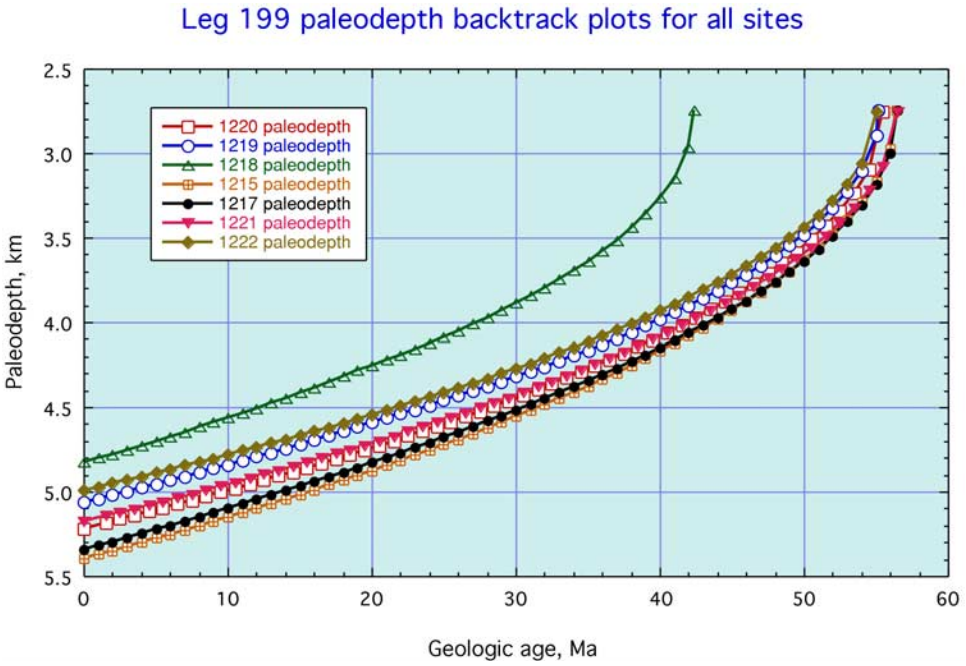

Figure 2. Subsidence curves for the Leg 199 drill sites calculated and plotted at 0.5 m.y. intervals.

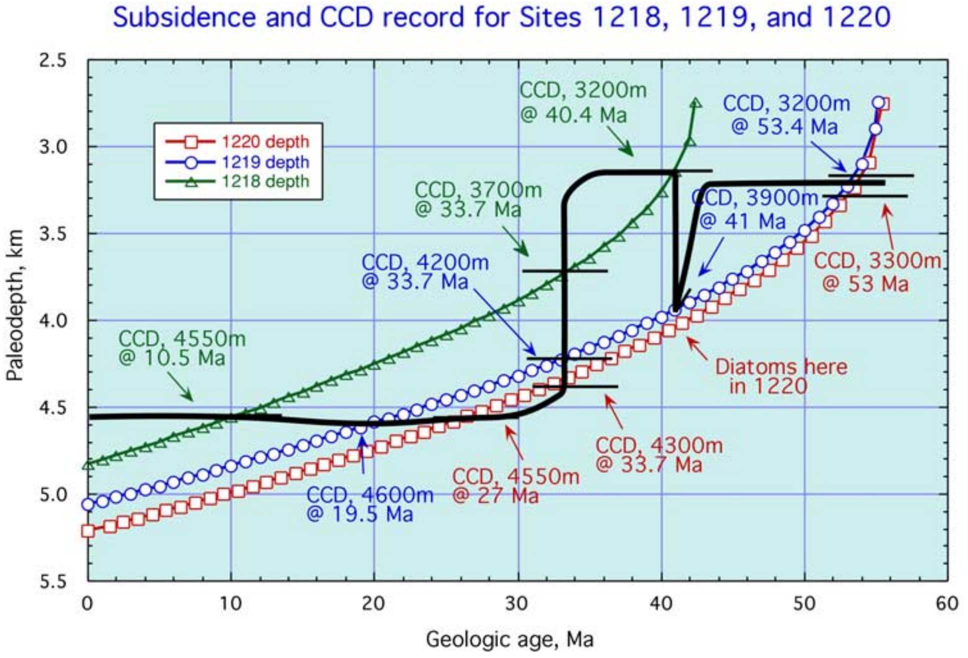

Figure 3. Subsidence histories and CCD record of Leg 199 drill sites 1218, 1219, and 1220 near the Eocene paleoequator.

