Equatorial ocean circulation in an extremely warm climate

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[1] The warm climates of the early Paleogene and the associated diminished near-surface winds should have resulted in a reduction in near-surface ocean circulation. One check on this deduction is the delineation of biogenic sediments associated with an equatorial current system of the early Eocene Pacific. A latitudinal seismic reflection transect across the tropical Pacific along early Paleogene ocean crust reveals a basal high-amplitude reflection package that we take to be the lower Eocene section. This unit varies in thickness by a factor of about two, with the thickest portion forming a low mound some 3°–4° north of the 56 Ma paleoequator. This mound may represent the position of a divergence generated in the frontal region between two currents flowing in opposite directions, and its position suggests that the wind-driven equatorial circulation of the early Eocene was one without a pronounced equatorial divergence. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 3022 Marine Geology and Geophysics: Marine sediments–processes and transport; *KEYWORDS:* paleocirculation; Paleogene; Pacific

1. Introduction

[2] It has long been known that the shift in the sign of the Coriolis effect at the equator results in wind-induced divergence and the upwelling of deeper waters. These more nutrient-rich waters give rise to higher rates of organic production that result in a high delivery rate of organic debris to the seafloor. Sediment trap studies across the Pacific equatorial region have shown that a strong maximum in sediment rain rate is located on the equator and falls off rapidly within 2°–4° latitude north and south of the equator [*Murray and Leinen*, 1993; *Murray et al.*, 1995]. Over the last 34 m.y., biogenic debris has built an elongate mound of sediments parallel to the modern equator [*Ewing et al.*, 1968].

[3] The thickest part of this mound is shifted slightly to the north of the present equator. In an early synthesis of scientific ocean drilling results from the tropical Pacific Ocean, it was shown that the location of the thickest sedimentary section representing any middle to late Cenozoic time interval was displaced to the north of the modern equator in a way that was consistent with Pacific plate motion [*van Andel et al.*, 1975]. In fact, by tracing the thickest part of the equatorial sediments through time, *van Andel et al.* [1975] were able to locate the positions of the paleogeographic equator and determine a pole of rotation for the Pacific plate that was independent of assumptions regarding the paleomagnetic pole position.

[4] Both a very shallow calcite compensation depth (CCD) and the nearly pervasive occurrence of chert in Eocene and older sections has challenged our ability to extend paleoceanographic reconstructions much beyond 34 Ma. However, stratigraphic and paleoclimate information accumulated over the years from studies of both marine and land sections has gradually revealed a picture of an early Paleogene world very different from our own. This was a time of extremely warm climates, with faunas and floras typical of modern tropical to subtropical latitudes existing in midlatitude continental interiors and ranging poleward to near the Arctic circle [*Estes and Hutchinson*, 1980; *Wing and Greenwood*, 1993; *Marwick*, 1994]. Oxygen isotopic data available from this time interval suggest that the pole-to-equator temperature gradient was half that of today and that deep water temperatures were some 10°–12°C warmer than today [*Kennett and Stott*, 1991; *Pak and Miller*, 1992; *Zachos et al.*, 1994]. Dust records indicate that atmospheric circulation during the Eocene may have been much more sluggish than at present [*Rea et al.*, 1985; *Rea*, 1994].

[5] In recent years, we have become more conscious of the potential impact of an extremely warm climate in our own future. Global circulation models (GCMs) have been used in attempts to "hindcast" the extremely warm climates of the early Paleogene and Cretaceous. However, simply raising the level of atmospheric CO_2 to emulate these past extreme warm climates tended to warm the tropics more than most oxygen isotopic data would support as reasonable (although more recent analyses have questioned estimates of relatively cool tropics in the "hothouse" world [*Zachos et al.*, 1994; *Schrag et al.*, 1995; *Norris and Wilson*, 1998]). These hindcast models have usually proven inadequate unless some deus ex machina enhancement of poleward heat transport was imposed [*Barron et al.*, 1981; *Barron*, 1987; *Covey and Barron*, 1988; *Rind and Chandler*, 1991; *Barron et al.*, 1993; *Sloan et al.*, 1995]. Accounting for such increased poleward transport of heat using wind-driven mechanisms results in a paradox: the lower the pole-to-equator temperature gradient, the weaker the near-surface wind systems and the lower the rate of heat transport by winds and the wind-driven surface ocean [*Barron*, 1987; *Sloan et al.*, 1995]. So how do you warm the poles and keep them warm under these conditions?

