

Leg 199 Preliminary Report

Paleogene Equatorial Transect

23 October–16 December 2001

Shipboard Scientific Party

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February 2002

PUBLISHER'S NOTES

This report was prepared from shipboard files by scientists who participated in the cruise. The report was assembled under time constraints and does not contain all works and findings that will appear in the *Initial Reports* of the ODP *Proceedings*. Reference to the whole or to part of this report should be made as follows:

Shipboard Scientific Party, 2002. Leg 199 Preliminary Report. *ODP Prelim. Rpt.*, 99 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/prelim/199_prel/199PREL.PDF>. [Cited YYYY-MM-DD]

Distribution: Electronic copies of this series may be obtained from the Ocean Drilling Program's World Wide Web site at <http://www-odp.tamu.edu/publications>.

This publication was prepared by the Ocean Drilling Program, Texas A&M University, as an account of work performed under the international Ocean Drilling Program, which is managed by Joint Oceanographic Institutions, Inc., under contract with the National Science Foundation. Funding for the program is provided by the following agencies:

Australia/Canada/Chinese Taipei/Korea Consortium for Ocean Drilling
Deutsche Forschungsgemeinschaft (Federal Republic of Germany)
Institut National des Sciences de l'Univers-Centre National de la Recherche Scientifique (INSU-CNRS; France)
Ocean Research Institute of the University of Tokyo (Japan)
National Science Foundation (United States)
Natural Environment Research Council (United Kingdom)
European Science Foundation Consortium for Ocean Drilling (Belgium, Denmark, Finland, Iceland, Ireland, Italy, The Netherlands, Norway, Spain, Sweden, and Switzerland)
Marine High-Technology Bureau of the State Science and Technology Commission of the People's Republic of China

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ABSTRACT

Ocean Drilling Program (ODP) Leg 199, “The Paleogene Equatorial Transect” (Sites 1215 through 1222), was designed to study the evolution of the equatorial Pacific current and wind system as the Earth went from maximum Cenozoic warmth to initial Antarctic glaciations. The drilling program was primarily devoted to a transect along 56- to 57-Ma crust, old enough to capture the Paleocene/Eocene boundary in the basal, more carbonate-rich sediments. The Leg 199 transect extends from a paleolatitude of $\sim 4^{\circ}\text{N}$ – $\sim 4^{\circ}\text{S}$ to encompass a relatively thick lower Eocene sediment section perhaps 8° north of the paleoequator. One drill site (Site 1218) was also drilled on 40-Ma crust to collect a near-equatorial sediment sequence from the middle Eocene–late Eocene in order to investigate the transition in global climate from the Eocene “greenhouse” to Oligocene “icehouse.”

The Pacific plate has drifted northward through Cenozoic time, transporting biogenic sediments deposited under the high-productivity equatorial belt into a zone of extremely slow sediment (red clay) accumulation. Thus, the central tropical North Pacific Ocean is an ideal region in which to sample shallowly buried Paleogene sequences of equatorially deposited biogenic sediments. The thin Neogene cover of red clay in the area means that the entire Paleogene sediment section is potentially drillable by ODP advanced piston corer and extended core barrel methods.

BACKGROUND AND OBJECTIVES

Upwelling, Productivity, and Equatorial Sedimentation

The complex system of equatorial currents is one of the most persistent and clear traces of wind-driven circulation in the oceans. The Leg 199 drilling program (Fig. F1; Table T1) was designed to study the evolution of this system in the Pacific Ocean as the Earth went from maximum Cenozoic warmth to initial Antarctic glaciations. In the Neogene, the northern position of the Inter-tropical Convergence Zone (ITCZ) relative to the equator has given rise to tradewind-induced divergence at the equator and has caused a narrow band of equatorial upwelling (Fig. F2), as well as an equatorially asymmetric zonal current system. High productivity associated with equatorial upwelling results in a high rain of biogenic debris to the seafloor within 1.5° – 2° of the geographic equator, with peak values restricted to an even narrower zone. In the Pacific Ocean, this biogenic rain has built, over Neogene time, a mound of almost pure calcareous and siliceous sediments stretching along the equatorial region and reaching a thickness of >500 m (Fig. F3). The little that we knew about Paleogene sequences in the central tropical Pacific Ocean prior to Leg 199 suggested that pre-Oligocene latitudinal patterns of sedimentation were significantly different to this narrowly focused Neogene arrangement (Moore et al., in press). Sedimentation rates appear significantly slower in the Eocene, and the distribution of sediments from seismic reflection profiles appears different than a pattern resulting from a single linear source of biogenic sediments along the equator. ODP Leg 199 was designed to collect sediments along a latitudinal transect in order to better understand Eocene and Oligocene sedimentation patterns and thereby reconstruct the dynamics of Eocene biogeochemical cycles.

Pacific Plate Movement and the Cessation of Biogenic Sedimentation

The central equatorial Pacific is unique in the world’s oceans because the path of plate motion carries this linear trace of equatorial upwelling and productivity northward with time (van Andel,

1974). There are two clear implications of this northward plate motion: (1) the thickest part of the equatorial mound of biogenic sediment is displaced several degrees to the north of the equator and (2) sediments deposited a few tens of millions of years ago have moved completely out of the region of high sediment flux. In principle, this set of circumstances presents an excellent opportunity to recover relatively undisturbed sediments through climatologically and paleoceanographically important time intervals that are notorious for extensive chert formation (e.g., the middle Eocene) and thus grossly undersampled in the deep oceans.

Despite the high quality of plate tectonic models, the path of movement of the Pacific plate is still not perfectly understood, and it is not yet possible for us to backtrack drill sites to their paleopositions in the early Eocene with confidence. Therefore, paleomagnetic studies aimed at locating our drill sites with respect to the Eocene equator were an important component of the Leg 199 shipboard science. An equally important aim of the shipboard paleomagnetic program was to cross-calibrate paleomagnetic reversal stratigraphy with biostratigraphy. In fact, the likelihood of recovering sediments with compositional changes linked to orbitally forced insolation variability made the production of astronomically calibrated timescales an ultimate scientific goal for Leg 199.

Early Paleogene Warm Climates

The early Paleogene (~60–45 Ma) witnessed the warmest global climates recorded on Earth in the entire Cenozoic. It has long been appreciated that abyssal ocean-water temperatures were significantly warmer than today during the early Paleogene (e.g., Shackleton and Kennett, 1975). This observation has led to widespread speculation that these warm temperatures originated through low-latitude water mass formation (e.g., Brass et al., 1982). Yet, this explanation has always posed formidable problems for dynamicists and recent numerical experiments support the alternative, more conservative view, that the warm abyssal water masses of the Paleocene and Eocene are more likely linked to deepwater formation in high-latitude regions having warmer sea surface temperatures than today (Bice and Marotzke, 2001). Support for warmer surface temperatures in high-latitude oceans (and the interiors of continents) than today is widespread (Zachos et al., 1993). Diverse sets of paleontological, sedimentary, and geochemical proxy records indicate that, at this time, subtropical to temperate fauna and flora extended to subpolar regions of both hemispheres where continental polar ice sheets were conspicuously absent (Shackleton and Kennett, 1975). The surface temperature regime of the early Paleogene tropics is an ongoing subject of investigation (Bralower et al., 1995; Andreasson and Schmitz, 1998; Pearson et al., 2001), but the very warm temperatures (~12°C) estimated for high latitudes and deep waters mean that there can be little doubt that latitudinal temperature gradients during the early Paleogene were substantially smaller than today (Crowley and Zachos, 2000). This observation raises an intriguing paleoclimate problem because, if warmer high-latitude climates depend on enhanced wind-driven ocean currents or wind-carried heat and moisture to transport heat to the poles, it is difficult to explain how this transport was maintained under the weaker pole-to-equator thermal gradients. Instead, weaker latitudinal temperature gradients should give rise to weaker winds and diminished wind-driven transport. This apparent paradox is a persistent problem in numerical general circulation model reconstructions of warm paleoclimates (Barron and Washington, 1984; Manabe and Bryan, 1985; Sloan and Huber, 2001).

New data from the tropical oceans are necessary to define the climatic and oceanographic processes associated with early Paleogene warmth. Measurement of tropical sea-surface temperature

gradients, for example, is an important way to distinguish between greenhouse-induced warming of the poles and warming by either atmospheric or oceanic heat transport (e.g., Crowley, 1991; Bralower et al., 1995; Wilson and Opdyke, 1996; Wilson and Norris, 2001; Pearson et al., 2001). Data on winds and currents are needed to partition heat transport between the atmosphere and oceans. Finally, the patterns of tropical wind and ocean circulation are key elements of global circulation, and existing records indicate that these patterns may have been markedly different from today during the early Paleogene (Hovan and Rea, 1992; Janecek and Rea, 1983; Rea et al., 1990).

ODP Leg 199, the “Paleogene Equatorial Transect,” was designed to drill a lower Paleogene transect across the world’s most long-lived wind-driven current structure that features the confluence of the Northern and Southern Hemispheric winds and has a pattern, strength, and biogenic productivity linked to global climate patterns. The lower Eocene transect was aimed at providing basic records of sediment composition, mass accumulation, plankton communities, sea-surface and abyssal temperatures, and paleoproductivity across the paleoequator. These sorts of data are needed in order to assess the stability of the water column, the magnitude of heat transfer out of the tropics, surface ocean circulation, and the location and strength of the trade wind belts and the location of the ITCZ. The location of the ITCZ and the transition from the trade winds to the westerlies can be determined by the changes in the composition and rates of deposition of wind-blown dust, whereas mass accumulation rates (MARs) of biogenic debris can be used to assess the position and the strength of upwelling zones. Stable carbon isotope data will be used to assess nutrient flows in the water column and to constrain the global carbon cycle.

General Circulation Model Reconstructions

Model reconstructions of Eocene climate have been hampered by a severe lack of data to constrain marine boundary conditions and, until recently, the need to specify either the atmospheric or oceanic part of the heat transport equation. In addition, lack of adequate control on bathymetry and topography in the Eocene, particularly in ocean gateway regions, severely weakens the capacity to model climate accurately from first principles (Deconto et al., 2000). Finally, computational constraints generally force the number of model years to be short (a few thousand years or less), so long-term transitions cannot be easily modeled. Most paleoclimate modeling is therefore performed on time slices for which reasonable initial conditions are established. Thus, in order to adequately understand Paleogene ocean dynamics and climate, there must be a strong interaction between paleoceanographers who gather new observations and climate modelers who make use of them to develop more realistic models (Sloan and Huber, 2001; Huber and Sloan, 2000).

One recent development in paleoclimate modeling is the application of coupled ocean-atmosphere global circulation models. These types of models produce physically consistent worlds and can be used to study ocean-atmosphere interactions rather than to specify them. An example of the results of such modeling can be seen in Figure F4 with the 56-Ma paleopositions of the Leg 199 drill sites superimposed. The figure shows annual upwelling velocity and indicates that the eastern Pacific should have been a relatively productive region with respect to much of the world ocean in the early Eocene. Model results such as these can then be used as a set of hypotheses to be tested by drilling, recovery of sediments, and the proper paleoceanographic analyses.

Paleoceanographic Time Slices

We have known for many years that the early Paleogene, particularly one interval in the early Eocene (~53–50 Ma), represents the most extreme long-lived interval of global warming witnessed on Earth since the well-documented mid-Cretaceous greenhouse (e.g., Shackleton and Kennett, 1975). Yet little is known about the number of constituent hyperthermals, the range of temperatures, or their effects on biotic evolution (Thomas and Zachos, 1999). Similarly, although we know that the Eocene greenhouse period was followed by a long shift toward lower temperatures and ice sheet growth into the late Eocene through Oligocene, the detailed history of these events and consequences for oceanic and atmospheric circulation, carbon cycling, and biotic evolution are only vaguely understood. The late Eocene is also interesting from the perspective of the response of global climate and biodiversity to the history of large impact extraterrestrial bodies on Earth. Thus, the Paleogene can be thought of as containing numerous critical time slices that provide an excellent opportunity to improve our understanding of important paleoclimatic problems involving the dynamics of greenhouse gas release, warm climate stability, biotic turnover associated with extreme climate transitions, extraterrestrial impacts, and initiation of major continental ice sheets.

Paleocene/Eocene Boundary

It is now well accepted that the Paleocene/Eocene (P/E) boundary involved a substantial (~5°–7°C) warming in the Southern Ocean and subtropics, a 35%–50% extinction of deep-sea benthic foraminifers, and rapid perturbation to the global geochemical carbon cycle (e.g., Kennett and Stott, 1991; Zachos et al., 1993; Koch et al., 1992). A growing body of evidence attributes these events to the massive release and oxidation of methane from the marine gas hydrate reservoir (e.g., Dickens et al., 1997; Katz et al., 1999). High-resolution stable isotope analyses (Bains et al., 1999) and orbitally tuned chronologies from sites in the Atlantic and off Antarctica (Norris and Röhl, 1999) suggest that carbon release occurred extremely rapidly (within one precession cycle). Thus, the P/E boundary event may represent the best example in the geologic record of the response of the Earth ocean-atmosphere climate system to greenhouse warming on a timescale approaching that of the ongoing global anthropogenic experiment. Recently, elevated barium accumulation rates have been reported across the P/E in various deep-sea sites. These data have been interpreted in terms of enhanced deposition of organic matter in deep-sea sediments that may have acted as a negative feedback on atmospheric CO₂ levels and global temperatures to return Earth to average late Paleocene conditions (Bains et al., 2000). Alternatively, this signal may reflect increased ocean barite saturation levels possibly driven by the injection of barium into the global ocean from the marine gas hydrate reservoir (Dickens, 2001).

Whereas recently developed data sets lend considerable support to the methane hydrate hypothesis, considerable uncertainty remains about the mechanism and location of carbon release, the response of the calcite compensation depth (CCD), and biotic overturn. Furthermore, the recent discovery of P/E-like geochemical signals in the Mesozoic (e.g., Opdyke et al., 1999; Hesselbo et al., 2000) raises the distinct possibility that further “hyperthermals” might have existed in Paleogene time (Thomas and Zachos, 1999). Leg 199 presents a major opportunity to help improve our understanding of the climatic chain of events during the Paleogene. Results from the leg should prove particularly useful given the volumetric significance of the Pacific Ocean to geochemical mass-balance simulations (e.g., Dickens et al., 1997) and the current paucity of P/E boundary records from the basin.

Eocene–Oligocene Transition

The Eocene/Oligocene (E/O) boundary represents an important point in the transition from the greenhouse world of the Cretaceous and early Paleogene into the late Paleogene-Neogene “icehouse.” Attempts to estimate global ice volumes from deep-sea benthic $\delta^{18}\text{O}$ records have prompted very different conclusions as to the timing of the onset of the accumulation of continental-scale ice sheets. These range from the Early Cretaceous (Matthews and Poore, 1980) to the middle Miocene (Shackleton and Kennett, 1975). However, recent improvements in the stratigraphic resolution of the $\delta^{18}\text{O}$ record have led to suggestions that either the late middle Eocene (~43 Ma) or the earliest Oligocene (~34 Ma) are better estimates of the timing of the initiation of greenhouse to icehouse transition (Shackleton, 1986; Miller et al., 1987, 1991; Zachos et al., 1992). Supporting evidence for this interpretation comes from oceanic records of ice-rafted debris, weathered clay mineral compositions, microfossil assemblages, and sequence stratigraphic analyses (Kennett and Barker, 1990; Browning et al., 1996). Yet, the rarity of complete deep-sea sections across these intervals has limited our understanding of the dynamics of this important step to the modern icehouse world.