may contain siliceous biogenic debris at the more southerly of our sites. Site 1221 is more severely eroded and has only a thin layer of reworked Eocene and younger radiolaria and clay atop the lower Oligocene carbonate ooze.

[13] The compensation depth of the northeastern subtropical Pacific in Oligocene and younger times is constrained to lie between 4550 and 4600 m by the data from Sites 1218, 1219, and 1220 (Figure 3). Sites 1215 and 1217 were always beneath the CCD in the Oligocene and Neogene, and the younger record at 1221 is missing, likely a result of erosion. The data are too few to test the validity of the modest Miocene rise and fall of the eastern subtropical Pacific CCD as interpreted by *van Andel et al.* [1975], *Rea and Leinen* [1985], and *Lyle* [2003]. However, a large change would likely have been manifest even in our sparse Neogene data set. Regardless, the CCD depths reported in these studies for the North Pacific are about 500 m deeper than those for the southeastern Pacific [*Rea and Leinen*, 1985].

[14] The sharp and sudden deepening in the CCD that occurs associated with the Eocene-Oligocene boundary is recorded in five of our six drill sites that recovered useful information regarding this interval. We find that the CCD deepens from 3200 m at Site 1218 to a depth constrained to 4400 m by the subsidence and facies patterns at Sites 1217 and 1215 (Figure 4). The most complete record of this event was captured at Site 1218 where the physical properties data and calcite abundance information show a two-step change from older uppermost Eocene sediment with essentially no $CaCO_3$ to lowermost Oligocene sediment characterized by 85 to 90% $CaCO_3$ (Figure 5). *Coxall et al.* [2005] have shown that the two steps were each of 40 kyr duration, separated by a pause of about 200 kyr. This deepening in the CCD is a global phenomenon that reflects the single largest change in Cenozoic oceanic paleochemistry. Following the time of the E/O boundary, the CCD in the eastern subtropical Pacific deepened slowly by another 200 m to about 4600 m at approximately 20 Ma (Figure 3).

[15] In the later part of middle Eocene time there was a sharp drop and recovery of the CCD (Figure 3). This event, studied in detail by *Lyle et al.* [2005], happened at about 41 Ma in radiolarian zone RP15, close to the boundary between nannofossil zones CP14a and CP14b. Prior to this event the CCD is not well constrained by our data, but probably hovered near 3200 to 3300 m [cf. *van Andel et al.*, 1975] and deepened to at least 3950 m as seen at Site 1219 which displays a 4.4-m-thick interval of contemporaneous nannofossil ooze bracketed by diatom-rich radiolarian ooze. Just slightly deeper, Site 1220 at 4025 m and Site 1221 at 4050 m paleodepth show only the increase in the abundance of diatoms within the radiolarian ooze. At relatively shallow depths Site 1218, barely above the middle Eocene CCD of 3200 m, the 41 Ma event is recorded by the addition of 10 to 15% diatoms to the normal nannofossil ooze. Together, these data indicate a CCD deepening of more than 700 m. The rate of deepening is not resolved by our data, but the ensuing CCD rise must have been quite rapid. The presence of diatoms in all four or these sites suggests that the middle Eocene CCD event is more likely related to enhanced surface water productivity at these low latitude sites rather than to a change in deep-water dissolution rates.