[6] In the equatorial Pacific we have an opportunity to verify our assumptions about near-surface winds and wind-driven ocean circulation during a hothouse climate. The equatorial current system of the Pacific is one of the world's most extensive and most complex wind-driven current systems, a system largely unconstrained by irregular boundaries. The behavior of this system has been traced back to 34 Ma using geochemical, biotic, and sedimentologic techniques and has shown only relatively minor variations. Any fundamental change in this circulation in the older,

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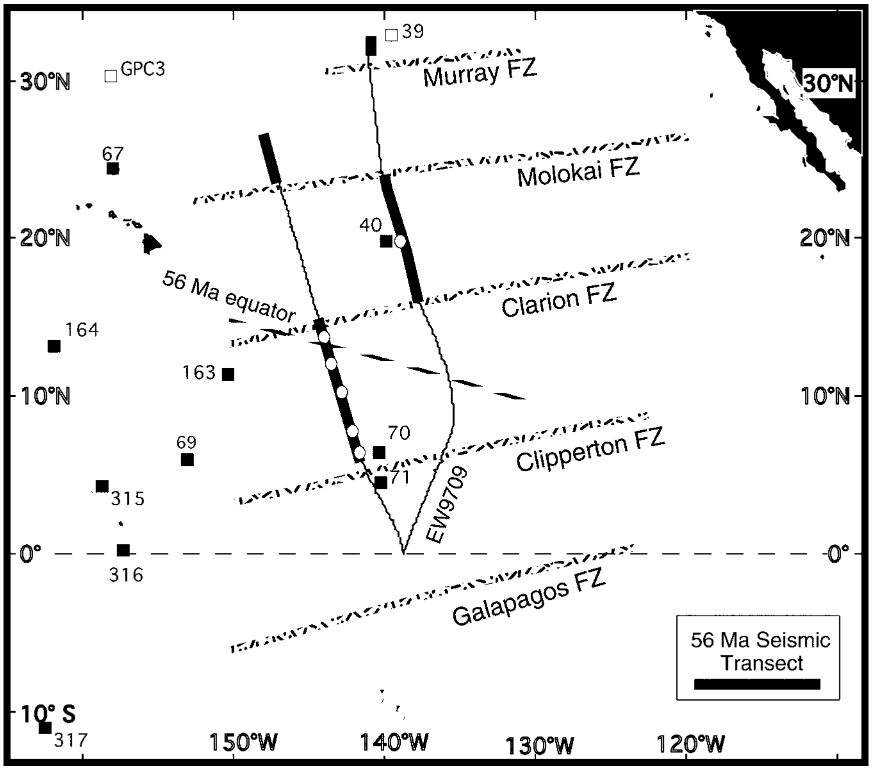

Figure 1. The track of the R/V *Maurice Ewing* (cruise EW9709). Thick solid lines indicate that part of the survey that is along 56 Ma ocean crust. Oceanic fracture zones (FZ), indicated by broad dotted lines, offset the ridge crest and produce offsets in the age of the crust. A thinner hatched line indicates the position of the 56 Ma paleoequator using the fixed hot spot rotation scheme used in this paper [*Engerbretson et al.*, 1985; *Gripp and Gordon*, 1990]. Open circles indicate locations of the cores shown in Figure 2. Solid squares and associated numbers indicate DSDP sites containing middle to lower Eocene siliceous oozes and cherts. Open squares indicate DSDP sites and Giant Piston Core 3 containing no middle to lower Eocene siliceous oozes and cherts.

extremely warm climates of earlier Paleogene times should be evident in the patterns of sediment deposition associated with patterns of near-surface oceanic circulation and divergence.