The Eocene–Oligocene transition is marked by a large rapid increase in the benthic foraminiferal calcite $\delta^{18}\text{O}$ record in earliest Oligocene time (Oi-1; Fig. F5). This excursion was first ascribed to a 5°C temperature drop associated with the onset of thermohaline circulation, but more recently Oi-1 has been associated with the onset of continental ice accumulation on Antarctica. Such confusion reflects the long-standing difficulty of separating the effects of temperature and ice on benthic $\delta^{18}\text{O}$. Recent application of an independent paleothermometry technique based on Mg/Ca in benthic foraminifers shows no significant change corresponding to “Oi-1” (Lear et al., 2000). This result suggests that all of the $\delta^{18}\text{O}$ increase associated with Oi-1 can be ascribed to ice growth with no concomitant decrease in polar temperatures. Apparently, according to these data, the trigger for continental glaciation lay in the hydrological cycle rather than the carbon cycle. Specifically, it has been proposed that the opening of the Australian-Antarctic seaway in earliest Oligocene time might have enhanced the supply of moisture as snow to the Antarctica interior (Lear et al., 2000). Support for this suggestion exists from both ocean drilling and numerical modeling experiments (Bartek et al., 1992; Hine et al., 1999). On the other hand, paleoproductivity studies suggest that the contemporaneous increase in seawater $\delta^{13}\text{C}$ was driven by increased rates of organic carbon burial in marine sediments and that this factor may be implicated in global cooling and ice sheet growth (Diester-Hass and Zahn, 2001). Either way, long-standing global compilations indicate a pronounced deepening of the CCD associated with the Eocene–Oligocene transition (van Andel et al., 1975). Unfortunately, our most complete records of the E/O boundary come from only two mid-latitude sites (Deep Sea Drilling Project [DSDP] Site 522 and ODP Site 744). Leg 199 offers an excellent opportunity to generate low-latitude records of the Eocene–Oligocene transition and thereby fully evaluate the competing roles played by global cooling and ice growth in the transition from the Cretaceous greenhouse into the Neogene “icehouse.”

Late Eocene Impact Events

Widespread evidence now exists to support the occurrence of at least two large closely spaced extraterrestrial impact events on Earth during early late Eocene time. In particular, two large craters (order ~100 km diameter; Chesapeake Bay, North America and Popigai, Northern Siberia) have been proposed to explain impact-ejecta strewn fields that are documented in deep-sea sediments from

around the world (e.g., Koeberl et al., 1996; Bottomley et al., 1997). Proxy records for fine-grained extraterrestrial dust (^3He measurements) in correlative marine carbonate strata have been interpreted as evidence for a comet shower triggered by an impulsive perturbation of the Oort Cloud (Farley et al., 1998). Intriguingly, unlike the more famous and pronounced precursor extraterrestrial impact event at Cretaceous/Paleogene boundary time, biostratigraphic studies indicate that the late Eocene impact horizons do not correspond to major extinctions among marine organisms. Only four or five radiolarian species seem to disappear from the record accompanied by modest compositional changes in planktonic foraminifers and organic walled dinoflagellate cysts (Sanfilippo et al., 1985; Keller, 1986; Brinkhuis and Biffi, 1993). On the other hand, although little evidence exists in the literature for climate change across the Cretaceous–Paleogene transition, recent work has suggested that the late Eocene impact event was associated with a short-term (~100 ka), albeit modest (maximum 2°C), cooling event at high latitude (Vonhof et al., 2000). Leg 199 presents an ideal opportunity to study the climatic and biotic effects of impacts that were too small to precipitate global mass extinctions but were apparently large enough to have engendered regional changes in climate.

Oligocene

In many ways the Oligocene (~33.5–23.5 Ma) represents something of the “neglected middle child” of Cenozoic paleoceanography—caught between the early Paleogene greenhouse and the well-developed Neogene “icehouse.” This situation is at least partly attributable to the perception that Oligocene marks a prolonged interval of relative stasis in paleoclimate and biotic turnover, reflected in deep-sea micropaleontological communities by conservative body plans confusing taxonomies and low biostratigraphic resolution. However, in some respects the Oligocene represents the most interesting piece of the Cenozoic paleoceanographic puzzle because it offers an opportunity to unravel the processes that lie behind the transition from a world free of large-scale continental icecaps and rapid eustatic sea level oscillations to one dominated by these climatic changes. To a large extent, recent progress in our understanding of Oligocene paleoclimates has been driven by seismic stratigraphy and scientific drilling in continental margin sequences (e.g. Browning et al., 1996; Miller et al., 1996; Pekar et al., 2000). In contrast, modern benthic stable isotope compilations (Fig. F5) show that our paleoclimate records for the deep oceans through the Oligocene rely heavily on old DSDP sites, largely from the Atlantic Ocean (Miller et al., 1987, 1988, 1990, 1991, 1993). Leg 199 offers an excellent opportunity to generate low-latitude deep-sea records throughout the Oligocene and thereby test models developed from continental margin sequences for the pattern and timing of changes in global temperature and continental ice volume.

Previous Drilling

Nearly 30 yr ago, DSDP rotary drilling and coring of the central Pacific equatorial mound of sediments (e.g., DSDP Legs 5, 8, 9, and 16) (Fig. F1) established the general pattern of equatorial sediment accumulation and plate migration through the Neogene and late Paleogene (e.g., van Andel et al., 1975; Berger and Winterer, 1974; Leinen, 1979). However, the rotary coring technology available to these very early legs could not provide undisturbed sections or complete recovery and was utterly defeated by middle Eocene chert layers encountered in some of the more deeply buried sections. Since these early efforts, one leg (DSDP Leg 85; Mayer et al., 1985) has revisited the region and obtained hydraulic piston core samples of Neogene sediments. However, the Paleogene sections

of the Leg 85 holes were rotary cored because they were deeply buried beneath the Neogene equatorial sediment mound. Much of the Paleogene section was not recovered. For these reasons, even the broad outlines of equatorial sediment accumulation in Paleogene sediments and the link of sedimentation to early Paleogene climate remain poorly defined. The P/E boundary interval in the central tropical Pacific Ocean has not been sampled, primarily because the DSDP sites were mostly placed on crust younger than the boundary. DSDP Site 163 (Fig. F1), on early Campanian-age crust, is the only drill site in the central tropical Pacific that has drilled the interval. Unfortunately, there was poor recovery over the lower Eocene caused by closely spaced cherts. The middle Eocene has been sampled at more sites. North of the Clipperton Fracture Zone, where Leg 199 sites are situated, drilling at DSDP Sites 161 and 162 recovered continuous sediment sequences, albeit with core gaps and disturbed by rotary coring, to middle Eocene basalt crust. Sediments from Sites 40 and 41, between the Clarion and Molokai Fracture Zones, were upper to middle Eocene radiolarian oozes beneath a 10 m thick layer of red clay.

Leg 199 Objectives

Leg 199 drilling was designed to accomplish the following scientific objectives:

1. To define sedimentation, paleoproductivity, circulation, and wind patterns in the Eocene equatorial Pacific;
2. To study the Paleocene–Eocene and Eocene–Oligocene transitions in the equatorial Pacific, as well as other boundaries mentioned above; and
3. To obtain complete, continuous Oligocene and lower Eocene paleoceanographic records to study the effects of glaciation in Antarctica upon equatorial Pacific circulation.

In addition, the following important but more general objectives shaped the Leg 199 drilling plan:

1. To collect continuous sequences of Paleogene biogenic sediments and thereby improve Paleogene biostratigraphy, tie this stratigraphy to paleomagnetic chronostratigraphy and generate high-resolution paleoceanographic records from the Paleogene central tropical Pacific Ocean;
2. To place new constraints on the late Paleocene and early Eocene equatorial position using paleomagnetic and micropaleontologic indicators;
3. To link seismic stratigraphy from the site survey to sediment chronostratigraphy to extend the Neogene equatorial Pacific seismic stratigraphy (Mayer et al., 1985, 1986; Bloomer et al., 1995) back in time;
4. To document the transition between Asian and American dust sources to understand the primary structure of the Paleogene wind field;
5. To provide new constraints on the early Paleogene mass balance of carbonate and opal burial and to track the Eocene movement of the CCD in detail;
6. To generate primary geochemical information needed to understand the widespread formation of Eocene cherts; and
7. To collect basal hydrothermal sediment sections for study of hydrothermal activity in the early Paleogene.

RESULTS

Major Lithologies of the Paleogene Equatorial Pacific

The sediments drilled during the Paleogene equatorial transect fall into the following five broad litho-chronostratigraphic units (Fig. F6): (1) a surficial clay unit, sometimes containing a basal radiolarian ooze with a basal age ranging from the middle Miocene in the south of the transect (Site 1218) to the early–middle Eocene in the north (e.g. Sites 1215 and 1216); (2) a nannofossil ooze/ chalk unit whose base is at the E/O boundary and whose top is of early Miocene age in the south (Sites 1218 and 1219) and Oligocene age in the central part of the transect (Sites 1217, 1220, 1221, and 1222); Oligocene–Miocene carbonates are nonexistent in the north (Sites 1215 and 1216); (3) a middle–upper Eocene radiolarian ooze and radiolarian clay that is present at all sites except those in the north (Site 1215 and 1216); (4) a lower middle–lower Eocene unit composed of cherts, clays, and radiolarian ooze that is present in varying thicknesses at all Leg 199 sites along the 56-Ma transect except one in the extreme north (Site 1215); and (5) a lower Eocene–upper Paleocene nannofossil ooze or chalk resting upon basalt basement that is recovered at all sites except Site 1222 (where cherts overlie basement) and Site 1216 (where the relevant stratigraphic interval was not drilled).

Surficial Clay and Radiolarian Ooze

The upper clay unit is composed of wind-blown dust, clays, and radiolarians eroded and reworked from older sediment outcrops, authigenic minerals, and in sites marginal to the modern equatorial region, freshly deposited radiolarians.

The clay mineral composition of eolian dust transported to Leg 199 sites may provide a way to track the latitudinal position of the ITCZ (Fig. F7). Enhanced precipitation in the ITCZ helps to “wash out” dust particles from the atmosphere, forming an effective barrier to interhemispheric dust transport. In other words, dust generated in the Northern Hemisphere is restricted to latitudes north of the ITCZ. Asian dust (rich in quartz and illite clays) dominates the composition of dust deposited in the Pacific north of the ITCZ. Just south of the ITCZ, a clay mineralogy dominated by smectite is transported via the trade winds from Central and South American source regions. During Leg 199 we used light absorption spectroscopy (LAS) to produce shipboard estimates of clay mineralogy. In Figure F7, plots of mineralogical change downcore are shown vs. depth in core. Using paleoposition information, one can then identify the change in ITCZ through time by the change from an illite-rich to smectite-rich clay suite (Fig. F8).

Radiolarian ooze or clayey radiolarian ooze are important sediment lithologies in the basal part of the surficial clay unit in Leg 199 sites drilled near the modern equator. These oozes are found at Sites 1219–1221 (Fig. F6). In each case, the site occupied an off-equatorial position at the time the radiolarian ooze was deposited, in the range of 3°–6° north of the paleoequator. Thus, in the Neogene and latest Oligocene, radiolarian ooze is deposited on the fringes of the equatorial upwelling zone. The zone of radiolarian ooze deposition is bound on the south by the appearance of foraminifers and disappears to the north as primary productivity decreases.

Oligocene–Lower Miocene Nannofossil Ooze/Chalk

The second broad litho-chronostratigraphic unit along the Leg 199 transect is the nannofossil ooze that first appears at the base of the Oligocene. The clay or radiolarian ooze to carbonate transition is an outstanding marker for the E/O boundary because it is very abrupt (see “Eocene/

Oligocene transition"). The unit has cyclic variations of carbonate content related to orbitally driven changes in insolation. This cyclic variability will be key to construct an orbitally tuned Oligocene age model of the sediments and to calibrate ages for magnetostratigraphy and biostratigraphy (see section on stratigraphic intercalibrations).

The nannofossil ooze/chalk unit is thickest at sites near the Oligocene equatorial region and thins to the north (Fig. F6). Nevertheless, traces of the lower Oligocene carbonate can be found as far north as Site 1217 (16°52'N). At the beginning of the Oligocene, Site 1217 was located ~9° north of the equator at a water depth of 4400 m.

The age of the uppermost nannofossil ooze/chalks depends on the paleoposition and water depth of each drill site. In the south (Sites 1218 and 1219), the uppermost nannofossil ooze unit has an age near the late Miocene. Traversing north, the uppermost nannofossil ooze at Site 1220 (10°11'N) is late Oligocene in age. Sites 1221 (12°02'N), 1222 (13°49'N), and 1217 (16°52'N) exhibit a carbonate interval only in the sediments of early Oligocene age.

Late–Middle Eocene Radiolarian Ooze

The third broad litho-chronostratigraphic unit along the Leg 199 transect consists of radiolarian ooze, clayey radiolarian ooze, and radiolarian clays (Fig. F6). Clay content tends to be higher at the top and bottom of the unit. The radiolarian oozes are characteristic of the Eocene section and are the most enigmatic facies from a modern perspective because of the lack of a true modern analog.

In the southern sites of the Leg 199 transect (Site 1219) and in shallower drill sites (Site 1218 and DSDP Site 162) carbonate can be found at low concentrations in the upper Eocene and at higher levels in the middle Eocene, especially within magnetic Chron C18 (~39–41 Ma). For the rest of the transect, CaCO₃ is absent from this unit even in sites located at the contemporaneous paleoequator. The latitudinal width of the late–middle Eocene zone of radiolarian deposition varies through time. The middle Eocene, between ~40 and 45 Ma, represents the greatest latitudinal expansion—radiolarian oozes were found from the equator to a paleolatitude between 10° and 11°N (between DSDP Site 40 and Site 1216). In contrast, radiolarian deposition is confined to within a few degrees of the equator in the latest Eocene. Along the 56-Ma transect, radiolarians are deposited only to the south of Site 1221, located at a paleolatitude of ~°N. Sites 1221, 1222, and 162 all have a hiatus just below the Oligocene.

One of the striking features of a unit with such high biogenic silica content is the relative absence of diatoms. Only one major interval in the Eocene radiolarian ooze contains a relatively high diatom content (>10% diatoms in smear slides; Fig. F9). High numbers of diatoms appear in magnetic Chron C18 (radiolarian zone RP15; 39–41.5 Ma) and are associated with the appearance of carbonates in the same sediment interval at Sites 1218 and 1219.

Lower Middle–Lower Eocene Cherts, Clay and Radiolarian Ooze

The fourth broad litho-chronostratigraphic unit along the Leg 199 transect consists of cherts, clays, and radiolarian oozes (Fig. F6). Despite high numbers in the test of the Eocene, radiolarians are rare to absent in the basal carbonates. This unit proved predictably troublesome to recover. Leg 199 drilling results indicate that cherts are present at the boundary between the lower and middle Eocene throughout the transect with the exception of Site 1215 in the extreme north. A younger cherty interval is present at Site 1218 near the middle/upper Eocene boundary, but this interval was continuously cored and recovered with the extended core barrel (XCB) (Fig. F10).

The lower–middle Eocene chert interval is relatively thin at Site 1219 in the south (~8 m thick; 7°48'N) but thickens to the north. At Site 1220 (10°11'N) the unit, including recovered cores of early Eocene radiolarian ooze, spanned 40 m. Poorly recovered cherty intervals span 30–40 m at Sites 1221 (12°02'N), 1222 (13°49'N), and 1217 (16°52'N). The unit is chronologically extensive. It typically first appears in radiolarian Zone RP11-12 (~45–49 Ma) and continues into the lower chalk unit around the top of radiolarian Zone RP7 (~53 Ma). Its relationship with the lower nannofossil chalk is not yet clear. At Site 1219 a transition from zeolitic clay to nannofossil chalk was recovered, suggesting that the base of the unit may be marked by a gradational transition from clay to CaCO₃. However, chert was recovered associated with most of the basal nannofossil chalk recovered on the leg, so this lower unit is not free from chertification.

Lower Eocene–Upper Paleocene Nannofossil Ooze or Chalk

The basal litho-chronostratigraphic unit along the Leg 199 transect consists of nannofossil ooze or chalk of early Eocene–upper Paleocene age overlying basement basalt. This unit is present at all sites except perhaps Site 1222, (where only chert was recovered in the one hole drilled to basement) and Site 1216 (where the relevant stratigraphic interval was not drilled). In three of the seven sites targeted to recover the P/E boundary (1215, 1220, and 1221), this objective was fulfilled (see “Paleogene/Eocene Transition”). Where present, the basal carbonate unit is most lithified in the south where overburden is greatest (~250 m burial depth; Sites 1218 and 1219). In contrast to the nannofossil chinks recovered from these two sites, at Site 1215, where the burial depth is significantly shallower (~25 m), we recovered a nannofossil ooze. At three of the sites containing basal chinks (Sites 1217, 1218, and 1220) the sediments are partially to extensively dolomitized. It is unclear how the dolomite was formed, but it appears to be related to proximity to basement. Dolomitization of the basal sediments bears no clear relationship to location along the latitudinal transect.

Paleogene CCD

One of the most striking features of the Paleogene equatorial Pacific sediments is the rapid appearance and disappearance of CaCO₃ through the stratigraphic record. Leg 199 drilling has significantly increased stratigraphic control for many of the Paleogene and early Neogene carbonate–noncarbonate transitions.