[16] In general, our study serves to confirm and better constrain previously documented changes in CCD behavior but our findings with regard to the early Eocene CCD are completely novel. The Leg 199 record shows an early Eocene equatorial CCD of 3200 m, similar to that estimated by *van Andel et al.* [1975]. The fundamentally new information is that the early Eocene CCD deepens with increas-

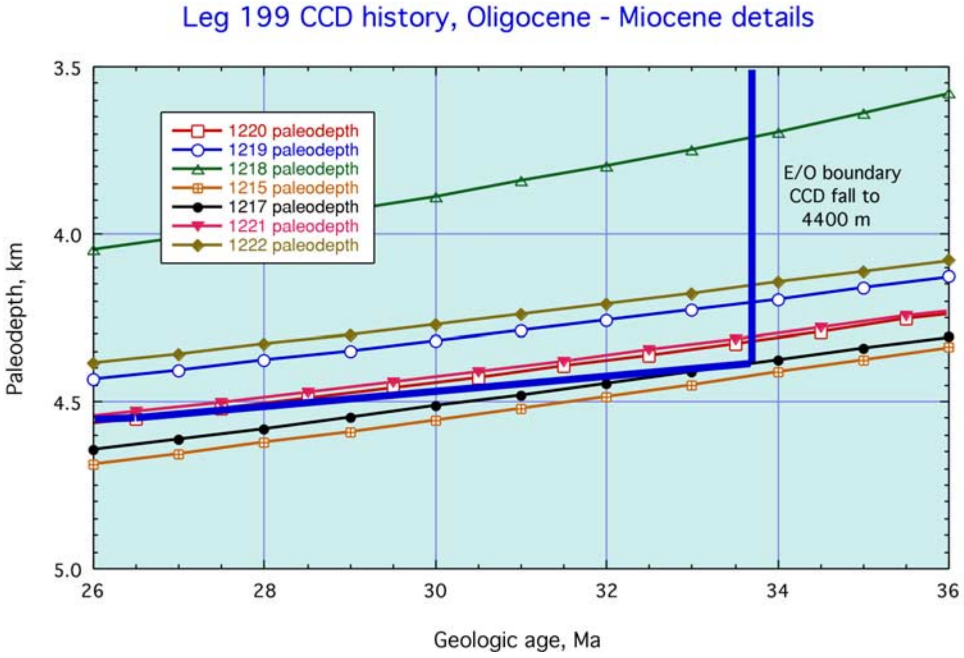

Figure 4. Details of the CCD drop at 33.7 Ma, the Eocene/Oligocene boundary. The post-fall depth of the CCD is constrained by the paleodepths of Site 1215, where there is no Oligocene calcite, and 1217, where there is lower Oligocene calcite.

ing latitude to a depth of 3600 m at site 1215 (paleolatitude ~10°N; Figure 6). This trend, hinted at in the figures of *Heath et al.* [1977], is clear in all sites and well beyond the uncertainties in the paleodepth reconstruction method. In all modern settings the CCD is deepest beneath the high-productivity zone that is associated with equatorial upwelling and where the calcite production rate depresses the CCD. The observation of no clearly focused biological