2. Methods

[7] Our strategy in exploring the equatorial circulation of the early Paleogene is to drill a latitudinal transect of sites in the tropical North Pacific along oceanic crust that was formed about 56 Ma, just prior to the time of maximum warmth in the early Eocene. With an early Paleogene CCD of ~3300 m [*van Andel et al.*, 1975], carbonate sediments should have accumulated and been preserved on crestal regions of the Pacific basin spreading center. As the newly formed crust gradually cooled and eventually sank below the CCD, there should have been an interval of 5–10 m.y. during which carbonate sediments could have accumulated atop the Paleocene and Eocene crust. The recovery of these carbonate sediments in a transequatorial cross section is a key first step in defining low-latitude wind-driven circulation in the Paleogene ocean. In preparation for this drilling effort we conducted a seismic reflection survey of the sediments lying on the 56 Ma (uppermost Paleocene) crust (Figure 1) from ~5° to 26°N. The age of the crust was identified on the basis of the magnetic anomaly patterns of the seafloor along which we tracked the magnetic chron 25n [*Atwater and Seveinghaus*, 1989]. Swath bathymetry collected in real time allowed us to remain parallel to the grain of the bottom topography. Offsets in the track of the survey reflect offsets in the age of the crust at the Murray, Molokai, and Clarion Fracture Zones. Detailed predrill bathymetric and seismic surveys were conducted, and piston cores (~15 m long) were taken at several locations along the track (Figure 1).

[8] During cruise EW9709 onboard the R/V *Maurice Ewing* we collected seismic reflection data using a single 80 in^3 air gun as a source. The air gun signal extended to 160 Hz, and data were recorded with a four-channel streamer. Initial selection of survey and coring sites was based on the shipboard analog data. Subsequent to the cruise, selected parts of the transect were reprocessed using ProMAX seismic processing software. We spectrally whitened the reflection data from 25 and 120 Hz, then applied an *f-k* (frequency-wave number) migration to spatially position each reflector. These reprocessed data were used as guides in the seismic interpretation and in the illustrations presented in this paper

3. Results

[9] Both the seismic data and the cores collected on this survey indicate the gradual thinning of the total sediment cover on the 56 Ma crust as we moved north along the northern flank of the equatorial sediment mound (Figure 2). The oldest ages in sediments from cores collected on our transect increase to the north. This pattern documents the near outcropping of older Cenozoic sediment with increasing latitude to the north as northward plate motion has carried the crust farther and farther from the equatorial zone of high deposition rates.

[10] At the base of the sediment layer seen in the seismic sections, there is a package of relatively high amplitude reflectors.