Van Andel et al. (1975) compiled DSDP data from all the drill sites within the region and used subsidence curves of ocean crust to develop the Cenozoic history of calcium carbonate deposition. This compilation shows that the Eocene was marked by a shallow CCD or level in the water column where the pelagic rain rate of biogenic carbonate is equal to the rate of dissolution at depth. Specifically, the Eocene CCD in the equatorial Pacific is estimated to have been ~3400 m, shoaling to ~3200 m beyond 4° from the equator to either the north or south. Furthermore, one of the most prominent changes in the CCD through time captured in this early compilation was a pronounced deepening (by ~1600 m in the equatorial region) associated with the transition from the Eocene to the Oligocene. Shipboard results from Leg 199 support this early interpretation of events. In fact, our shipboard data demonstrate that the correlation between the Eocene–Oligocene transition and the CCD deepening is strikingly precise and consistent across wide tracts of the tropical Pacific. These findings, raise the intriguing possibility that this pronounced deepening of the CCD is in some way related to the first widely accepted sustained glaciation in Antarctica (Oi-1; Fig. F5). The nature of the

relationship between these two important paleoceanographic signals will be an important component of shore-based Leg 199 research. In addition, our shipboard data also demonstrate that the transition from silica-rich/carbonate-poor Eocene to silica-poor/carbonate-rich Oligocene deep-sea sediments is remarkably rapid. The transition from carbonate-free to carbonate-bearing sediments is sharp, typically occurring over a 10- to 20-cm interval (Fig. F11) and implying that it took only a few tens of thousands of years to introduce the changes in ocean chemistry that depressed the CCD to >1 km below its Eocene depth.

Leg 199 sediments define other major CCD changes within the Eocene that will be better studied after the cruise. The Paleocene–lower Eocene basal chalks define a relatively shallow CCD in the beginning of the interval drilled during Leg 199 (Fig. F12). The transition from chalk to clay and radiolarian ooze occurs when near-equatorial sites passed through a water depth of only ~3200–3300 m (Sites 1219–1221), whereas the off-axis sites record a shift from carbonate to clay when they passed below 3400–3600 meters below sea level (mbsl) (Sites 1215 and 1217). In contrast, the Oligocene and Neogene CCD is ~4500–4600 m (Fig. F12). The difference in early Eocene CCD between equatorial and northern sites is greater than the errors associated with the estimation and is the reverse of the Neogene trend. Typically, in the Neogene the CCD is deeper beneath the equatorial region because of higher carbonate production in the equatorial region relative to periequatorial regions, but this situation seems not to have been the case in the early Eocene.

Although carbonate disappears from the equatorial Pacific in the lower Eocene, CaCO₃ is not absent from the Eocene record. A prominent CaCO₃ event appears within magnetic Chron C18r at ~40–41 Ma (defined by Sites 1218 and 1219 in the south) that can also be found at DSDP Site 162 (van Andel et al., 1973) (Fig. F12). Smaller carbonate events occur within magnetic Chron C20n (~43 Ma) and near the base of C17n (~38 Ma) at Site 1219. The younger event can also be found at Site 1218. In contrast, none of these carbonate events can be found further north, nearer the middle Eocene paleoequator (Site 1220). In fact, there is no CaCO₃ in the middle and late Eocene section at Sites 1220, 1221, or 1222.

The transition from chalks to radiolarite at ~40 Ma in Site 1218 appears as abrupt as the transition from radiolarian clay to nannofossil oozes at the E/O boundary. The rapid transitions of sediment type in either direction suggest that there is a strong climate switch at work. Sediments with poor carbonate preservation have also been identified during each of the Oligocene intervals that correlate to warm intervals between the “Oi” glacial advances of Miller et al. (1991). Thus, the Leg 199 shipboard scientists have developed a working hypothesis that carbonate deposition in the tropical Pacific is in some way associated with continental glaciations, whereas tropical Pacific radiolarian oozes are associated with warm global climates. If this hypothesis is substantiated, one implication would be that the transition from cold to warm climates can be as abrupt as the transition from warm to cold climates.

Equatorial Position

Drill sites move with their respective plates and must be backtracked in space as well as depth. Van Andel et al. (1975) recognized the paramount importance of backtracking tropical Pacific drill sites with respect to the motion of the Pacific plate, because the equatorial upwelling system leaves a strong imprint on the sediment column when the site passes underneath the equator. This generalization holds for the Oligocene and Neogene. We can recognize the passage of Site 1219

under the equator in the Oligocene by the sedimentary changes, but we find confusing sedimentary signals in the earlier record.

We expected that sedimentation patterns might be different in the Eocene, and so we made it a primary leg objective to obtain independent evidence for the position of the paleoequator through the Paleogene. This objective is especially important because the backtrack paths we have used to find paleopositions of Leg 199 sites assume a fixed Hawaiian hotspot, and there is good evidence that the Hawaiian hotspot moved with respect to the Pacific plate prior to 42 Ma (Tarduno et al., in press). In addition, small errors in the plate tectonic model, when propagated over long periods of time, may lead to relatively large errors in a drill site position over long intervals of time.

Shipboard whole-core paleomagnetic analysis has been sufficient to make a preliminary definition of the position of the paleoequator and the change in paleolatitude of Leg 199 drill sites in the Oligocene and in the late middle Miocene (Fig. F13, F14). These data will be refined postcruise with discrete sample analyses. They suggest that the fixed hotspot backtrack of paleopositions is sufficiently accurate to estimate paleopositions back to the middle Eocene. Paleomagnetic analysis of older sediments should yield further evidence for equatorial positions in the early Eocene.

Fluxes and Paleoproductivity

Another primary objective of Leg 199 science is to assess the level of productivity over the Paleogene by using biogenic MARs in concert with other geochemical and micropaleontological data. With this goal in mind we designed a shipboard program to monitor the composition of pore waters in the sediments and measure the bulk chemical composition of recovered sediments.

Organic Carbon Diagenesis and Interstitial Waters

In the context of productivity and biogenic sediment flux considerations it is notable that none of the Leg 199 sediments contained significant organic carbon (C_{org}). As measured on board the ship, C_{org} levels in Leg 199 sediments were consistently low (~0.1–0.2 wt%), essentially the detection limit for the analysis at sea. Chemical gradients in Leg 199 interstitial waters primarily reflect the relatively limited organic matter diagenesis, as well as dissolution of biogenic silica and varying amounts of diffusive influence of reactions in the underlying basalt (Fig. F15). Sulfate concentrations are high (>25 mM) throughout the transect, indicating little oxidation of labile organic matter (Fig. F15). These high sulfate levels mean that barite in the sediments will be well preserved and therefore will potentially be useful for paleoproductivity studies. This is especially important because it appears that any organic matter that may have been delivered to these sites has long since been degraded, if in fact it ever was deposited at all. Ammonium, another by-product of organic matter degradation, is only present in extremely low levels at all sites.

Dissolved silica concentrations generally increase with depth at all sites (Fig. F15). These high interstitial water silica values are consistent with the presence and dissolution of biogenic silica throughout the sediment. Strontium concentrations are generally constant at about seawater value (87 mM) for several of the sites containing little carbonate (Sites 1215–1217, 1220, and 1221), but strontium increases with depth at Sites 1218 and 1219, reflecting the presence and dissolution of biogenic carbonate (Fig. F15).

Calcium, magnesium, and potassium concentrations at most Leg 199 sites show little evidence for exchange with basalt and subsequent diffusion (Fig. F15). However, the increase in calcium concentration and decrease in magnesium, potassium, and lithium concentrations decreases with

depth at Site 1219 are significantly greater than that seen at other Leg 199 sites. These patterns are consistent with alteration of basement rocks and with the recovery of highly altered basalt at Site 1219, unlike the other sites in the Leg 199 transect. The high levels of lithium at Site 1215 could be linked to the volcanic ash layers recovered at that site.

Bulk Sediment Analyses

The Leg 199 shipboard geochemical program differed from typical ODP protocol by incorporating relatively detailed downcore profiles of bulk sediment composition. The resulting profiles primarily reflect the shifts in lithology between sediments dominated by silica to those dominated by carbonate (Fig. F16). When these data are combined with sedimentation rates (Fig. F17) and with bulk density data, it is possible to examine burial fluxes through the Paleogene. MAR calculations are a means to distinguish rates of elemental deposition even under conditions of significant dilution by other sedimentary phases. This is best shown by comparing Si weight percent profiles at Sites 1218 and 1219 to the Si MAR profiles (Fig. F16). Low Si contents between 20 and 30 Ma are primarily caused by dilution of Si by CaCO_3 . The MAR profile indicates that Si fluxes decreased much less dramatically than percentage data might seem to indicate.

Changes in Si MARs should reflect biogenic opal production because the detrital Si contribution by aluminosilicates is relatively low and constant. Al analyses reflect the detrital aluminosilicate contribution (Fig. F18) and are relatively low with respect to the high Si MAR in the Eocene and Oligocene. A rough indicator of baseline aluminosilicate contribution to Si MARs is given by the Si MAR in the period younger than 15 Ma, when clays were the principal sediment accumulating at all Leg 199 drill sites. By comparison to this baseline (15 Ma to present value) it is clear that biogenic Si deposition has decreased since a peak in the middle Eocene between ~38 and 45 Ma.

Virtually all calcium MAR results from the deposition of CaCO_3 (Fig. F16). High Ca contents and high Ca MARs occur in the high- CaCO_3 intervals of the Oligocene and lower Miocene. Smaller events can be seen in the middle Eocene, particularly ~40 Ma. The lower Eocene Ca MAR is approximately one-half to two-thirds of the high rates of deposition in the Oligocene. Phosphorus has a primary source term driven by primary productivity, but its burial in sediments can be affected by early diagenesis (Fig. F18). The phosphorus MAR peaks in the early Oligocene and also in the period ~40–45 Ma in the middle Eocene, suggesting that this part of the middle Eocene had elevated paleoproductivity relative to the late Eocene.

Ratios to an element assumed to be constantly delivered (or nearly so) is another quick way to assess changes in deposition. Figure F19 illustrates this approach by showing ratios of Si, Ba, and Al to Ti. We assume that titanium is bound to aluminosilicates and has relatively constant deposition. The plots of Si/Ti and Ba/Ti suggest that there was relatively high burial of Ba and Si during the Eocene. The relatively constant Al/Ti is an indication that clay minerals are a primary contributor of the Ti flux.

Latitudinal MAR Transects

Observing MARs in time slices along latitudinal transects is another way to assess how sedimentation in the Eocene differs from that in the Neogene and Oligocene. We have chosen three time slices for shipboard comparison: (1) an early Eocene time slice (50–55 Ma), when all parts of the 56-Ma transect were above the CCD; (2) a middle Eocene time slice (38–45 Ma), during the period of

highest radiolarian ooze deposition; and (3) an Oligocene time slice (25–34 Ma) when high CaCO_3 sedimentation had been established.

The Si MAR is highest in the middle Eocene (Fig. F20), but the latitudinal gradient of the Si MAR does not peak in the equatorial region as it does in the Neogene. Instead, the Si MAR increases southward. A high Si MAR in the middle Eocene may be in part because Eocene radiolarians are heavily silicified (Moore, 1969). An individual middle Eocene radiolarian test has an average weight about four or five times that of an average Pleistocene radiolarian test and is much less susceptible to dissolution at the seafloor. The high Si MAR may represent low dissolution prior to burial, as well as relatively high Si flux to the sediments.

In the early Eocene, we observe low Si MARs at all latitudes—sufficiently low that a large contribution to Si MARs must be from clay minerals. Only the Oligocene has a MAR pattern that resembles that of the Neogene, with the highest MAR peaking in the equatorial region. The flux of Si at the Oligocene equator is roughly equivalent to the modern MAR at 110°W (Lyle, 1992). Lyle (1992) expressed the modern flux as opal (SiO_2), rather than biogenic Si. The opal fluxes in the Holocene equatorial region are equivalent, however, to $\sim 50 \text{ mg/cm}^2/\text{k.y.}$ biogenic Si.

Ca MARs in the early Eocene time slice (Fig. F21) are actually equivalent to or higher than modern fluxes of Ca from CaCO_3 along a 110°W transect, except in the equatorial region (Lyle, 1992). There is no well-developed equatorial maximum in CaCO_3 deposition. In fact, the equatorial region may bury only half as much CaCO_3 as the subtropical flank of the transect. In the middle Eocene, essentially no CaCO_3 is deposited anywhere except the southernmost part of the transect, reflecting the shallow middle Eocene CCD. Only the Oligocene latitudinal transect resembles a Neogene equatorial profile. CaCO_3 deposition at the equator is as high as Holocene deposition.

It is clear from our shipboard examination that sedimentation patterns of the Eocene are significantly different from modern equatorial sedimentation. Postcruise analyses utilizing other paleoproductivity indicators will be needed to understand the development of primary productivity through the Eocene. Nevertheless, there are few indicators that productivity was high in the Eocene central tropical Pacific Ocean.

One important problem to be approached by postcruise studies is whether C_{org} levels are low in Eocene sediments because of a long period of exposure to oxidants diffusing into the sediment from seawater, or whether C_{org} levels were never high in the first place. Shipboard paleomagnetic studies provide one further clue to the riddle of low C_{org} . Normally, paleomagnetic studies are limited by diagenesis. Fe^{3+} - Fe^{2+} reduction dissolves magnetite and eventually destroys the capability of the sediments to retain a magnetic signal. Along the Leg 138 transect, the Neogene equivalent of the Leg 199 transect, sites at the equator or under regions of relatively high C_{org} deposition have short paleomagnetic records (Mayer, Pisias, Janecek, et al., 1992), whereas sites under regions of low primary productivity have long paleomagnetic records. The long paleomagnetic records obtained on the Leg 199 transect suggest that there never were high levels of C_{org} deposition in the Eocene.

Stratigraphic Intercalibrations

A major success of Leg 199 is the recovery of continuous sedimentary records with uninterrupted sets of distinct Cenozoic geomagnetic polarity zones from the paleoequatorial Pacific Ocean (Fig. F22). The sedimentation rates of the recovered and complete composite sections provide acceptable resolution for meaningful magnetobiochronologic calibrations for the early middle Eocene–early Miocene time interval. Biogenic silica is ubiquitously present and will permit, for the first time, the

establishment of a precise Cenozoic biochronology of radiolarians, diatoms, and silicoflagellates from a tropical Pacific Ocean setting.

Biogenic carbonate shows variable states of preservation, from moderate to complete dissolution. The upper Paleocene–lower Eocene and Oligocene–lower Miocene intervals show best preservation, thus offering huge potential for establishing a tropical Pacific Ocean biochronology of calcareous nannofossils and planktonic foraminifers tied to magnetostratigraphy. Nannofossils can also be calibrated through much of the Eocene. As most existing age estimates for these groups have been derived from the Atlantic Ocean region, the establishment of an accurate biochronology based on Leg 199 sediments will permit assessments of the degree of interbasin synchrony among the calcareous plankton.

It follows that the sediments recovered during Leg 199 from the paleoequatorial Pacific Ocean will be an exceptionally valuable reference material for years to come for paleoceanography, as well as, studies of the evolution, biochronology, and intergroup and interbasin correlations among siliceous and calcareous micro- and nannofossils.

One of the enduring legacies of Leg 199 will undoubtedly be the revision of tropical radiolarian biostratigraphy. The opportunity to tie radiolarian biostratigraphic events directly to unambiguous magnetostratigraphy will provide some of the first direct ties between the tropical siliceous microfossil record and the absolute timescale of the Paleogene. Furthermore, the repeated recovery of lower Miocene, Oligocene, and middle and upper Eocene radiolarian-rich sediments in four sites makes it possible to check the reliability of radiolarian events.

Most radiolarian bioevents have been calibrated indirectly to the absolute timescale by correlation to calcareous nannofossil biostratigraphy. On Leg 199, radiolarian bioevents were accompanied by high-resolution magnetostratigraphy, allowing the ages of biozone boundaries to be determined directly from the Cande and Kent (1995) timescale. Figure F23 shows a comparison between the newly determined zonal boundary ages, calibrated using the reversal boundary stratigraphy from Site 1218–1220, with those estimated by Sanfilippo and Nigrini (1998) (SN98). The age estimates of SN98 are based on an unpublished catalog and chart constructed from a reexamination of all Paleogene low- and middle-latitude DSDP/ODP sites from Leg 1 through 135 in which there is a recognizable radiolarian fauna. The published information was reevaluated using current, uniform species concepts and integrated, where possible, with published nannofossil and paleomagnetic data. Sanfilippo and Nigrini (1998) cautioned that their chronology of Paleogene radiolarian zonal boundary events is at best a good approximation.