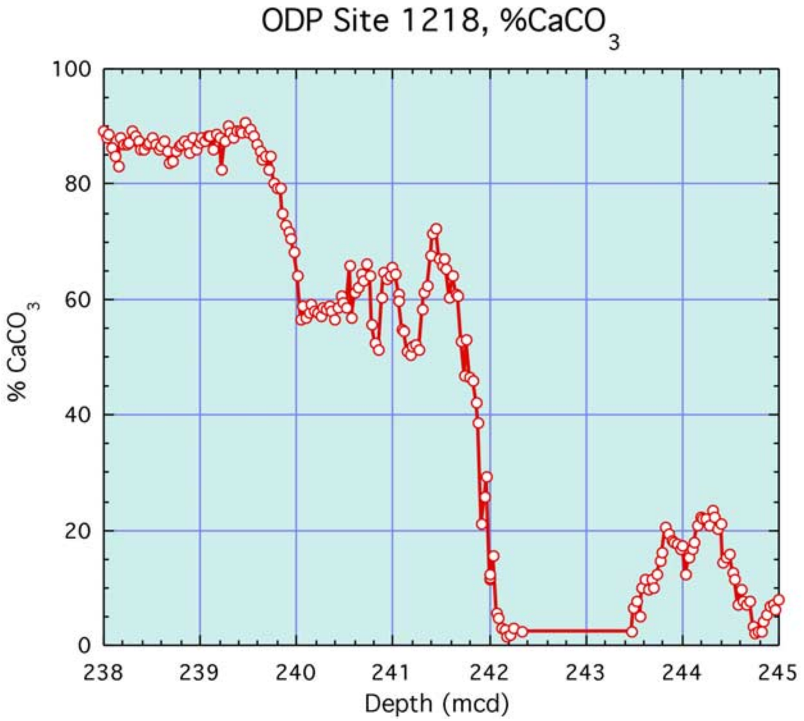

Figure 5. $CaCO_3$ content of sediment across the Eocene/Oligocene boundary at Site 1218, courtesy of H. Palike and J. Backman.

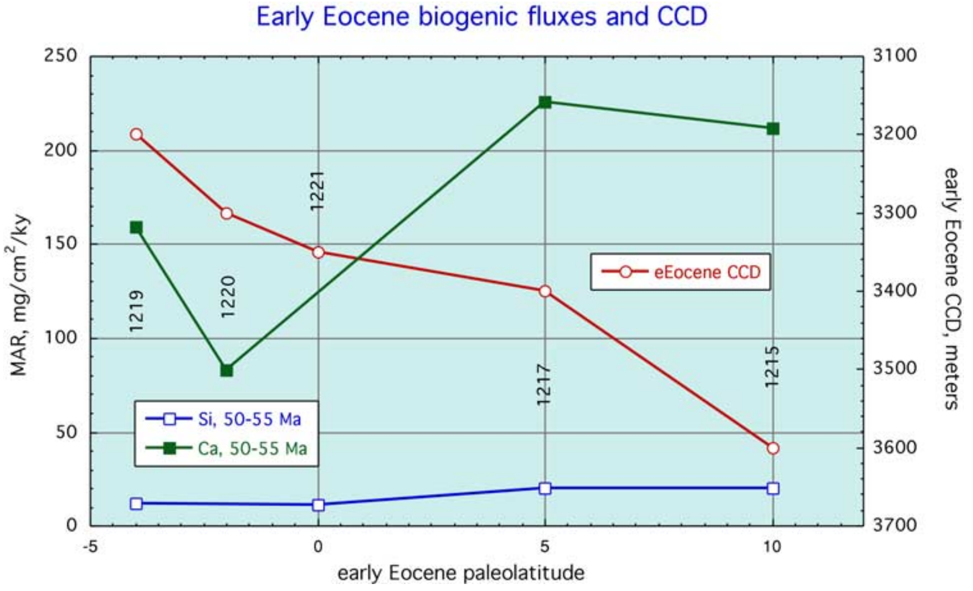

Figure 6. Early Eocene CCD depth and calcium and silica fluxes across the Pacific equatorial zone. Ca flux increases and the CCD deepens to the north of the early Eocene paleoequator, and the silica flux is low across the entire equatorial system. Flux data from *Lyle et al.* [2002].

productivity at the equator and of the early Eocene CCD deepening away from the equator (Figure 6) may reflect either relatively less calcite production at the equator or less dissolution to the north of the equator. Either explanation is contrary to conditions in the modern ocean and suggests very different patterns of circulation, and/or productivity, in the early Eocene [*Moore et al.*, 2004].

5. Discussion

5.1. Middle Eocene CCD Excursion

[17] The 700+ m middle Eocene CCD excursion (Figure 3) is new information with regard to the global CCD history. It is likely a productivity event as suggested by the associated facies changes, perhaps an early interlude of focused biological productivity along the equator as finally instigated in the early Oligocene [*Moore et al.*, 2002; *Lyle et al.*, 2002]. This 41 Ma CCD excursion and its related interval of calcite accumulation are associated with a 1.2‰ positive, transient shift in δ^{18}O values, requiring some combination of cooling and/or ice volume buildup then [*Lyle et al.*, 2005].