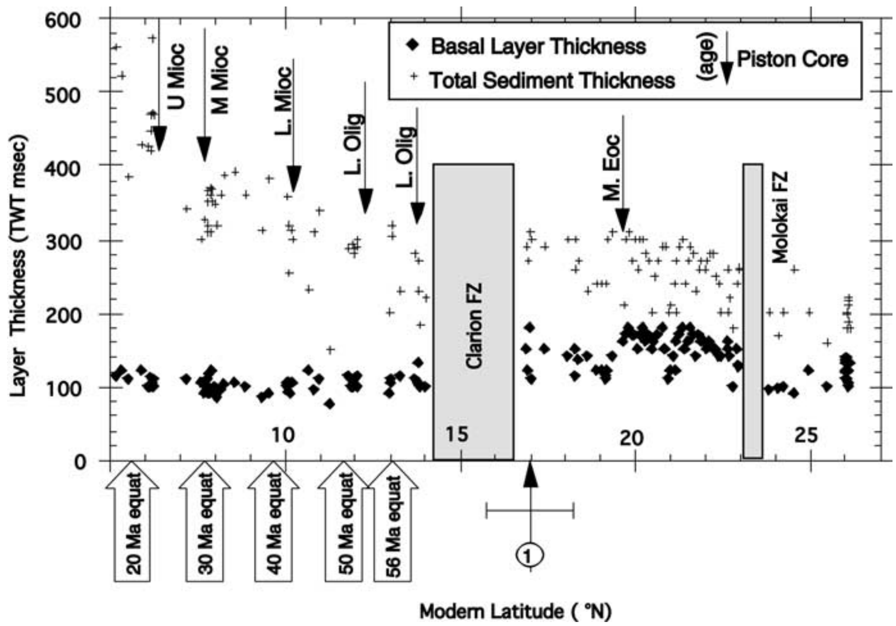

Figure 2. Total sediment thickness (plus signs) and thickness of the basal package of high-amplitude seismic reflections (diamonds) lying over 56 Ma oceanic crust plotted versus modern latitude. Offsets in the transect at fracture zones (Figure 1) are shown as shaded rectangles. Thicknesses are measured in two-way travel time (TWTT). Locations of the paleoequator as determined by plate rotations [*Engerbretson et al.*, 1985; *Gripp and Gordon*, 1990] are indicated below the latitude axis for various times in Cenozoic. A vertical upward arrow with crossbar indicates the estimated position (with error bar) of the 56 Ma equator after correction for hot spot motion (see text). Vertical downward arrows indicate the age and location of the oldest sediments recovered in piston cores taken along the transect.

This package can be traced throughout the length of the 56 Ma crustal transect (Figure 1). These high amplitude reflections are thought to represent carbonate-rich sediments deposited near the ridge crest, an interpretation supported by results from regional DSDP sites. As the crust subsided away from the crestal area, the seafloor soon sank beneath the very shallow CCD of early Paleogene times. Younger opal- and clay-rich sediments that have a markedly different seismic signature were deposited below the CCD on top of the carbonate layer. The upper surface of this reflective sediment package is thus thought to represent a facies change that may only approximate a chronostratigraphic horizon. At latitudes where the rain rate of carbonate debris was high, accumulation of carbonate sediments may have persisted longer than at latitudes where the carbonate rain rate was low. Given the relatively shallow CCD of the Paleogene and the relatively rapid subsidence rates of young oceanic crust, it is thought that the age range of the upper surface of this carbonate package might vary by only ±1 or 2 million years. The youngest age of the top of this package is constrained by that of the siliceous-rich (carbonate-free) lower middle Eocene sediments recovered in the piston core taken near 20°N (Figure 2). The age of the base of this package is constrained by the age of the crust on which it lies.

[11] What we interpret to be a basal carbonate sequence ranges in thickness from slightly less than 100 ms to ~200 ms two-way travel time (TWTT), with most of the transect having a moderately thin basal section (~70 m). The thickest part of the basal section (~150 m) lies at present-day latitudes of 19°–22.5° N (Figure 2). Within this high-amplitude basal section, a pair of higher-amplitude, relatively coherent reflections is usually seen lying on either side of a lower amplitude, less continuous reflection (Figure 3). This reflection pattern is found in nearly all sections and is used to correlate the basal seismic package in areas separated by topographic disruption. In the thinner sections this high-amplitude doublet is found near the middle of the basal unit. In the thicker part of the basal section it is found in the upper third of the basal high-amplitude unit. This suggests that the basal part of the thicker section between 19° and 22.5°N accumulated more rapidly than elsewhere along the transect.

[12] In other middle to late Cenozoic latitudinal transects shown by *van Andel et al.* [1975] the on-axis to off-axis thickness ratios range from 3 to 6 for sections representing 5–10 m.y. of deposition. The only Pacific equatorial transect drilled on constant-age crust was of late Miocene age (~10 Ma): Ocean Drilling Program (ODP) Leg 138, Sites 848 through 854 [*Mayer et al.*, 1992]. The time represented in the Leg 138 equatorial sections is thought to be approximately the same or slightly greater than that represented by the basal high-amplitude section of our 56 Ma transect. The thickness of the 0–10 Ma section away from the late Neogene equatorial mound of sediment is comparable to that along the 56 Ma transect away from the thick portion centered at 21°N. The region of thicker sediments in the 56 Ma transect is comparable in latitudinal width to that of the late Neogene transect; however, the late Neogene mound of sediments is over 5 times as thick as the sedimentary sections a few degrees away from its center, whereas the 56 Ma mound is only about twice as thick as the sections a few degrees away from 19°–22.5°N.