However, it is apparent that most radiolarian events are synchronous (or nearly so) among the Leg 199 sites. The Leg 199 age estimates tend to be older than the published estimates for 11 of 17 events whereas the others agree to within 100 k.y. or less of previously published ages. Discrepancies in published vs. Leg 199 ages may reflect, for example, uncertainties in the age estimates of SN98 (“at best a good approximation”), paleobiogeographic diachroneity of the events, and difficulties in consistently recognizing evolutionary transitional events. The current radiolarian tropical biostratigraphic zonation includes numerous evolutionary transitions that tend to be subject to interpretation more than distinct first or last occurrence datums.

Postcruise refinements of the biostratigraphy of each site will improve the overall estimate of the ages for both zone marker events and recognition of new bioevents. A cycle stratigraphy based on physical properties measurements in each core will help refine the age estimates of biostratigraphic datums within magnetochrons. The ability to compare the timing of the same events at different Leg 199 sites can identify biostratigraphic datums that may be locally unreliable owing to reworking or

latitudinal differences in the timing of evolutionary first or last appearances of species. The abundant, well preserved radiolarian assemblages will permit the recognition of other, easily identified datum levels with a consequent increase in the resolution of siliceous biostratigraphy.

Oligocene–Miocene Boundary Interval

In compilations of benthic foraminifer stable isotope data, one of the most striking features of the Cenozoic record is also one of the least studied—the late Oligocene (Zachos et al., 2001a, 2001b) (Fig. F5). Much of the Cenozoic record younger than ~51 Ma is characterized by a series of increases in benthic foraminifer $\delta^{18}\text{O}$ that record the gradual refrigeration and polar ice sheet growth that led up to the current icehouse planetary climate. The late Oligocene is a prominent exception to this descent into a glaciated world. Compiled oxygen isotope data from benthic foraminifers display an ~1.5‰ shift to more negative values that results in isotopic ratios in the uppermost Oligocene that are the same as, or even more negative than, the upper Eocene prior to the first large-scale glacial advance on Antarctica (Zachos et al., 2001a). This decrease appears to represent the largest event of its kind in the pre-Pleistocene record of the Cenozoic. At least two competing end-member hypotheses exist to explain this isotope shift: either Antarctica was rapidly deglaciated to a large extent or global deep-water temperatures warmed by 5°–7°C. To date, geochemical data are too sparse for the late Oligocene to either test the deglaciation hypothesis or evaluate the rate and timing of the change in ocean chemistry associated with this climate transition. In fact, because our current records for this time interval are derived from several different sites that lack adequate stratigraphic overlap, even the magnitude and rate of $\delta^{18}\text{O}$ decrease across this time interval are poorly constrained.

The late Oligocene deglacial/warm climate state persisted for ~1.5–2 m.y. and was terminated at the Oligocene/Miocene (O/M) boundary by an episode of polar ice buildup and/or global cooling—the Mi-1 event (Fig. F24). An astronomically tuned record in the equatorial Atlantic has been used to suggest that the Mi-1 event represents a glaciation triggered by changes in orbital insolation (e.g., Zachos et al., 2001b). The coincidence of both the $\delta^{18}\text{O}$ decrease in the late Oligocene and the Mi1 event with erosion surfaces and inferred sea level falls provide support for the hypotheses that both involve significant changes in polar ice sheets. However, direct confirmation from coordinated shifts in both benthic and planktonic stable isotope records or from temperature proxies such as Mg/Ca are mostly lacking.

During Leg 199, we recovered remarkably complete sequences through the upper Oligocene and lower Miocene at Sites 1218 and 1219. These sites display unambiguous magnetostratigraphy, a distinct record of cyclic alternations in sediment physical properties that offers potential for development of an astronomically tuned timescale, and a series of biostratigraphic events in calcareous nannofossils, planktonic foraminifers, and radiolarians that afford direct correlation to previously drilled sites that lack magnetostratigraphy. Sedimentation rates through the late Oligocene and O/M boundary average almost 1 cm/k.y. and will permit the development of a standard Pacific reference stable isotope stratigraphy and Mg/Ca data set that can be correlated at orbital resolution to records throughout the tropical and subtropical oceans. The excellent timescales for Site 1218 and 1219 and potential for further refinements will help to evaluate the rates of change in ice volume and deep-ocean temperatures.

Oligocene

In the context of paleoceanographic research, perhaps the single most important scientific rationale that lies behind scientific ocean drilling is the argument that deep-sea sediments provide the most stratigraphically complete and globally representative proxy records of paleoclimate change. One of the outstanding highlights of Leg 199 in general is our recovery of stratigraphically complete sequences (the sections drilled are virtually free of hiatuses at the biostratigraphic zone and magnetostratigraphic level) that appear representative of substantial tracts of the central tropical Pacific Ocean. Undoubtedly the most elegant demonstration of this important leg highlight is the detailed stratigraphic correlation of Oligocene (including the Oligocene–Miocene and Eocene–Oligocene transitions) sedimentary sequences recovered at Sites 1218 and 1219 as seen in MST data. These data show consistent cycles between these two sites on a submeter scale, allowing a detailed correlation between the two sites. Consistent cycles persisted over at least 22 m.y., from the early Miocene to the middle Eocene. During coring of Site 1219, it was possible to predict a priori both bio- and magnetostratigraphic datum points from those obtained at Site 1218. This important shipboard finding suggests that it is possible to identify signals that act on a larger scale within the equatorial Pacific, and a close comparison allows the identification and estimation of core gaps and short (subzonal scale) hiatuses.

The quality of the MST data obtained allowed the shipboard construction of not only spliced records from both sites, but also an intersite correlation, which is supported by available bio- and magnetostratigraphic datum points that occur at both sites. MST data from Site 1218 and Site 1219, illustrated in Figure F25, were adjusted to a common timescale that was obtained mostly from magnetic reversals. The two sites show very similar records down to a small scale for gamma ray attenuation (GRA) bulk density, magnetic susceptibility, and color reflectance data. Yet, the different paleodepths of both sites also lead to differences and offsets (particularly in the Eocene part of the interval) that are mostly attributed to different amounts of calcium carbonate present in the two sites, probably due to a different paleodepth with respect to the CCD.

The magnetic reversal records from both sites are good and allow the construction of a detailed, yet preliminary, timescale. The application of this common timescale to data from both sites allows the calculation of linear sedimentation rates. These are also illustrated in Figure F25, averaged over 400 k.y. segments. Sedimentation rates from both sites track each other well, and Site 1219 shows a consistently slower sedimentation rate throughout the younger two-thirds of the Oligocene. Between ~40 and 42 Ma an increase in sedimentation rate at both Sites 1218 and 1219 corresponds to the presence of a calcium carbonate-rich section during a time when the CCD must have fluctuated strongly.

On the shipboard timescale the MST data show quasi-cyclic patterns, where the dominant frequency appears to change throughout time partly as a function of lithology. These cycles are consistent with an orbital forcing that has been observed in the Miocene, Oligocene and Eocene (Shackleton et al., 1999; Shackleton et al., 2000; Pälike et al., 2001). The lithologic cycles observed will allow the postcruise generation of a detailed astronomical age calibration of bio- and magnetostratigraphic datums throughout the Oligocene and early Miocene. In detail, the shipboard data already allow the evaluation of the quality of previous age calibrations of datum events. For example, the last occurrence of the calcareous nannofossil *R. umbilicus* ($\geq 14 \mu\text{m}$) close to 32 Ma leads to an exaggerated jump in sedimentation rates at both sites (Fig. F25). Interpolated between the base of magnetostratigraphic C12n and the top of magnetostratigraphic C13n, the stratigraphic position of this

biostratigraphic datum suggests an older age that would be compatible with that given by Shackleton et al. (1999). This is just one example of how further postcruise studies will allow the refinement of many datum events throughout the early Cenozoic.

The remarkable fidelity of the correlation between these two sites, separated by more than 1° latitude and 7° longitude, suggests that drilling results from these two sites are representative of large-scale paleoceanographic forcing functions in the late Paleogene eastern equatorial Pacific Ocean. We anticipate that the continuously cored sediments from Site 1218 with supplementary control from correlative sediments in Site 1219 will provide a paleoceanographic reference section for the late Paleogene tropical Pacific Ocean. In particular, these two sites offer an excellent opportunity to generate high-resolution geochemical records in deep-sea foraminiferal calcite with excellent age control throughout the entire Oligocene from a single deep Pacific Ocean site and thereby test models for the pattern and timing of changes in global temperature and continental ice volume developed from Atlantic Ocean DSDP sites and recent ODP transects on continental margin sequences (e.g., Miller et al., 1998, 1991, 1987) and Antarctic drilling (e.g., Wilson et al., 1998).

Eocene–Oligocene Transition

A major highlight of Leg 199 is the recovery of multiple E/O boundary sections from the central tropical Pacific Ocean (Fig. F11). Elsewhere, in the deep oceans, this important paleoceanographic boundary is often marked by condensed sequences containing poorly preserved microfossils or a hiatus. For these reasons, reliable geochemical records across the E/O boundary are rare and limited to mid- to high-latitude sites from the Southern Hemisphere (e.g., Zachos et al., 1996; Diester-Haas and Zahn, 2001; Gersonde et al., 1999). Leg 199 recovered E/O boundary sections from five Northern Hemisphere sites (Sites 1217, 1218, 1219, 1220, and 1221). Taken together, these sites provide a valuable opportunity to study the chain of events across the E/O boundary within the framework of a depth and latitudinal transect (Figs. F1, F11). Throughout this transect, the transition from the Eocene to the Oligocene is instantly recognizable by a sharp upsection shift from opal-rich and carbonate-poor to carbonate-rich and opal-poor sediments (Fig. F11).

The pronounced lithologic transition associated with the E/O boundary is sharper in all of the Leg 199 sites drilled on older (~56 Ma) ocean crust than the single site (Site 1218) drilled on 42-Ma crust. Furthermore, among the sites situated on 56-Ma crust, the thickness of the carbonate-rich lowermost Oligocene sediments and their carbonate content generally decreases with increases in both latitude and water depth (Fig. F11). These observations indicate that the CCD deepened substantially and rapidly during the Eocene–Oligocene transition (see “Paleogene CCD”).

In detail, the Eocene–Oligocene transition in Site 1218 is marked by a distinct two-step upsection shift from dark radiolarian-rich clay to pale nannofossil chalk (Fig. F26). This two-step shift from carbonate-poor to carbonate-rich sediments is also evident as a two-step increase in GRA bulk density and decrease in magnetic susceptibility values in MST data (Fig. F26). At the other deeper and/or higher latitude sites the lithologic and physical properties transition across the E/O boundary is more of a single, sharp step (Fig. F26).

One stratigraphic complication that we faced during Leg 199 is that the E/O boundary is formally defined by the extinction of the planktonic foraminifer genus *Hantkenina* (Zone P18/P16 boundary, Premoli-Silva et al., 1988) but planktonic foraminifers are absent in sediments of this age in all sites. The extinction of the planktonic foraminifer genus *Hantkenina* occurs toward the younger end of Chron C13r and within calcareous nannofossil Subzones CP16a and CP16b (NP21). The age of the

P18/P16 boundary, and thus the E/O boundary, is presently estimated to 33.70 Ma on the seafloor magnetic anomaly timescale (Cande and Kent, 1995). This age estimate for the E/O boundary will likely be further refined as soon as an astronomically tuned timescale becomes confidently established across the Eocene–Oligocene transition interval.

For the above reasons, the exact placement of the E/O boundary at Leg 199 sites will remain unresolved, perhaps until the problem can be addressed through shore-based high-resolution stable isotope stratigraphy. Nevertheless, the availability of high quality paleomagnetic reversal stratigraphies for all of the Leg 199 sites drilled on 56-Ma crust (Sites 1217, 1219, 1220, 1221) combined with high-resolution nannofossil biostratigraphy made it possible to establish good shipboard approximations for the position of the boundary (Fig. F27). Specifically, age control across the Eocene–Oligocene transition in Leg 199 sites is provided by magnetostratigraphy at the four of the five sites where the E/O boundary interval was recovered by the ODP advanced piston corer (APC) (Sites 1217, 1219, 1220, and 1221). Calcareous nannofossil and radiolarian biostratigraphy provides the age control at Site 1218 and aids the identification of the geomagnetic polarity zones in the four remaining sites. In order to compare the timing of the lithologic change from dark-colored Eocene radiolarite to light-colored Oligocene nannofossil chalk among the five Leg 199 sites with E/O boundary intervals, we have aligned all sites along a 37.7-Ma isochron, calculated through linear interpolation between paleomagnetic and/or biostratigraphic indications (Fig. F28; Table T2).

Discoaster barbadiensis and *D. saipanensis* are constrained to have disappeared over narrow (~20–30 cm) intervals in Site 1218 sediments, just below the major change in lithology (Fig. F27). These findings reveal that the entire two-step change in lithology occurred within Zone NP21 (CP16c), above the extinction of the last Eocene discoasters. By assuming a linear sedimentation rate within Zone NP21 in this composite section, an age estimate of 33.3 Ma was obtained for the initial change (midpoint of transition) in lithology, and an estimate of 32.9 Ma for the midpoint of the second, final step. The boundary condition change of the ocean-climate system that caused the first step of this drastic deepening of the CCD and accompanying change in sedimentation in the tropical Pacific Ocean thus occurred in middle of Oi-1 (33.–33.1 Ma) (Zachos et al., 2001a) (Fig. F5) on the common timescale used (Cande and Kent, 1995). Thus, our records from Site 1218 imply that the change in CCD occurred in the earliest Oligocene in two steps, as a rapid increase in CaCO₃ over 10–20 k.y. followed by a pause of ~100 k.y. and then another rapid increase in CaCO₃ over 10–20 k.y. (see “Paleogene CCD”).

The above findings raise the intriguing possibility that this pronounced deepening of the CCD is in some way related to the first widely accepted sustained glaciation in Antarctica (Oi-1; Fig. F5). The nature of the relationship between these two important paleoceanographic signals will be an important component of shore-based Leg 199 research. Calcareous benthic foraminifer assemblages indicate lowermost bathyal and upper abyssal paleodepths at Site 1218. The calculated age-depth curve for Site 1218 indicates a paleodepth of 3700 ± 50 m for sediments of the E/O boundary at this site. Examination of test walls under transmitted light indicates that benthic foraminifers are well preserved and suitable for benthic foraminifer stable isotope stratigraphy. Average sedimentation rates in the lower Oligocene are relatively high for a deep-ocean Pacific setting (~1–2 cm/k.y.). Together with the sections from the sites drilled on older (~56 Ma) crust, the section from Site 1218 offers exciting prospects for shore-based investigation of the first Pacific Ocean depth and latitudinal transect across this paleoceanographically important interval. For example, application of combined stable isotope and Mg/Ca records in benthic foraminifer calcite will allow us to separate the temperature and ice volume components of “Oi-1” (e.g. Lear et al., 2000). This information, together

with new constraints on the phase relationships between these signals and the deepening CCD will help to evaluate the role of the hydrological cycle vs. the carbon cycle in triggering the onset of the first persistent large-scale ice sheets during the Cenozoic.

Eocene Radiolarian Ooze

The difference between equatorial Pacific Eocene sediments and those of the Oligocene and Neogene is striking. Everywhere along the Leg 199 transect, upper lower Eocene to uppermost Eocene sediments consist primarily of one microfossil group, the radiolarians, mixed with varying amounts of clay. In contrast, Oligocene sediments are dominantly nannofossil rich and also contain a diverse mixture of foraminifers, radiolarians, and diatoms. One of the primary tasks of Leg 199 is to decipher why radiolarian ooze is so common in the Eocene.

The task is made more difficult because analog Neogene and Holocene radiolarian oozes are rare and occupy a specific zone in the equatorial sedimentation regime that is not the same as the equivalent deposit in the Eocene. For example, the “type” Eocene radiolarian ooze (e.g. the middle Eocene ooze of Site 1220 at ~120 mbsf; more specifically, Core 199-1220B-9H, roughly Chron C20n, or 43 Ma) consists of 80%–90% radiolarians, <2% diatoms, and 10%–15% clay. The rest of the sediment is made up of opaque minerals. The sedimentation rate for this interval is 8.3 m/m.y. The total thickness of middle–upper Eocene radiolarian ooze at Site 1220 is 80 m, and it was deposited over 13 m.y. During that time, Site 1220 traversed from ~1°S to 1.5°N, based upon a fixed hotspot model to determine paleopositions.