5.2. Global Change at the Eocene/Oligocene Boundary

[18] The 1200-m CCD drop at the Eocene/Oligocene boundary appears to be a widespread, possibly global, event. The CCD in the Indian ocean is not as well constrained as it is in the eastern Pacific, but stood at about 3300 m in the middle to late Eocene [*Peterson et al.*, 1992], deepening to more than 3600 to 4000 m in the early Oligocene. South Atlantic drilling by DSDP Legs 73 [*Hsu et al.*, 1984] and 74 [*Moore et al.*, 1984] show the Eocene CCD to be at 3300 m in the mid to late Eocene, and at 4300 m in the Oligocene. Actual depths naturally depend on the calculations of paleodepths, not always apparent in these earlier works. The important point is that a 1 km drop of the CCD is a widespread phenomenon.

[19] It is instructive to compare a 1200 to 1400 m deepening in the CCD to a hypsographic curve (and assume that overall hypsometry is similar in the latest Eocene to the modern). Present hypsometry is based on 50-m depth intervals (Figure 7, modified from R. H. Stewart, online textbook "Introduction to Physical Oceanography," Texas A&M Univ., College Station, Tex., available at http://oceanworld.tamu.edu/ocean410). Examination of these curves show that the area of the seafloor lying between 0 and 3250 m depth represents 20% of the entire Earth, or 29% of the seafloor. The area of the seafloor between 3250 and 4550 m, the interval of the CCD drop, is 25% of the Earth's surface or about 36% of the sea floor. Thus on a timescale estimated to be less than 300 kyr [*Coxall et al.*, 2005], the area of ocean floor covered by deposits of $CaCO_3$ increased by a factor of 2.25. The implications of more than doubling of the area subject to calcite deposition have neither been pointed out nor discussed previously.

[20] Among the earlier marine geological investigations of climate change at the E/O boundary were those of J. Kennett and his coworkers. *Kennett and Shackleton* [1976] noted the 1.25‰ increase in δ^{18}O values at this boundary. They calculated from sedimentation rates that this shift was accomplished in only 75,000 to 100,000 years, and observed that it was accompanied by a "major and apparently rapid deepening" of the CCD. This early estimate of the CCD change across the E/O boundary, and by extension, the association with the contemporaneous δ^{18}O increase in marine calcite is confirmed by our findings. The increase in δ^{18}O can be interpreted in terms of either a cooling of ambient waters, in this case about 5°C, or a buildup of ^{18}O-depleted ice on land. *Kennett* [1977] called on an influx of oxygen-rich, cool waters from high latitudes to explain

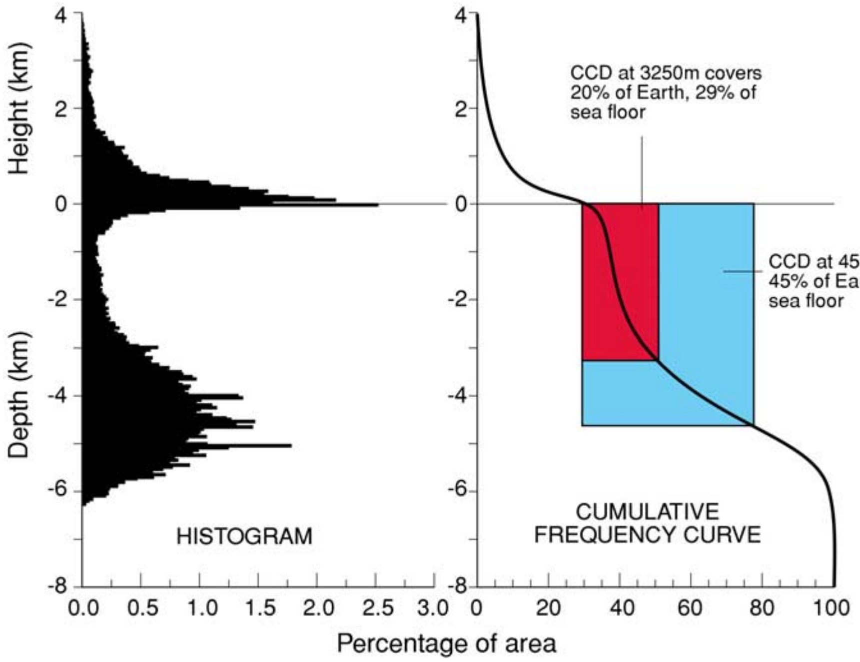

Figure 7. Hypsographic curve (after R. H. Stewart, available at http://oceanworld.tamu.edu/ocean410) illustrating the more than doubling in area of calcite deposition following a CCD drop from 3250 to 4550 m.