[13] The basal high-amplitude unit in our transect extends somewhat beyond the 5°–26°N limits of the present survey. On the basis of older drilling results and the initial detailed survey area of our transect (Figure 1) we know that the total sediment cover overlying the 56 Ma crust at 31°N does not show a basal high-amplitude package and is <20 ms (~15 m) thick. This compares well with DSDP Site 39 [*McManus et al.*, 1970] at 32°48’N which bottoms in lower Eocene sediments and has a total thickness of 17 m. To the south of the mound, the basal high amplitude section extends at least 16° of latitude.

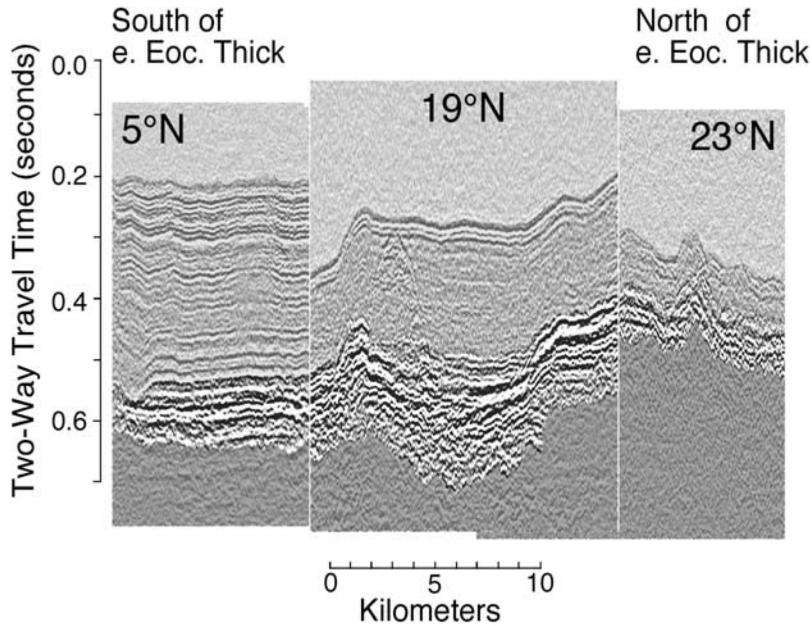

Figure 3. Example seismic sections taken along the 56 Ma transect near the northern and southern extremes of the transect and near the thicker part of the section (19°N). Dark shading indicates acoustic basement. Unshaded intervals indicate the high-amplitude reflection package lying on acoustic basement and taken to represent the lower Eocene calcareous section. Lighter shaded intervals indicate the overlying Cenozoic clays and siliceous-calcareous oozes. Modern latitude of each section is shown at the top of each section. Vertical scale is in milliseconds two-way travel time. Sections have been shifted vertically to achieve a seismic character match of two prominent high-amplitude, continuous reflections.

[14] Similarly, the 0–10 Ma section recovered by ODP Leg 138 [*Mayer et al.*, 1992; *Pisias et al.*, 1995] thins markedly within 10° of latitude north of the mound axis. Although the data from Leg 138 do not extend very far to the south, data from Deep Sea Drilling Project (DSDP) Leg 92 [*Leinen et al.*, 1986a] indicate that the late Neogene section is of the order of 70 ms thick 20° south of the axis of the equatorial mound. If anything the lower Eocene section appears to be slightly thicker than this in the south.