In contrast, one of the best examples of a lower Miocene radiolarian ooze can be found in the upper sediments of Site 1220 as well. It also is composed dominantly of radiolarians (40%–80%), <2% diatoms, and has ~20% clay. The remainder of the sediment is made up of nannofossils. The sedimentation rate, however, is 2.3 m/m.y., the total thickness of the radiolarian ooze is 18 m, and the sediment was deposited when Site 1220 was between the latitudes of 4° and 6°N. This deposit was formed just beneath the early Miocene CCD but also at the edge of the equatorial productivity zone and as such is oceanographically somewhat similar to modern Pacific radiolarion deposits.

Neogene material deposited beneath the equatorial region, even without carbonate, would still contain large numbers of diatoms and would not be equivalent to the Eocene radiolarian oozes. Site 849, located at the modern equator, is roughly at the equivalent longitude and latitude as occupied by Site 1220 in the early Eocene. The sediments of Site 849 contain from two to ten times as many diatoms as radiolarians throughout the entire sediment section, based upon smear slides (Mayer, Pisias, Janecek, et al., 1992). An Eocene radiolarian ooze cannot simply be created by raising the CCD above the seafloor in a modern equatorial environment. Diatom production in the Eocene must have been significantly lower than Neogene production. The lack of diatoms is another indication, along with the low levels of organic carbon deposition (see “Fluxes and Paleoproductivity”), that primary productivity levels in the Eocene were significantly below Neogene levels.

Diatoms are occasionally found in the Eocene radiolarian oozes in relatively large abundances (Fig. F29). We checked whether occurrences of diatoms are related to when Leg 199 drill sites crossed the paleoequatorial region. Green arrows on the figure mark when diatom numbers increase to >5% in smear slide counts. In the Eocene section they occur primarily around one interval marked by radiolarian Zone RP15 (~39–41.5 Ma based on the preliminary Leg 199 age recalibration) rather than clustering near where we expect equator crossings. The RP-15 interval is also the time of maximum radiolarian ooze deposition at Site 1217, then at a paleolatitude of ~8°N. In contrast, maximum

sedimentation rates of radiolarian ooze occurred roughly coincident with paleoequator crossings. The presence of diatoms seems to be related to a production event that is also associated with carbonate deposition at Sites 1218 and 1219, not with passage through the equatorial zone.

One of the important observations along the transect is that the radiolarian deposition zone in the uppermost Eocene is restricted to Sites 1218, 1219, and 1220 in the Leg 199 transect. These sites lie in a paleolatitudinal range from 1° to 2°N. All other sites exhibit a hiatus during this interval or have only clay deposition. The uppermost Eocene is marked by a hiatus of ~2 m.y. at Site 1221 (12°02'N), which expands to 5–6 m.y. at Site 1222 (13°49'N) and at DSDP Site 162 (14°52'N) based upon a recalibration of the DSDP biostratigraphy. Sediments deposited in the late Eocene at Site 1217 (16°52'N) are zeolitic clays. Assuming that radiolarian deposition marks some moderate level of productivity, the latest Eocene was a truly impoverished interval for regions beyond several degrees of latitude from the equator. In contrast, in middle Eocene time, significant radiolarian production occurred over a broad latitudinal range. Siliceous middle Eocene sediments are formed along the entire transect save only for the northernmost Sites 1215 and 1216. Therefore, the zone of radiolarian production may have been broader in middle Eocene time (reaching ~10°N latitude) than it was in the late Eocene (when it was only a few degrees wide). Therefore, not only was there a significant change in the type of sediments deposited in the equatorial Pacific during the later Paleogene but also a distinct narrowing of the focus of siliceous sedimentation between the middle Eocene and late Eocene.

Paleocene/Eocene Boundary

A principal objective of Leg 199 was to recover shallowly buried sections across the P/E boundary that could be used for paleoclimate and evolutionary studies. It has been known for several years (e.g. Thomas, 1990, 1998; Kaiho et al., 1996; Aubry et al., 1996, 1998; Kelly et al., 1996, 1998; Sanfilippo and Blome, 2001) that the negative carbon isotope anomaly and transient global warming associated with the P/E boundary are accompanied by carbonate-poor sediments overlying more calcareous sediments. A mass extinction of benthic foraminifers occurs at the same time as the carbon isotope anomaly, suggesting that the boundary records major changes in deep-ocean chemistry and habitats. Carbonate preservation tends to be poorest at the initiation of the carbon isotope anomaly and then improves over an interval several tens of centimeters to several meters thick that records several hundred thousand years of sedimentation. Two drill sites (ODP Sites 690 and 1051) have been reported with an interval of laminated sediment just above the base of the carbon isotope anomaly. Laminations have been interpreted to record low-oxygen environments that prevailed during the initial phases of the P/E boundary and may be partially responsible for the benthic foraminifer extinction (Kaiho et al., 1996; Thomas and Shackleton, 1996). Dickens et al. (1995) and Dickens (2001) have suggested that outgassing of submarine gas hydrate deposits could produce both low-oxygen conditions and carbonate dissolution by oxidation of methane in the water column. However, other than the changes in carbonate content and laminated sediments, most P/E boundary sections display a relatively simple internal stratigraphy.

Leg 199 drilled the first P/E boundary sections (Sites 1215, 1220, and 1221) ever to be sampled in the central tropical Pacific. Furthermore, these sites record a more complex stratigraphy for the P/E boundary than has been recognized previously (Fig. F30, F31). Sediments from both ODP Sites 1220 and 1221 change from calcareous ooze containing Paleocene microbios to a distinctive layered sedimentary unit in the vicinity of the benthic foraminifer extinction. The first beds at or above the

benthic foraminifer extinction horizon consist of light yellowish brown sediments 8–12 cm thick. The yellow bed contains layers of volcanic ash at Site 1220 but is massive at Site 1221. The top of the yellow bed is burrowed and overlain by ~2 cm of rose-pink-colored sediment that displays laminations and a few discrete burrows. A layer of black, manganiferous sediments overlies the rose-pink bed and grades upward into brownish, partly laminated and burrowed calcareous clays. The sequence of yellow, pink, black, and brown beds all have low carbonate contents typical of the core of the P/E boundary at other localities. However, the interbedding of sediments with different color and sedimentary structures have not been observed in P/E boundary sections from elsewhere in the world. The presence of similar sequences of color bands in Sites 1220 and 1221 that are situated >200 km from one another suggests that the stratigraphy of these P/E boundaries has at least regional significance and may record changes in deep-ocean chemistry and sedimentation that reflect different phases of the development of the boundary interval on a global scale.

Biostratigraphy of the P/E Boundary Interval

Although the P/E boundary is marked by a major extinction of benthic foraminifers (~53% species extinction), surface ocean microbiotas display mostly temporary changes in taxonomic diversity. Unfortunately, most P/E boundary sections are highly condensed or have severely dissolved calcareous faunas, so the sequence of biotic events has not been worked out in detail. A few tropical–subtropical sites record the presence of three short-lived species of planktonic foraminifers (“excursion fauna”) (Kelly et al., 1998) that are believed to have evolved shortly after the beginning of the global climate change associated with the P/E boundary and then become extinct ~200 k.y. later. Calcareous nannofossils show elevated rates of both extinction and speciation in the ~500 k.y. after the onset of Eocene time, but the sequence of evolutionary turnovers is still much in debate.

Results for Leg 199 drill sites suggest that, contrary to previous interpretations, the various biotic events associated with P/E boundary time (e.g., the extinction of the nannofossil species *Fasciculithus tympaniformis* and many benthic foraminifer taxa together with the evolution of the planktonic foraminifer “excursion fauna”) are not synchronous within the P/E boundary interval. At both ODP Sites 1220 and 1221, Paleocene benthic foraminifers become extinct at the start of the deposition of the sequence of multicolored beds (Fig. F32). The reduction in carbonate content (from ~80 to ~12 wt%) associated with the benthic extinction and reduced preservation of foraminifers makes it difficult to precisely define the level of the extinction. However, a sharp drop in carbonate content is observed at the same level as the carbon isotope excursion in other deep-sea sites. Therefore, it is reasonable to conclude that the base of the multicolored beds at Leg 199 sites will ultimately prove to contain the initiation of the carbon isotope anomaly. Data from Site 1220 make it quite clear that the “excursion fauna” (composed of the planktonic foraminifers, *Acarinina africana*, *A. sibaiaensis*, and *Morzovella allisonensis*) predates the extinction of Paleocene benthic foraminifers. Hence, Leg 199 results strongly suggest that the “excursion Fauna” evolved before the P/E boundary. These species also range above the top of the multicolored beds and may survive termination of the carbon isotope anomaly. Counts of the abundance of the calcareous nannofossils at both ODP Sites 1220 and 1221 show that *Fasciculithus* is replaced by *Rhombaster* well above the multicolored beds believed to represent the start of the Paleocene-Eocene thermal maximum. We have also documented the appearance of *Thoracosphaera* cysts in the boundary interval. Thoracosphaerid blooms are frequently associated with sediments immediately above the Cretaceous/Paleogene mass

extinction horizon and have been interpreted to represent an opportunistic “disaster” flora (Brinkhuis and Biffi, 1993).

Geochemical Profiles of the P/E Boundary Interval

The shipboard inorganic geochemistry protocol for Leg 199 incorporated a program of bulk sediment analysis, including a detailed analysis of the P/E boundary interval at Sites 1220 and 1221 (Fig. F33). Results for the two sites are very similar although changes in elemental concentrations are somewhat sharper at Site 1220 than at Site 1221. Both sites have a significant enrichment in Mn concentration associated with the black layer, which probably contains Mn oxides. The dark, carbonate-poor portion of the P/E boundary at Sites 1220 and 1221 is associated with high levels of Si, Al, Ti, Fe, and Mg. This is consistent with a higher proportion of silicate minerals such as clays compared to the more carbonate-rich portions of the sediment column and in keeping with the interpretation that the boundary lithology represents an interval of pronounced shoaling of the CCD.

At both Sites 1220 and 1221, the P/E boundary is associated with a double peak in levels of Ba and P across the interval of major color change. Superimposed on the center of these broad increases in Ba and P is an interval of very low Ba and P, which corresponds to the black Mn-rich layer and the red layer. This decrease is also present in the Sr profiles. The Ba and P profiles may be explained in several ways. One possibility is that the double peak seen in the profiles for these elements reflects real changes in the rate of Ba and P delivery to seafloor during P/E boundary time. Alternatively, it is possible that the rates of Ba and P delivery to seafloor were high throughout P/E boundary time and that the double peak is a dilution artifact arising from a shorter interval of rapidly accumulating black and red sediments, possibly as a result of nearby hydrothermal activity. A third possibility is that the double peak in Ba and P arises from diagenetic remobilization of primary Ba and P signals. Regardless, the levels of Ba and P recorded across the P/E boundary at Sites 1220 and 1221 are high in comparison to those measured in other Leg 199 sediments. This observation, together with the congruency of behavior between the two elements, raises the intriguing possibility that the shipboard data record an increase in surface ocean productivity across this important paleoceanographic interval (Thomas et al., 2000; Bains et al., 2000) rather than an increase in barite saturation arising from the injection of Ba into the global ocean from the marine gas hydrate reservoir (Dickens, 2001).

OPERATIONAL AND LOGISTICAL ASPECTS OF THE PALEOGENE TRANSECT

Five logistical issues make the design of the Leg 199 transect (or any other Paleogene/Cretaceous transect) significantly more difficult than the design of a Pleistocene study: (1) the Neogene sediments are overburden, not the target of drilling; (2) because ocean crust is old, the sites are deep; (3) errors in plate tectonic models accumulate, and paleopositions are hard to predict with confidence; (4) the sedimentation regime is more poorly known and the type of sediments that will be encountered can be hard to predict; and (5) cherts commonly occur in the sediments and disrupt recovery, but, chert formation is poorly understood and not yet predictable. An ODP leg with Mesozoic or early Cenozoic objectives must have a large component of exploration attached to it, as well as some well-conceived studies with guaranteed payoff.

Burial of the Paleogene section by Neogene sediments has important impact on diagenesis and on the time needed to recover the interval of interest. Even minimal diagenesis (e.g., carbonate ooze–chalk transition) affects both recovery and the ability to perform later paleoceanographic studies. For example, at Site 1218 deeply buried lower Oligocene nannofossil oozes were converted to chalk at ~200 mbsf, which necessitated a switch from APC to XCB drilling at 189 mbsf. XCB drilling disturbs the sediments more extensively than piston coring and effectively ended our ability to develop a paleomagnetic reversal stratigraphy even though a continuous sediment column splice was completed to 263 mbsf. Completing a sediment column splice by multiple offset holes at a drill site is also more of a challenge because significant time can be lost drilling to the sediments of interest. The presence of the Neogene equatorial sediment bulge immediately to the south of the Clipperton Fracture Zone effectively limited our ability to sample the Eocene from southern tropical paleolatitudes.

Sediments over young ocean crust are relatively shallow, situated under ~3 km of overlying water. Because ocean crust cools and deepens when it ages, an older transect is under a much deeper water column. All drill sites along the 56-Ma transect of Leg 199 were deeper than 5 km. Because the water is deeper along an older transect, normal drilling operations such as recovering core take significantly longer than they would along a younger transect. Any failure of equipment leads to a larger time penalty and standard pipe trips at the beginning and end of a site take significantly more time than in shallow water. Fewer holes can therefore be drilled in the same amount of time for a Paleogene or Cretaceous transect.

Errors in plate tectonic models are relatively small for the Neogene, but even small errors accumulate with time. The resultant error may amount to several degrees of latitude in the Paleogene Pacific, and the ability to predict paleopositions becomes less reliable. In the case of Leg 199, uncertainties in the motion of the Pacific plate required that we drill a larger latitude span than may have been strictly necessary to study Paleogene equatorial Pacific circulation because prior to drilling we were not certain where the equator crossed our 56-Ma transect in the Eocene and Paleocene.

Even with prior DSDP drilling, it was only possible to predict in a very general way the type of sediments we would find. We were often surprised by the lithologies we drilled, and the scientific party had to be flexible to revise both the drilling plan and postcruise studies. During Leg 199, it was important to have alternate drill sites to choose from after new material was discovered. Any Paleogene drilling leg should have a variety of alternate sites to optimize drilling time.

Cherts are always a consideration when drilling Paleogene and older sediments. Improvements in drilling technology, such as better cutting shoes and active heave compensation, make cherts a less fearsome challenge than early in the DSDP program. Nevertheless, recovery in cherty sediments is still generally poor. In the case of Leg 199, we were able to core a continuous section through cherty chalk at Site 1218 but were generally frustrated in recovering sediments with chert near the early–middle Eocene boundary. We believe that these sediments were still unlithified because we were able to recover radiolarian ooze right up to the upper boundary of chert zones and recovered radiolarian ooze and carbonates below. Understanding where chert zones lie helps to minimize sediment loss but new drilling technology is still needed.

SITE SUMMARIES

Site 1215

Site 1215 is located north of the Molokai Fracture Zone in 5406-m water depth. It is situated on typical abyssal hill topography in an area of thin but continuous sediment cover. Based on magnetic lineations, basement age at this site should be in the youngest part of C26r, or ~58 Ma. This site was the northernmost of the transect drilled on crust of this age during Leg 199. Double APC/XCB coring at Site 1215 recovered a sedimentary section from red clays at the seafloor to hydrothermal sediments immediately above basalt. The 70-m-thick sediment section consists of pelagic red clay (Unit I; ~0–26 mbsf) overlying 42 m of clayey calcareous ooze with chert (Unit-II; ~26–68 mbsf) and a thin basal unit of hydrothermal sediment (Unit III; ~68–70 mbsf) over basalt. The upper and lower units of the section are unzoned biostratigraphically, but calcareous fauna and flora and magnetostratigraphy indicate that Unit II is complete (to the zone/chron level) from the upper Paleocene through lower Eocene section (NP8 through NP12; C25n–C23n or ~56.2–52 Ma). Porosity values increase steadily with depth from ~73% near the seafloor to ~91% at the bottom of the red clay unit (25.8 mbsf) and then decrease steadily to values near 58% at the base of the Unit II carbonates (67.2 mbsf). The one sample analyzed from the lithologic Unit III hydrothermal sediments has a porosity of ~82%. Interstitial pore water profiles from Site 1215 primarily reflect the dissolution of biogenic silica, alteration of underlying basalt, and extremely low levels of labile organic matter available for oxidation.