both the isotope and CCD information. However, higher resolution δ^{18}O records, together with records of changes in clay mineralogy and occurrence of ice rafted debris at high latitude suggested that a significant component of the δ^{18}O signal was attributable to the onset of Antarctic glaciation [e.g., *Miller and Thomas*, 1985; *Ehrmann and Mackensen*, 1992; *Zachos et al.*, 1992, 1999]. This E/O boundary cooling versus ice volume discussion continues to this day.

[21] New records of Mg/Ca in benthic foraminiferal calcite, an independent paleotemperature proxy, indicate little or no change in the temperature of middepth waters at the E/O boundary (one site may even show a warming) suggesting that the δ^{18}O transition is, perhaps, entirely attributable to increasing ice volume [*Lear et al.*, 2000; *Billups and Schrag*, 2003]. We note, however, that sequence stratigraphic records across the E/O boundary are interpreted in terms of only a modest, approximately 50 m, sea level fall [*Haq et al.*, 1987; *Pekar et al.*, 2002], which constrains the possible amount of ice accumulation on land and the likely change in δ^{18}O to 0.4 to 0.5‰, leaving about a 3° temperature change. Furthermore, a considerable body of data from other oceanic [*Haq et al.*, 1977; *Prothero et al.*, 2003] and continental [*Wolfe*, 1978, 1994; *Ivany et al.*, 2000] sources suggest that at least a seasonal mid to high latitude cooling in the early Oligocene.

5.3. Relative Efficacy of Shelf-Basin Fractionation and Rapid Continental Weathering

[22] A 50-m drop of sea level would expose less than half of the world's continental shelves, and in the warmer late Eocene half of those continental shelves might have been loci of carbonate deposition. The carbonate from this 3 or 4% of the Earth's surface is unlikely to have been responsible for covering the 25% of the Earth between 3250 and 4550 m depth.

[23] Does the boundary event therefore require a doubling of the amount of Ca coming into the ocean? Does this change the Mg/Ca ratio? If every mole of $CaCO_3$ deposited releases a mole of CO_2 this would result in a modest rise in pCO_2, perhaps by 80–100 ppm (M. Huber, personal communication, 2003), so how does this fit with suggestions of CO_2 decline (see below) at the boundary?

[24] We find several contra-indicatory events happening at the E/O boundary. *DeConto and Pollard* [2003] have tried to explain the apparently rapid ice volume increase on Antarctica by ice growth threshold phenomena in a time of declining atmospheric CO_2. *Rea* [1993] pointed out that two of the main indicators of continental chemical weathering, the input of Ca and radiogenic Sr [see also *Zachos et al.*, 1999] to the oceans, both increase markedly beginning at the E/O boundary, and denote the Oligocene and earlier part of the Miocene as a time dominated by worldwide chemical weathering [*Ravizza and Peucker-Ehrenbrink*, 2003]. Calcium isotopic data, δ^{44}Ca, are consistent with an increased flux of Ca to the oceans beginning in early Oligocene time [*De La Rocha and De Paolo*, 2000]. The awkward part of this weathering discussion has been that the Oligocene and Miocene are regarded as colder climatically than the warmer Eocene and Paleocene, when all weathering processes seem subdued [*Rea*, 1993]. Another awkward problem is that oceanic Ca contents should not change rapidly without a huge change in the Ca input to the ocean. On the basis of roughly a million year residence time for Ca [*Broecker*, 1971] the Ca input to the oceans would have to triple to cause as rapid a change in the carbonate system as observed

at the Eocene/Oligocene boundary. Such large changes in the weathering cycle are hard to imagine. Nonetheless, it is interesting, although perhaps coincidental, that the doubling of seafloor area covered by $CaCO_3$ should require about the same magnitude of change in the Ca cycle as a rapid change in CCD, if driven by Ca input from the continents.