[15] Although not of an impressive thickness, the width of the basal sediment mound in the 56 Ma transect and the latitudinal extent of the basal unit sediments on either side of the mound are similar to that of sediments laid down under and near the equatorial divergence of later times. However, do they represent sediments deposited beneath the early Eocene region of equatorial divergence? To locate the Pacific equator at 56 Ma, we initially used plate rotation schemes which assume a fixed hot spot reference system [*Engerbretson et al.*, 1985; *Gripp and Gordon*, 1990]. This rotation moves the plate gradually northward and places the 56 Ma equator near 13°N in our transect (Figures 1 and 2). Other authors have suggested that the classic Hawaiian hot spot is not fixed but rather moved with time, particularly in times older than ~39–43 Ma [e.g., *Molnar and Stock*, 1987; *Petronotis et al.*, 1994; *Tarduno and Gee*, 1995; *Cande et al.*, 1995; *Steinberger*, 1996; *Tarduno and Cottrell*, 1997; *Petronotis and Gordon*, 1994]. The sense of correction to the "fixed hot spot" models implied by the "nonfixed" Hawaiian hot spot models is to shift the estimated position of the early Paleogene equator several degrees to the north. We have corrected the estimated position of the 56 Ma equator using an average rate of 40 mm/yr (±10 mm/yr) of hot spot motion between the 43 Ma bend in the Hawaii-Emperor Seamount chain and the dated paleomagnetic pole position of Suiko Seamount (~65 Ma) [*Kono*, 1980; *Tarduno and Cottrell*, 1997]. The 40 mm/yr rate of Hawaiian hot spot motion is similar to the long-term average prior to 39 Ma calculated by *Petronotis and Gordon* [1994]. The correction to the fixed hot spot plate rotation scheme used here places the corrected latest Paleocene (56 Ma) equator at a present-day latitude of ~17°N (±1.2°) near 140°W, slightly south of the southern edge of the mound of thicker lower Eocene sediments seen in our transect (Figure 2). A correction that would place the 56 Ma equator directly under the central part of the lower Eocene sediment mound would require a rate of hot spot motion or true polar wander (or a combination of both [*Sager and Koppers*, 2000]) equivalent to ~74 mm/yr between 43 and 56 Ma. Although such a high average rate of motion is not totally excluded by the available paleomagnetic data, it does approach the limits of credibility.

4. Discussion

[16] In addition to the small size and puzzling location of the early Eocene sediment mound, there is another aspect of Eocene sediments in the tropical Pacific that is different. In the younger times, sediments rich in biogenic silica are confined to a relatively narrow latitudinal band of ±5° around the equator. Surface tropical Pacific sediments with >80% biogenic silica (carbonate-free) are confined to within ±2° of the equator [*Leinen et al.*, 1986b]. This is not true of the Eocene. Siliceous-rich sediments, radiolarian oozes, and cherts are found far south of the Eocene equator (e.g., DSDP Sites 69, 315, 316, and 317, Figure 1). However, they are only found up to a present-day latitude of ~24°N in the North Pacific. Specifically, middle to lower Eocene radiolarian ooze and cherts were found in DSDP Site 40 (at

19.8°N), and a few specimens of radiolaria were found in a poorly recovered porcellanite in DSDP Site 67 (at 24.4°N). But DSDP Site 39 (at 32.8°N) and GPC3 (at 30.3°N) are barren of radiolaria (Figure 1).

[17] Thus there are three somewhat puzzling aspects to the lower Eocene sediments of the tropical Pacific: (1) the zone of siliceous-rich sediments in the tropical Pacific of the Eocene is at least 30° wide (more than 6 times the width of the band of siliceous-rich sediments associated with the equatorial divergence of later times), (2) the sediment mound in the basal section of our latitudinal transect is small, about one fifth the size of the 0–10 Ma mound, and (3) the lower Eocene mound seems to be located a few degrees north of the 56 Ma equator.

[18] There is the possibility that very rapid hot spot movement and/or true polar wander between 43 and 56 Ma placed the 56 Ma geographic equator at what is now 21°N. In this case, the diminutive size of the mound could be attributed to the weak trade winds and low overall productivity of the early Eocene tropical ocean. What would not be explained is the broad expanse of relatively thick siliceous-calcareous sediments that extend to the south of the mound. *McGowran* [1989] has called for an Eocene ocean very rich in silica derived from volcanic outpourings and their rapid weathering in the warm climate of the time to explain the widespread occurrence of siliceous oozes and cherts. However, this explanation fails to address the relatively abrupt disappearance of Eocene siliceous sediments north of the mound.