Highlights

Red Clay Transition

A light to dark color change occurs in the upper portion of lithologic Unit I (red clay) and has been observed in cores of pelagic clay throughout the north central Pacific Ocean. Light absorption spectroscopy, elemental solid phase chemistry, and both discrete and GRA bulk density data from Site 1215 indicate a downcore transition from illite to smectite between ~5 and 10 mbsf consistent with a change in the source of wind-blown dust from Asia (illite rich) to America (smectite rich) during late Miocene time.

Recovery of Chert with Host Sediments

Recovery of chert nodules together with their host sediments at Site 1215 represents a new achievement in ocean drilling. Despite intervals where chert fragments blocked the core barrel and occasioned “flow-in” and core disturbance, composite data from the MST and color reflectance show that cores from the two holes at Site 1215 provide a continuous overlap to ~50 meters composite depth (mcd).

Composite Lower Eocene Section of Clay–Calcareous Ooze Cycles

The interval between ~30 and ~50 mcd at Site 1215 shows a clear succession of cycles in color reflectance and physical properties data on a decimeter scale that appears modulated in amplitude as well as in thickness. This amplitude modulation, when combined with biostratigraphic time control, is consistent with a climatic forcing related to climatic precession (~19,000- to 23,000-yr period). In the calcium carbonate-bearing sediments, both nannofossil assemblages and planktonic foraminifers are strongly affected by dissolution, but the former provide well-constrained biostratigraphic control. The benthic foraminifers present are characterized by hyaline calcareous

tests, are better preserved than the planktonic foraminifers, and are promising for shore-based paleoecological and paleoceanographic studies.

First Paleocene/Eocene Boundary Section from the Central Tropical Pacific Ocean

An interval of dark brown (10YR 2/2) nannofossil clay at ~54.7 mbsf in Hole 1215A (interval 199-1215A-8H-3; 128–148 cm) is interpreted to represent the first P/E boundary section to be recovered from the central tropical Pacific Ocean. Calcareous nannofossil biostratigraphy indicates that the boundary occurs within NP9, and the P/E benthic extinction event is observed to occur between ~54.5 and ~55.5 mbsf.

Site 1216

Site 1216 is located on abyssal hills just south of the Molokai Fracture Zone at a water depth of 5163 m. The crustal age based on magnetic lineations is ~57 Ma (C25r). The site was chosen for drilling because it is near the thickest section of lower Eocene sediments along the 56-Ma transect. Based on previous coring and drilling ~1° in latitude to the south, we expected to find a moderately thin red clay section overlying middle Eocene radiolarian oozes and lower Eocene carbonates. Instead we drilled a 50-m section of red clay overlying thin cherts in sediment. We recovered only chert in the chert-sediment section. Microfossils are absent until ~40 mbsf, where small numbers of middle Eocene radiolarians appear. The cherts are early middle Eocene–early Eocene in age. We abandoned the site after drilling to 62 mbsf and before drilling to basement because of the likelihood of large amounts of chert in the section with little sediment recovery and because we could use the saved time to ensure more complete programs at the remaining sites.

The red clay unit is similar to the red clay section of Site 1215 but expanded (40 m vs. 25 m thick). The upper part of the Site 1216 red clays are illite rich (based upon LAS), grading to smectite rich at the base. The transition begins at ~10 mbsf. Fe-Mn oxyhydroxides are also abundant in the lower part of the red clays, reaching a maximum ~29 mbsf as shown by bulk sediment analyses and by grain density. A transition from relatively high to low natural gamma ray activity occurred at ~25 mbsf. A similar transition in natural gamma ray activity was observed at Site 1215.

The sediments at Site 1216 were surprisingly barren of microfossils. Upper middle Eocene radiolarian oozes are absent at the site, and lower middle Eocene radiolarians are not abundant. Calcareous microfossils are absent in the drilled section. Only agglutinated benthic foraminifers were found, but none are age diagnostic. The uppermost radiolarians (from RP 13 Zone; ~44 Ma) occur at ~40 mbsf. The base of the drilled section (62.2 mbsf) is in radiolarian Zones RP9 and RP10, which straddle the middle/early Eocene boundary (~49 Ma). The first cherts encountered downhole occurred at ~50 mbsf. These upper cherts thus appear in an interval of slow sedimentation, at most 4–5 m/m.y., presumably at the top of more rapidly deposited lower Eocene sediments with larger amounts of biogenic components. We estimated from the seismic reflection profile that ~90 m of sediments remained to be drilled within the cherty section until basement was reached.

It was possible to detect magnetic reversals in the red clay section, but none were detected in sections with microfossils because of coring disturbance. Based on the microfossil dates, the lowest magnetic chron detected is probably C20n. Magnetic intensity of the red clays is strong, and drilling-induced magnetic overprints appear to be mostly removable by standard procedures.

Highlights

Red Clay Section

The red clay section at Site 1216 has several similarities to the red clay section cored at Site 1215, although it is 60% thicker. Both red clay units have a transition from illite to smectite with depth. Both show a significant decrease in natural gamma ray activity downcore. The lower parts of the red clay unit are enriched in Fe-Mn oxyhydroxides. When MST records are compared, smaller events appear to correlate between these two sites. Provided that some age control can be developed, it may prove possible to develop a much more detailed red clay stratigraphy for the North Pacific.

Missing Middle Eocene Radiolarian Oozes

One of the major surprises found from dilling Site 1216 is the remarkable lack of late or middle Eocene radiolarian oozes. These are biogenic sediments that have no modern analog but are prominent sedimentary features from piston cores and drill sites only 1° to the south. DSDP Site 40 recovered 140 m of upper-middle Eocene radiolarian ooze beneath ~10 m of red clay. DSDP Site 41 with a thinner sediment column (34 m of sediment above basalt) contains 16 m of radiolarian ooze below 18 m of red clay. Piston core EW9709-3PC, taken on the site survey for the potential Leg 199 drill site PAT-13 (19°46'N, 138°55'W) also cored 5 m of middle Eocene radiolarian ooze beneath 10 m of red clay. On the basis of this apparent sharp zonation in tropical biotic communities, we hypothesize that a major oceanographic boundary existed between the position of Site 1216 and the position of sites presently situated at ~20°N in the middle and late Eocene.

Site 1217

Site 1217 is situated approximately 1° latitude north of the Clarion Fracture Zone on abyssal hill topography typical of the Central Pacific. The site was chosen for drilling because it is thought to have been located just outside of the equatorial region at 56 Ma (~5°N, 106°W, based upon a fixed hotspot model; Gripp and Gordon, 1990, for 0- to 5-Ma Pacific hotspot rotation pole and Engebretson et al., 1985, for older poles). At 40 Ma the site was located at ~8°N, 111°W. Thus, Site 1217 should help define the paleoceanography of the northern tropical Pacific and, in particular, help to locate the ancient North Equatorial Countercurrent (NECC) region. Based on site survey seismic data and piston coring together with results from the nearest drill site (DSDP Site 162, situated on 48-Ma crust ~300 km south and west), we expected the sedimentary sequence at Site 1217 to comprise a relatively thick (25–35 m thick) section of red clays, overlying a radiolarian ooze. We also expected a basal carbonate section with possible chert near basement (estimated total depth of ~125–150 mbsf) deposited when the site was near the ridge crest in the late Paleocene and early Eocene.

The sedimentary section overlying basalt at Site 1217 is ~138 m thick and records a lower Eocene nannofossil chalk overlain by a poorly recovered lower-middle Eocene chert-clay sequence. Middle Eocene-Holocene deposition is represented by radiolarian ooze followed by red clays at the surface. The recovered sediments from all three holes at Site 1217 were affected by coring disturbance, downhole debris, and flow-in associated with chert fragments blocking the core liner. One stratigraphic interval in the APC-cored section was highly disturbed or not recovered in all three holes (~37–49 mbsf), preventing the recovery of a complete continuous sedimentary section. Nevertheless, it was possible to generate a spliced, but discontinuous, record in the upper 90 m of the section.

The uppermost red clays at Site 1217 (Unit I) are ~39 m thick. The clays show a downhole mineralogical transition from illite to smectite at ~7 mbsf, indicating a change in wind-blown dust provenance from American to Asian sources associated with the movement northward of the Pacific plate. These clays also contain a thin (~2.5 m thick, ~30 mbsf) subunit of nannofossil ooze interbedded with nannofossil clay. Below the red clays are a radiolarian ooze with clay grading to clayey radiolarian ooze (Unit II; ~39–90 mbsf). The radiolarian ooze is of middle Eocene age (~38–43 Ma) and contains a rich and well-preserved middle Eocene radiolarian fauna. Below 90 mbsf we encountered a unit of chert and interbedded clay (Unit III; 190 and 128 mbsf) before recovering a thin (~1.13 m thick) section of early Eocene chalk (Unit IV; 128–129 mbsf). The chalk is partially to extensively dolomitized (washed core catcher samples yield abundant near-perfectly euhedral rhombs ~100 mm in size) but contains nannofossils and planktonic and benthic foraminifers. Basement basalt was encountered at 138 mbsf.

Wet bulk density values at Site 1217 are high between the seafloor and 22 mbsf (mean values = 1.37 g/cm³) and decrease sharply to a minimum of 1.18 g/cm³ at 25.58 mbsf—a value that is very similar to the density of the radiolarian oozes at the site. In contrast, the wet bulk densities of the Oligocene nannofossil ooze subunit and lower Paleocene nannofossil chalk are distinctly higher (~1.28 and 1.79 g/cm³, respectively).

The magnetic intensity of the sediments is relatively strong, and drilling-induced magnetization was mostly removed with mild alternating-field (AF) demagnetization. Site 1217 sediments provided a good record of geomagnetic reversals that could be easily interpreted as magnetozones. Characteristic remanent magnetization (ChRM) inclinations are usually shallow, as expected in these latitudes. A reversal record from Chron 20 to Chron 12 was established for the middle Eocene–early Oligocene sediments, but the reversal stratigraphy in the upper 15 m (late Oligocene to recent) could not be established because of the low sedimentation rate of the upper sediments and the lack of either core orientation or an independent age model.

High levels of sulfate and concomitant low levels of ammonium in interstitial pore waters at Site 1217 indicate a relatively oxic system, consistent with very low levels of labile organic matter, occurrences of metalliferous oxides, and the strong and stable magnetic signals within the host sediments. Relatively high pore water silica concentrations are consistent with dissolution of biogenic silica within the sediments. The solid phase chemical content reflects the microfossil content and the low level of reductive diagenesis. The whole section at Site 1217 shows relatively high levels of Mn and Fe in the solid phase. Within the upper red clays, solid phase Si levels generally increase southward in the Site 1215, 1216, and 1217 transect, presumably indicating higher export of biogenic debris to the ocean floor closer to the paleoequator.

The average linear sedimentation rates in the red clays (shallower than 23 mbsf) are very low (~0.8 m/m.y.). Sedimentation rates in the underlying fossiliferous and cherty lower sections are substantially higher but are, nevertheless, relatively modest (~5 m/m.y.).

Highlights

Lower Oligocene Nannofossil Ooze

Assuming that a distinct polarity reversal seen in paleomagnetic data at 23.27 mbsf in Hole 1217A represents the base of Chron 12n, the succeeding downhole normal polarity interval is interpreted to represent Chron 13n, which lies at the base of the Oligocene. This interpretation is consistent with the underlying spacing and length of several normal and reversed intervals and places the thin

subunit of nannofossil-rich carbonate ooze (all from nannofossil Zone NP22) in the lowermost Oligocene. We hypothesize that this brief interval of carbonate sediment preservation represents the dramatic deepening of the CCD recorded elsewhere in the deep-sea tropical Pacific Ocean (e.g., DSDP Sites 42, 70, 161, and 162) associated with the Eocene–Oligocene transition.

Middle Eocene Radiolarian Ooze

At Site 1217 we collected the first near-continuously drilled sequence of Eocene radiolarian oozes by deep-sea drilling. In the presence of a well-defined magnetostratigraphy, this section will help to define and calibrate radiolarian stratigraphic zonation. Radiolarian oozes have no modern analog but are prominent sedimentary features of the middle Eocene low-latitude Pacific Ocean having been recovered from piston cores and drill sites up to 4° to the north (e.g., DSDP Sites 40 and 41) and 10° to the south (e.g., DSDP Sites 70 and 162). In contrast, middle Eocene radiolarian oozes were absent at Site 1216. Thus, Sites 1216 and 1217, along with DSDP Sites 40 and 41, appear to define the northern extent of this type of biogenic sedimentation. We anticipate that further recovery of middle and upper Eocene sediments will better define the oceanographic conditions that lead to radiolarian ooze formation.

Lower to Middle Eocene Chert and Dolomitized Nannofossil Chalk

By coring to basement at Site 1217 we recovered sediments needed to address a number of Leg 199 objectives, including an improvement in our understanding of the following: (1) the location of the Eocene/Paleocene paleoequator, (2) the biotic composition and rate of accumulation of sediments within the tropical Eocene Pacific Ocean, (3) the behavior of the silica budget and CCD during the early Eocene, and (4) the sedimentary expression of the P/E boundary in the central tropical Pacific Ocean. Broadly speaking, the sequence drilled at Site 1217 conforms to the classical sedimentary succession predicted for a deep-sea drill site situated on relatively old oceanic crust in the Central Pacific (red clays overlying siliceous and, in turn, carbonate biogenic sediments). However, the lowermost sediments drilled (lower to middle Eocene chert and chalk) surprised us in two ways. First, these sediments show average linear sedimentation rates are relatively slow (<5 m/m.y.), consistent with results from Site 1216. Second, the basal lower Eocene cherts that overlie basement are, like their Site 1215 counterparts, dolomitized—an intriguing discovery given their proximity to what is generally considered to be a kinetically more favorable geochemical sink for Mg (alteration minerals in the upper oceanic crust).

Site 1218

Site 1218 (8°53.378'N, 135°22.00'W) is the only Leg 199 drill site to be located over ~40-Ma crust. It was chosen for drilling in order to investigate paleoceanographic processes in the equatorial Paleogene Pacific Ocean during the inferred transition of Earth's climate from the early Paleogene greenhouse into the late Paleogene icehouse state. Site 1218 is situated on a basement swell ~3°N of the Clipperton Fracture Zone in the central tropical Pacific. Pacific plate motion carried it across the equator at ~40 Ma based upon a fixed hotspot model (Gripp and Gordon, 1990, for 0- to 5-Ma Pacific hotspot rotation pole and Engebretson et al., 1985, for older poles). Based upon the same model the site remained within 2° of the equator from the time crust was formed until 27 Ma. The sediments recovered from Site 1218 should therefore record equatorial oceanographic conditions from the middle Eocene until the early Oligocene. The precise age of basement at the site was poorly

constrained prior to Leg 199 because little magnetic anomaly data are available between the Clipperton and Clarion Fracture Zones (Cande et al., 1989).

At Site 1218 we recovered a complete sediment section to within 15 m of basalt basement. Cores recovered from three holes were spliced into a continuous section from the seafloor to 263 mbsf (~41–42 Ma, nannofossil biostratigraphic Subzone CP14a). The sediments immediately overlying basalt are from near the CP14a/CP13 boundary (42 Ma), which indicates that basement Site 1218 is slightly older than expected. A full suite of downhole logs were obtained to the base of the Hole 1218A, and the data are of excellent quality.

The sediment column at Site 1218 is made up of four sedimentary units. At the top of the sedimentary column is 52 m of yellowish brown radiolarian clay with occasional barren intervals and intervals with nannofossils. The age of this unit is Pleistocene–middle Miocene. Below this unit are nannofossil ooze and chalk of early Miocene–Oligocene age from 52 to 217 mbsf. The boundary below with the Eocene section is abrupt. The upper and upper middle Eocene sediments (217–250 mbsf) are composed of radiolarites and nannofossil chalk with occasional chert beds. The cherty sections were completely recovered by XCB coring. The base of the sediment column is middle Eocene chalk (250–274 mbsf). The lower 7 m of the chalk is dolomitized with up to 20% dolomite in the coarse fraction.

Planktonic foraminifers occur sporadically through the lower Miocene, Oligocene, and middle Eocene sediments at Site 1218 with generally less consistent occurrence than other calcitic groups such as benthic foraminifers and calcareous nannofossils. Most samples show at least some dissolution of planktonic foraminifers with preferential preservation of thick-walled, large specimens in many cases. Middle Oligocene sediments (Zones P21 and P20) were generally the best preserved and most species rich. Benthic foraminifers are present in core catchers throughout the cored interval except in the upper radiolarian clays and the upper Eocene interval. Calcareous nannofossils, in contrast, are present at varying concentrations and states of preservation from uppermost middle Miocene Zone NN8 (CN6; 37mbsf) to the base of the sediment section. Radiolarians were found in all recovered cores.