[25] Most of our discussion has focused on the likely addition of Ca to the early Oligocene oceans, but reference to the carbonate equilibrium equation given in the introduction shows that the same result could be achieved by removing CO_2, in the form of organic matter, from the ocean system. If this had happened at the E/O boundary, perhaps by more vigorous circulation enhancing upwelling and productivity, then we would expect a positive shift in the $\delta^{13}C$ values of oceanic calcite (observed [*Zachos et al.*, 2001]), and significant accumulations of sedimentary organic carbon at this time (not observed).

[26] We can not resolve all these issues. Going back to *Kennett*'s [1977] suggestions, we do know that drift deposits began to form in the early Oligocene in both the North Atlantic [*Kidd and Hill*, 1987] and in the North Pacific [*Rea et al.*, 1995; *Scholl et al.*, 2003], marking the beginning of northern source, presumably cool, deep waters in both locations. Results of ODP Leg 189 [*Exon et al.*, 2001] showed that the final opening of the Tasman gateway also happened at the time of the E/O boundary, allowing the onset of near-circumpolar circulation in the Southern Ocean and enhancing the thermal isolation of Antarctica. Hence an invigoration of abyssal circulation in the earliest Oligocene seems nearly certain, a suggestion further supported by the observation that hiatuses occur in more than 70% of all E/O boundary sections in the deep sea [*Moore et al.*, 1978].

[27] A doubling of the area of calcite deposition in the deep sea seems to require a doubling of the amount of calcium coming into the ocean. The Mg/Ca data don't respond to this, implying that the Mg/Ca ratios of incoming materials changed very little and thus implicating the weathering of marine carbonate rocks [*Sloan et al.*, 1997]. Numerous investigators have demonstrated either cooling or no change in temperature across the E/O boundary, but not a warming. Thus any increased in CO_2 production did not serve to warm Earth, implying that it was taken up rapidly by chemical weathering of carbonate and silicate rocks [*Ravizza and Peucker-Ehrenbrink*, 2003]. High latitudes were probably cooler, exporting cooler water in flows that formed the northern hemisphere drift deposits, and incurring stronger winds [*Rea et al.*, 1985; *Rea*, 1994]. The stronger winds are likely responsible for focusing productivity at the equator beginning at the E/O boundary [*Moore et al.*, 2004]. This is the quandary with regard to the Mg/Ca data; perhaps it is not indicative of the deep ocean, below the CCD. Nevertheless, at least a modest ice volume increase, as constrained by the sea level information, must be an important component of the $\delta^{18}O$ step at the E/O boundary [*Oerlemans*, 2004]. Finally, to have the whole ocean and climate system change in less than 300,000 years probably does require a dramatic threshold phenomenon.

6. Summary

[28] The early Eocene calcite compensation depth in the Pacific was at 3200 m in the equatorial region and deepened to the north by about 400 m to 3600 m at 10°N. In the modern ocean, the CCD deepens toward the equator in response to the focussed productivity zone there. These data and the mass accumulation rate of silica suggest a broad and diffuse low-latitude productivity region then [*Moore et al.*, 2004]. At 41 Ma there was a brief, 700 m, downward excursion and retreat of the CCD, likely in response to a productivity event. The major drop in the level of the CCD, by 1200 to 1400 m, occurred in two steps at the Eocene/Oligocene boundary and may have taken less than 300 kyr to complete. This >1 km drop of the CCD is an oceanwide event that served to more than double the area of the seafloor subject to calcite deposition. The E/O boundary is a time of worldwide change, the start of cooler and more energetic climate regimes, and marks the beginning of increased continental weathering and of ice growth on continents.

[29] **Acknowledgments.** We thank the Leg 199 Scientific Party, technical staff, and the crew of the *JOIDES Resolution*. Without them, none of this would have been possible. Ted Moore and Paul Wilson provided comments and insights on an earlier draft of this paper. Deborah Thomas and Gabriel Filippelli reviewed the manuscript and we thank them for their suggestions for improvement. Support for M. Lyle was provided by NSF grant OCE-0240906.

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