[19] We suggest that the mound may not be associated with an equatorial divergence at all. If our placement of the 56 Ma equator (Figure 2) is correct, the mound was formed at least 3°–4° north of the equator and may be associated with a divergence created at a frontal region between two currents flowing in opposite directions, similar to the divergence between the North Equatorial Current and the Equatorial Counter Current in the modern ocean. In the very warm early Eocene the vertical stability of the oceanic water column was likely diminished [*Lyle*, 1997]. With such lower vertical stability and enhanced delivery of recycled nutrients, perhaps a modest mound of biogenic sediments could have been formed at such a divergence. This scenario would require an eastward flowing current at or just north of the equator and a westward flowing current several degrees farther north.

[20] Evidence from the record of eolian deposition in the Pacific Basin suggests that there has been a significant hemispherical asymmetry in atmospheric circulation through much of the Cenozoic [*Rea*, 1994]. This asymmetry results in an Intertropical Convergence Zone lying well north of the Eocene geographic equator, a scenario in agreement with a northerly shift in the zone of maximum biological productivity proposed here [*Rea*, 1994; *Rea et al.*, 1999, 2000].

[21] With the very much reduced average pole-to-equator temperature gradient and weak zonal winds of the early Eocene, the annual shift of the seasons would be proportionally an even larger climatic signal than today. *Walker* [1999] proposed that seasonal shifts in solar heating could have caused significant seasonal shifts in the atmospheric and surface ocean circulation, much like what is seen in the modern Indian Ocean. The model of the early Eocene ocean run by *Huber and Sloan* [1999] seems to indicate substantial seasonal changes in the ocean and a broad, rather diffuse area of divergence in the tropical Pacific that is consistent with the broad region on siliceous-calcareous sediments found there. If there was a substantial seasonal shift in the tropical current system of the early Eocene Pacific, it did not result in the formation of a symmetrical set of sediment mounds at both extremes of the seasonal shift. There is no mound of sediment placed 3°–4° south of what we take to be the 56 Ma equator.

5. Summary and Conclusion

[22] The early Paleogene remains an enigma. We have identified a high-amplitude package of reflectors that we believe represents the carbonate-rich sediments laid down in the early Eocene. Our latitudinal transect shows a mound of sediment between 19° and 22.5°N. In <10° of latitude to the north of this mound the lower Eocene sediments become dominantly red clays, but to the south, calcareous-siliceous sediments extend at least 30° of latitude. Compared to the mounds of sediment associated with the equatorial divergence through the rest of the Cenozoic, this mound is puny. It is only about twice as thick as the sections to the north and the south. Our estimate of the paleoposition of the 56 Ma equator places the center of this mound at 3°–4° N in the early Eocene.

[23] At best, our present vision of circulation in the tropical Eocene ocean is speculative. There are several indications that it was markedly different from modern circulation in the tropical Pacific. However, did hot spot motion or true polar wander greatly shift our frame of reference in the Eocene? Was there a west-to-east flow at the equator? What effect did the hemispherical asymmetry of atmospheric circulation have on surface ocean currents? Did pronounced seasonal changes effect major changes in the circulation system in the tropical Pacific? And can such a seasonal sweep of tropical current systems in combination with a reduced veritical stability of the oceans explain the wide expanse of siliceous sediments found in the Eocene ocean, or must we call on bottom waters richer in silica that somehow help preserve siliceous sediments in the southern Pacific but not in the northern Pacific?

[24] Planned scientific ocean drilling in the near future will help constrain these ideas. ODP Leg 197 will drill the Emperor seamounts and better constrain the paleolatitudes of the Pacific plate. Drilling along the transect presented here during ODP Leg 199 will better constrain the thickness, age, and composition of the sedimentary section imaged in our seismic data. Studies of the recovered microfossil assemblages will better delineate the near-surface water masses that existed in and on either side of this mound in the early Paleogene.

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