Pore water chemical profiles are subtle. Sulfate concentrations are near seawater values throughout the section, indicating the lack of significant organic matter diagenesis, whereas trends in Ca and Mg reflect modest basement alteration. Bulk sediment concentrations (measured every 1.5 m) outline the major lithologic units described above. Only Ca and Sr concentrations are high in the lower Miocene–Oligocene nannofossil oozes, and all other elements tend to be higher in the clays and radiolarite sediments. Biogenic enrichment of Ba can be detected through Ba/Ti ratios. High Mg concentrations can be found in the basal dolomitized chalk.

Natural remanent magnetization (NRM) intensity of the sediments at Site 1218 is relatively strong, and magnetic overprint from drilling can be mostly removed by AF demagnetization. An excellent record of magnetic reversals was made for the entire APC-cored sediment section (0–189 mbsf) to Chron C12r of the early Oligocene. In addition, magnetic inclinations were determined on discrete samples after more thorough demagnetization. Middle and early Miocene samples have an average inclination of 5.2° ($+2.2^\circ$ – 8.4°), whereas the Oligocene samples have an average inclination of 3.8° ($\alpha_{95} = 6.2$), which is indistinguishable from the paleoequator.

Highlights

Composite Section

Recovered sediments at Site 1218 have high signal-to-noise ratio MST data sets such that it was possible to direct drilling in real time in Holes 1218B and 1218C to construct a complete composite sediment section to a depth of ~263 mbsf (~287 mcd). The sediments recovered at Site 1218 retain high-quality paleomagnetic reversal stratigraphy for the entire APC-cored sedimentary section (to C12r; ~31 Ma; 188.7 mbsf). In the presence of well-preserved siliceous and carbonate microfossils, this section will help to define and calibrate Cenozoic radiolarian stratigraphic zonation, to develop an astronomically tuned Cenozoic timescale, and to generate high-resolution paleoceanographic and paleoclimatic records of the Paleogene–Neogene transition.

Oligocene–Miocene Transition

The short-range of nannofossil species *Sphenolithus delphix* provides a reliable marker close to the O/M boundary between Chrons C6Cn.3n and C6Cn.2n2 (Raffi, 1999), and on this basis the O/M boundary in Site 1218 occurs at ~98 mbsf. The first occurrence of the planktonic foraminifer *Paragloborotalia kugleri* (the marker for the O/M boundary) and first occurrence of the radiolarian *Cyrtocapsella tetrapera* also occur at this depth as well.

Calcareous benthic foraminifer assemblages indicate lowermost bathyal and upper abyssal paleodepths at Site 1218. Examination of test walls under transmitted light indicates that most of the benthic foraminifers at this site have suffered little or no postburial diagenetic alternation. Average sedimentation rates across the Oligocene–Miocene transition (~1–2 cm/k.y.) are relatively high for a deep-ocean Pacific setting.

Eocene–Oligocene Transition

The E/O boundary interval at Site 1218 is characterized by a major lithologic change involving a two-step downcore shift from pale nannofossil chalk to dark radiolarite. This transition from carbonate-rich to carbonate-poor sediments is also evident as a two-step decrease in GRA bulk density and a decrease in magnetic susceptibility values in MST data. Based upon biostratigraphic information, this transition occurs across or just above the Eocene–Oligocene transition.

The extinction of the calcareous nannoplankton *Discoaster saipanensis* is estimated to have occurred ~0.3 m.y. prior to the E/O boundary event sensu stricto (extinction of the planktonic foraminifer genus *Hantkenina*) and the last representative of the Paleogene rosette-shaped discoasters, *Discoaster barbadiensis*, disappeared ~0.2 m.y. before *D. saipanensis*. *Discoaster barbadiensis* and *D. saipanensis* are constrained to have disappeared over narrow (~20–30 cm) intervals in Site 1218 sediments, shortly below the major change in lithology. These findings reveal that the entire two-step change in lithology occurred within Zone NP21 (CP16c), above the extinction of the last Eocene discoasters. By assuming a linear sedimentation rate within Zone NP21 in this composite section, an age estimate of 33.3 Ma was obtained for the initial change (midpoint of transition) in lithology, and an estimate of 32.9 Ma for the midpoint of the second, final step. The boundary condition change of the ocean-climate system that caused the first step of this drastic deepening of the CCD and accompanying change in sedimentation in the tropical Pacific Ocean thus occurred in middle Oi-1 (33.5–33.1 Ma) (Zachos et al., 2001a) on the common timescale used (Cande and Kent, 1995).

The abrupt change in the lithologies at the Eocene–Oligocene interval is a reflection of the rapid deepening of the CCD (van Andel et al., 1975) in the Oligocene. Site 1218 demonstrates that the

change in CCD occurred the earliest Oligocene in two steps, as a rapid increase in CaCO_3 over 10–20 k.y. followed by a pause of ~100 k.y. and then another rapid increase in CaCO_3 over 10–20 k.y. The CCD was shallower than ~3600 mbsl in the latest Eocene radiolarite interval based on the paleodepth of Site 1218.

Middle and Late Eocene Radiolarites

Coring results from Site 1218 show that radiolarian-rich sediments are characteristic of the late and late-middle Eocene Pacific Ocean even near the equator. Nannofossils occasionally dominate the sediments during parts of this interval, showing that the CCD deepened beyond the paleodepth of Site 1218 at times within the late and middle Eocene. The absence of planktonic foraminifers in the upper Eocene section is most probably related to dissolution, but it is unknown whether planktonic foraminifers were common in the plankton originally. The presence of radiolarians and occasional intervals of nannofossils and the absence of diatoms (except in specific intervals near the E/O boundary) is more typical of Neogene plankton assemblages found at the fringes of the equatorial high productivity zone than in the near-equatorial position that Site 1218 probably occupied during the middle and late Eocene.

Middle Eocene Basal Sediments

The basal nannofossil chalks of Site 1218 abruptly become radiolarites upcore at ~40 Ma (base of nannofossil Subzone CP14b; Core 199-1218C-21X). The transition from chalks to radiolarites occurs over only 1.5 m when the site was at a paleodepth of 3000–3100 m. The middle Eocene rise in CCD at 40 Ma is almost as abrupt as the drop in CCD at the E/O boundary.

Finally, the basal 7 m of nannofossil chalk at Site 1218 that overlie basement are, like their Site 1215 and 1217 counterparts, dolomitized—an intriguing discovery given their proximity to what is generally considered to be a kinetically more favorable geochemical sink for Mg (alteration minerals in the upper oceanic crust).

Site 1219

Site 1219 is the southernmost site to be drilled during Leg 199 on the 56-Ma transect and is situated ~3° north of the Clipperton Fracture Zone at a depth of 5063 mbsl on abyssal hill topography. The age of basement at Site 1219 was poorly constrained prior to Leg 199 because little reliable magnetic anomaly data are available between the Clipperton and Clarion Fracture Zones (Cande et al., 1989). At the outset of Leg 199, based on one interpretation of the location of magnetic anomaly C24r (~57 Ma) (Petronotis et al., 1994), previous drilling, and assumed spreading rates, we estimated the age of basement at Site 1219 to be ~55 Ma. Site 1219 is the only site to be drilled during Leg 199 that features all of the seismic horizons identified for a Paleogene equatorial seismic stratigraphy and our estimate of sediment thickness prior to drilling based upon the seismic reflection profile was 270–290 mbsf, depending on which reflector was chosen as basement.

Based upon a fixed hotspot model (Gripp and Gordon, 1990, for 0- to 5-Ma Pacific hotspot rotation pole and Engebretson et al., 1985, for older poles) Site 1219 should have been within 2° of the equator between 40 and 21 Ma and should have crossed the equator at 29 Ma. Thus the sediments should record equatorial conditions from the late middle Eocene through the early Miocene. In addition, Site 1219 should provide an analog for Site 1218, except that it is on older, deeper crust.

Two holes were drilled at Site 1219. Hole 1219A was a remarkable operations success. We advanced to ~225 mbsf using ODP's APC technology and thereby achieved one of our high-priority objectives by recovering sediments suitable for whole-core paleomagnetic analysis below the lower Oligocene (including the E/O boundary). Basement was reached at ~250 mbsf, shortly after switching to XCB coring. A full suite of downhole logs were obtained to the base of Hole 1219A, and the data are of high quality. In addition to these downhole logs, MST data from the latest Eocene to the earliest Miocene interval in this hole bore a striking resemblance to those recovered from Site 1218 such that it was possible to correlate between Sites 1218 and 1219 (which are separated by 7° of longitude and 1° latitude, or ~800 km) to a submeter scale.

In contrast to Hole 1219A, Hole 1219B was terminated when an APC core jammed in the bottom-hole assembly (BHA) at the depth of the E/O boundary (~155 mbsf). In light of these difficulties in Hole 1219B and the successes of both Hole 1219A and Site 1218, the shipboard party took a collective decision to abandon Site 1219 earlier than planned in order to target additional and more complete programs at forthcoming sites having early and middle Eocene objectives.

Holes 1219A and 1219B can be spliced to form a continuous section to 130 mcd (~30 Ma) with two apparent gaps at ~90 and ~100 mcd. Excellent correlations between Site 1218 and 1219 allow us to estimate the properties of the unrecovered intervals, whereas correlations between logging data and the cores can be used to estimate the size of core gaps deeper in the sedimentary section. Sedimentation rates over the Oligocene interval were ~16% slower than at Site 1218, based upon the site-to-site correlation.

The sediment column at Site 1219 has a strong resemblance to that of Site 1218. 30 m of clay (lithologic Unit I) overlie lower Miocene–Oligocene nannofossil ooze (Unit II; 30–151 mbsf). Strong cyclic variations in nannofossil content are apparent in both the upper and lower parts of Unit II. An abrupt change in lithology from nannofossil ooze to radiolarian clay and clayey radiolarian ooze occurs at 151 mbsf within the E/O boundary interval. The lithologic change marks the upper boundary of Lithologic Unit III, an upper and middle Eocene unit composed of radiolarian ooze and radiolarian clay, becoming radiolarite, chert, and zeolitic clay at the base. A short section in Unit III within magnetic Chron C18r (40.1–41.3 Ma) contains alternating diatom and nannofossil ooze. Below the cherty, clay-rich section at the base of Unit III are the chalks of lithologic Unit IV (234–243 mbsf; ~53–54.8 Ma). The oldest sediments above basalt are slightly younger than the P/E boundary.

NRM intensity of the sediments at Site 1219 is relatively strong, and magnetic overprint from drilling can be mostly removed by AF demagnetization. An excellent record of magnetic reversals was made for the entire APC-cored sediment section (0–223 mbsf), from Pleistocene Chron C1n to early middle Eocene Chron C20r (43.8–46.3 Ma). This remarkably clean magnetic reversal stratigraphy allows us to calibrate biostratigraphic events and to develop detailed sedimentation rate curves downhole through to lower middle Eocene sediments. Overall, declination and inclination patterns in discrete samples show that at least the lower part of the sedimentary section was located in the Southern Hemisphere during deposition. The mean inclination depicts a time-averaged paleolatitude of 1.6°S for the site, but this result is preliminary and will require further testing. The paleolatitude inferred from the inclination is consistent with the expected latitudes as calculated from both paleomagnetic pole positions and those based upon a fixed hotspot model.

Nannofossils are present to abundant in the middle Miocene through Oligocene sediments (~10–151 mbsf) but absent from upper Eocene sediments. Nannofossils reappear briefly in magnetic Chron C17r (~38.3 Ma) in the middle Eocene, disappear, and then reappear and are present between the middle of magnetic Chron C18r to the base of C20n (~40.5–43.8 Ma) and are found in the chalk

in the lower Eocene interval. Planktonic foraminifers are present in the lower Miocene to Oligocene sediments and in the lower Eocene chinks. Preservation quality and abundance are highest in the lower Miocene (Zones M4–M2) and the middle part of the Oligocene (Zones P20 and P21). Benthic foraminifers are consistently present and well-preserved through the Miocene and Oligocene at Site 1219 but are scarce and very poorly preserved through much of the Eocene sections. Radiolarians were found in all cores except the deepest one (Core 199-1219A-27X), which recovered chalk over basalt basement.

The magnitude of the downhole calcium concentration increase and magnesium and potassium concentration decrease in pore waters at Site 1219 is the greatest seen at all sites (Sites 1215–1219) drilled so far drilled during Leg 199. This pattern is consistent with the extensive alteration (e.g., chlorite formation) of basement rocks observed at Site 1219. Depth gradients of pore water alkalinity, pH, sulfate, and ammonium at Site 1219 reflect the small amount of organic matter degradation occurring in these sediments, whereas the chlorinity profile may reflect the diffusion of the more saline Pacific bottom water of the last glacial maximum. Bulk sediment geochemical analyses from Site 1219 reflect the shifts in lithology back and forth between sediments dominated by silica and carbonate. Clay-rich units are high in Ti and Al, but are also high in Fe and Mn, presumably reflecting the deposition of authigenic ferromanganese oxyhydroxides. Physical properties of the sediments also primarily reflect lithology. The carbonate sediments are higher in density, lower in porosity, and lower in magnetic susceptibility than the clay or radiolarian ooze lithologies. This is true even on a fine scale. The radiolarian ooze has higher compressional wave velocity than the carbonates despite having higher average porosity.

Highlights

Paleomagnetic Reversal Stratigraphy

The clean record of magnetic reversal history from Site 1219 (for the entire APC-cored sediment section; 0-223 mbsf) from the Pleistocene down to Chron C20r (43.8–46.3 Ma) is remarkable for a tropical site and, together with the superb cyclostratigraphic correlations to Site 1218 (see below), will provide invaluable time control for shore-based high-resolution paleoceanographic studies.

MST Correlation to Site 1218

The MST data from Site 1219 bear a striking resemblance to those recovered from Site 1218 from the middle Eocene to the lowermost Miocene interval. The excellent match in these data sets between the two sites made it possible to align both records on a common (Site 1218 mcd) depth scale. The two records show such high quality correlation (down to the submeter scale) that successful a priori prediction of biostratigraphic zones and paleomagnetic reversals was possible at Site 1219. The mapping from Site 1219 mcd to Site 1218 mcd results in relative sedimentation rates at Site 1218 that are ~16% higher than at Site 1219 over the Oligocene interval. The remarkable fidelity of the correlation between these two sites, separated by more than 1° of latitude and 7° of longitude, suggests that drilling results from these two sites are representative of large-scale paleoceanographic forcing functions in the late Paleogene eastern equatorial Pacific Ocean. We anticipate that the continuously cored sediments from Site 1218 with supplementary control from correlative sediments in Site 1219 will provide a paleoceanographic reference section for the late Paleogene tropical Pacific Ocean.

Oligocene–Miocene Transition

Calcareous nannofossils suggest a placement of the O/M boundary ~55 mcd at Site 1219, where the range of *Sphenolithus delphix* was observed and correlates to Chron C6Cr. On the Cande and Kent (1995) timescale, an age estimate of 24.28 ± 0.05 Ma is obtained for the base of *S. delphix* at Site 1219. Conversion to the orbitally tuned timescale of Shackleton et al. (2000) by subtracting 0.9 m.y. from the Cande and Kent (1995) timescale estimate, an age of 23.38 Ma is obtained for the base of *S. delphix*. This value is 0.14 m.y. older than the orbitally tuned estimate for this datum derived from the eastern South Atlantic (DSDP Site 522) and the western equatorial Atlantic (Sites 926, 928, and 929) (Shackleton et al., 2000). Yet the calibration of the *S. delphix* event to the geomagnetic polarity record is remarkably consistent in upper Chron C6Cr, from the South Atlantic Ocean to the Mediterranean region (Raffi, 1999) and to the tropical Pacific Ocean (Site 1219).

Eocene–Oligocene Transition

The Eocene–Oligocene transition at Site 1219 is associated with an abrupt lithological change from lithology at Site 1219 from radiolarian clays below to nannofossil ooze above. This transition is similar to but sharper than that observed at Site 1218, presumably reflecting higher rates of carbonate dissolution at Site 1219 (the contemporaneous paleowater depth is ~400 m deeper at Site 1219 than Site 1218). Together with drilling results from Site 1217, this finding offers exciting prospects for shore-based investigation of the first Pacific Ocean depth and latitudinal transect across this important paleoceanographic boundary.

Eocene Sediments

The Eocene sediments at Site 1219 are dominated by radiolarian oozes from the period between ~45 Ma through the E/O boundary. Nevertheless, there are intervals of carbonate within the section, most notably at ~40.5 Ma but also at ~38.3 and ~43.5 Ma. These carbonate units can be detected by density, reflectivity, velocity, and LAS mineralogy as well as by chemical analyses and microscopic examination of the sediments. The 40.5-Ma event and 38-Ma event are also found at Site 1218. The oldest of these events is older than basement at Site 1218.

The lower middle Eocene interval is represented by cherty sediments that were not recovered by drilling. This is the third site on the 56-Ma transect in which we encountered cherts in roughly the same interval. Immediately below the cherts at Site 1219 are zeolitic clays barren of microfossils, suggesting that the chertified interval was deposited slowly. The uppermost lower Eocene chalk in contact with the zeolitic clay has an age of ~53 Ma (nannofossil Subzone CP9b) whereas the lowermost radiolarian ooze above the cherty interval is dated to ~46 Ma. The average sedimentation rate over the 10-m-thick cherty interval could thus be as low as 1.4 m/m.y. The interval has been condensed by diagenesis, but an estimate of using sediment density measured by downhole logging (~2 g/cm³) is about half the bulk mass accumulation rate of the sediments immediately above it.

The lower Eocene chalks were poorly recovered but appear to be typical basal carbonate-rich sediments. There is little evidence of hydrothermal sediments within the chalks.

Site 1220

Site 1220 (10°10.601'N, 142°45.491'W) forms a southerly component of the 56-Ma transect to be drilled during Leg 199 and is situated about midway between the Clipperton and Clarion Fracture Zones at a water depth of 5218 mbsl in typical abyssal hill topography. On the basis of regional magnetic anomalies, we anticipated basement age at Site 1220 to be equivalent to C25n (~56 Ma;

Cande et al., 1989), slightly older than at Site 1219. At the outset of drilling at Site 1220, our estimate for total sediment thickness was ~225 m.

Based upon a fixed hotspot model (Gripp and Gordon, 1990, for 0- to 5-Ma Pacific hotspot rotation pole and Engebretson et al., 1985, for older poles) Site 1220 should have been located ~3°S of the equator at 56 Ma and in an equatorial position at 40 Ma. Thus, Site 1220 should have been situated beneath the South Equatorial Current in the early Eocene. A nearby piston core (EW9709-13PC) taken during the site survey cruise recovered more than 16 m of red clay with the base of the core dated as middle lower Miocene on the basis of radiolarian biostratigraphy (Lyle, 2000).

Site 1220 was drilled in order to study equatorial ocean circulation from the late Paleocene to the late Eocene during the early Cenozoic thermal maximum. Sediment records from this site will help to define the CCD and lysocline during the Paleocene–Eocene and Eocene–Oligocene transitions. In this and other respects, Site 1220 will act as an interesting analog to Site 1218. Both sites are thought to have been located in an equatorial position at ~40 Ma, but the older crustal age anticipated at Site 1220 dictates a greater paleowater depth than for contemporaneous sediments accumulating at Site 1218.

Three holes were drilled at Site 1220. Hole 1220A was terminated when an APC core jammed in the BHA at ~100 mbsf, but basement was reached in Holes 1220B and 1220C at ~200 mbsf. Cores from Site 1220 overlap and form a continuous sedimentary sequence down to ~144 mcd (base of Core 199-1220B-10H). The sedimentary sequence recovered at the site is divided into five major sedimentary units. The uppermost unit (~0–19 mbsf) consists of very dark grayish brown clay with zeolites and is underlain by a lower Miocene–Oligocene unit (~19–40 mbsf) of radiolarian and nannofossil oozes with varying clay content. The underlying Oligocene radiolarian and nannofossil oozes of Unit III (~40–67 mbsf) are notable by the presence of a significant (~15%–45%) diatom component toward the base. Unit IV (~70–185 mbsf) consists of upper Eocene radiolarian oozes with clay and middle to lower Eocene chert with clayey radiolarian ooze. These sediments are underlain by a lower Eocene to upper Paleocene unit (~185–200 mbsf) of partially dolomitized nannofossil ooze, radiolarian nannofossil ooze, radiolarian ooze, calcareous chalk, and black clay atop an aphanitic to fine-grained phaneritic basalt.

Paleomagnetic data from Site 1220 gave excellent results and a reliable record of geomagnetic reversals from the early Miocene to the early–middle Eocene. The composite depth record from Holes 1220A, 1220B, and 1220C shows a remarkable match of the cores between the different holes. In fact, the virtual geomagnetic pole (VGP) latitude changes were used in real time to help fit the cores to the mcd depth scale. Correlation of the magnetic stratigraphy at Site 1220 to the geomagnetic polarity timescale (GPTS) shows a record that spans from Chron C6An.1n to the top of Chron C21n (~20.5–46.3 Ma).

Biostratigraphic results indicate that we recovered a nearly complete sequence of lower Miocene–lower Eocene radiolarian zones at Site 1220, interrupted only by a poorly recovered chert sequence from the uppermost lower Eocene and the lowermost middle Eocene. Calcareous fossils are generally poorly preserved or absent through much of the sequence. Calcareous nannofossils are sufficiently well preserved in the lowermost Miocene and Oligocene to provide a basic zonation. Planktonic foraminifers are almost entirely absent above the lower Eocene, but dissolution-resistant species allow the upper/lower Oligocene boundary to be approximated. Both planktonic foraminifers and calcareous nannofossils provide a detailed zonation of a condensed sequence of lower Eocene nannofossil oozes and chert in the basal 10 m of Site 1220. The extinction of Paleocene benthic foraminifers, the appearance of the nannofossil genus *Rhombaster*, the extinction of the nannofossil

genus *Fasciculithus*, and the presence of “excursion fauna” of planktonic foraminifers provide a detailed biostratigraphy of the P/E boundary in Unit V. The nannofossil events occur 0.8–1.4 m above the extinction of Paleocene benthic foraminifers. The “excursion fauna” of planktonic foraminifers is present in sediments below the level of the benthic foraminifer extinction, in sediments immediately overlying basalt. Thus, none of these events are precisely synchronous with the benthic foraminifer extinction, the marker of the P/E boundary, at this site.

Interstitial pore water profiles from Site 1220 are very similar to the profiles of all other Leg 199 sites except Site 1219 and primarily reflect minor organic matter degradation, the dissolution of biogenic silica, and minor alteration of underlying basalt. The bulk geochemistry of the sediments from Site 1220 reflect the shifts in lithology between sediments dominated by silica and carbonate.

Physical properties of the sediments also primarily reflect lithology. The carbonate sediments are higher in density, lower in porosity, and lower in magnetic susceptibility than the clay or radiolarian ooze lithologies. The radiolarian-rich sediments of Units II and IV are marked by high porosities, which average 88% and 85%, respectively. The radiolarian oozes maintain their porosity despite burial. The Eocene radiolarian oozes have the highest *P*-wave velocities of the unconsolidated sediment lithologies.

Highlights

Paleomagnetic Reversal Stratigraphy

The clean record of magnetic reversal history from Site 1220 (for the entire APC-cored sediment section; 0–150 mbsf) spans the lower Miocene to lower–middle Eocene (Chron C6An.1n to the top of Chron C21; 46.3 Ma). This record is remarkable for a tropical site and will provide invaluable time-control for calibration of radiolarian biostratigraphy. Because there are cyclic variations in radiolarian content of the Site 1220 Eocene section presumably driven by orbital forcing of insolation. This record will be highly important for orbital tuning of the magnetic reversal timescale from the middle Eocene through the Miocene.

Eocene/Oligocene Boundary

A combination of paleomagnetic and nannofossil biostratigraphy indicates that we recovered a further E/O boundary at Site 1220 (~70 mbsf). Shore-based work on this section, together with those recovered at Sites 1217, 1218, and 1219, will allow us to improve existing constraints on the links between global cooling, Antarctic ice sheet growth, and a deepening CCD across this important paleoceanographic boundary.

Paleocene/Eocene Boundary

In Hole 1220B, just above basement basalt, we recovered a lithologically striking interval of calcareous chalk and clay (199–200 mbsf). Based on biostratigraphic data, this sequence represents the P/E boundary. Layers of calcareous chalk and clay display a large range in composition and color downcore. Alternating intervals of white and very pale brown calcareous chalk occur between 198.9 and 199.4 mbsf and contain a minor amount (5%–10%) of poorly preserved nannofossils. White layers occur between 199.15 and 199.23 mbsf and contain 15%–30% planktonic foraminifers. The sediments below this interval consist of faintly banded, dark yellowish brown calcareous chalk but are barren of microfossils. Dolomite (up to 10%) and clay (10%–35%) also occur in this lithology. Below 199.50 mbsf is a 4-cm-thick layer of very dark brown (7.5YR 2.5/3) calcareous chalk underlain by a black clay. Major components of both sediments are dolomite, iron manganese oxides, clay, and possibly sulfides. Volcanic glass occurs as a minor component. Dolomite content decreases over the

interval from 199.52 to 199.54 mbsf, and no calcareous or siliceous fossils were observed in smear slides. Directly beneath the black clay is a 4.5-cm-thick interval of yellowish red calcareous chalk. Within this interval is a 1-cm-thick brownish yellow layer of calcareous chalk. Sediments within the yellowish red layers are weakly laminated and contain clay, dolomite, calcite, and a minor percentage of nannofossils. Iron manganese oxides and opaque minerals are minor components. The brownish yellow chalk layer contains clay, dolomite, iron manganese oxides, volcanic glass, and abundant small mottles. Nannofossils are rare in these layers.

The base of the sedimentary section contains a 9-cm-thick interval of brownish yellow clayey calcareous chalk (199.59–199.68 mbsf) with thin black laminations. Dolomite comprises up to 10% of the sediment. Zeolites and nannofossils also occur as minor components. Iron manganese oxides are rare. Laminations contain clay, iron manganese oxides, dolomite, zeolites, and small amounts of volcanic ash and are barren of calcareous fossils.

Site 1221

Site 1221 (12°01.999'N, 143°41.572'W) forms an equatorial component of the 56-Ma transect drilled during Leg 199. It is situated about three quarters of the way between the Clipperton and Clarion Fracture Zones in typical abyssal hill topography at a water depth of 5175 mbsl. On the basis of regional magnetic anomalies, we anticipated basement age at Site 1221 to be equivalent to C25n (~56 Ma; Cande et al., 1989), about the same age as Site 1220. At the outset of drilling at Site 1221, our estimate for total sediment thickness was ~150 m.

Based upon a fixed hotspot model (Gripp and Gordon, 1990, for 0- to 5-Ma Pacific hotspot rotation pole and Engebretson et al., 1985, for older poles) Site 1221 should have been located ~1° south of the equator at 56 Ma, in an equatorial position at ~50 Ma and ~2° north at 40 Ma. Thus, Site 1221 should have been situated underneath the South Equatorial Current in the early Eocene. A nearby piston core (EW9709-14PC) taken during the site survey cruise recovered more than 11 m of red clay, with the base of the core containing a calcareous radiolarian ooze dated as early Oligocene in age on the basis of radiolarian biostratigraphy (Lyle, 2000).

Four holes were drilled at Site 1221. Hole 1221A was abandoned because of a stuck XCB barrel that resulted in a pipe trip to clear the BHA. Hole 1221B recored the Oligocene interval at the top of the sediment column, whereas Hole 1221C cored to cover the major gaps in the upper sediment column and then cored continuously to basement. Hole 1221D was drilled to obtain a second copy of the lower Eocene and Paleocene sediments.

The heave of the vessel frequently exceeded 5 m while we drilled at Site 1221. The ship heave compromised the quality and recovery of the core. The uppermost ~20 mbsf encountered severe flow-in problems, whereas in the remaining intervals, the often soupy nature of the sediment (radiolarian ooze) resulted in MST data that were not suitable for correlation purposes, with the exception of the P/E boundary interval. A continuous sediment column could not be correlated below 19.5 mcd.

The sediment column is a variation of lithologies seen before at other Leg 199 sites. A very thin clay and radiolarian ooze lithologic unit overlies lower Oligocene nannofossil ooze, terminated by an abrupt transition to clay rapidly grading to radiolarian ooze. The abrupt transition is typical of the E/O boundary. At Site 1221, however, latest Eocene and earliest Oligocene time is represented by a hiatus of perhaps 1 m.y. in extent. The middle and upper Eocene radiolarian ooze section is the

thickest of any site of Leg 199. Deposition of the radiolarian ooze was highest in the period between 45 and 43 Ma, when sedimentation rates reached 18 m/m.y.

A chert-rich section covering the time interval from ~48 Ma (radiolarian zone RP11) to 53.8 Ma (nannofossil Subzone CP9a) lies beneath the radiolarian ooze. Despite the fact that coring times were relatively fast, only chert was recovered, suggesting a significant amount of radiolarian ooze or clay is also present. Hole 1221C drilled somewhat faster than Hole 1221D, indicating some variability in the thickness and areal extent of the chert. In the recovered sediments below the chert unit, clay layers in Hole 1221C can be correlated to clay layers in Hole 1221D. Beneath the chert-rich interval are nannofossil cherts of early Eocene–Paleocene age that comprise the basal sedimentary unit. Within this basal chert we recovered two copies of the P/E boundary interval. The P/E boundary interval is recognizable by a multicolored clay-rich unit remarkably similar in structure to the P/E boundary interval at Site 1220, 206 km to the south. The lowermost cherts above basement were dated at 56.5–57 Ma with foraminifers and nannofossils.

Physical properties of the sediments follow lithology. The densest unit is the lower Eocene chert (~1.6–1.8 g/cm³) followed by the upper clays and nannofossil ooze. The radiolarian ooze has the lowest wet bulk densities (~1.14 g/cm³) and the highest porosities (~84%), as well as the highest velocities of the unconsolidated sediments (1530–1550 m/s).

Biostratigraphic analyses indicate that Site 1221 contains a continuous sequence of radiolarian-bearing sediments from the early Oligocene to the early Eocene. The uppermost sequence contains considerable quantities of reworked middle Eocene radiolarians, while the interval from ~7 to 111 mbsf is almost exclusively brown radiolarian ooze with a sugary texture. No radiolarians were recovered in the chert-rich interval except in the core catcher of Core 199-1221C-10X at a depth of 141 mbsf. These radiolarians are from the early Eocene–late Paleocene Zone RP7. No radiolarians are found in the basal chert.

The sediments of Site 1221 contain calcareous microfossils in only the uppermost and lowermost units. Calcareous microfossils are completely absent in the siliceous sediments between ~7 and ~111 mbsf, and biostratigraphic control through this interval was provided entirely by radiolarians. The carbonate content of sediments increased in the basal reaches of Holes 1221C and 1221D, and nannofossil and planktonic foraminiferal biostratigraphy allow basic zonation of a condensed sequence of lower Eocene nannofossil ooze and chert. Section 199-1221C-11X-3 contains an interval of dramatic and colorful banding, the base of which, as at Site 1220, corresponds to the extinction of Paleocene benthic foraminifers and therefore the P/E boundary. Preservation of calcareous microfossils improves below the P/E boundary, and planktonic foraminifers and nannofossils allow a detailed zonation of upper Paleocene nannofossil ooze and clay. Calcareous benthic foraminiferal assemblages occur only in the basal sediments below 140 mbsf. These assemblages are moderately well preserved, but the presence of small calcite microcrystals on the surfaces of the tests indicate some diagenetic alteration.

Interstitial pore water profiles from Site 1220 are very similar to the profiles of all other Leg 199 sites except Site 1219 and primarily reflect minor organic matter degradation, the dissolution of biogenic silica, and minor alteration of underlying basalt. The bulk geochemistry of the sediments from Site 1221 reflect the shifts in lithology between sediments dominated by silica and carbonate.

Highlights

Paleocene/Eocene Boundary

The P/E boundary was recovered twice (interval 199-1221C-11X-3; 50–90 cm and interval 199-1221D-4X-2, 70–125 cm). The two intervals are very similar, with the interval in Hole 1221D appearing slightly expanded relative to that in Hole 1221C and exhibiting more disturbance.

The benthic foraminiferal fauna were examined in small surface scrapes prior to more complete shore-based analysis. The first occurrence of Eocene benthic foraminifers is at 50 cm in Section 199-1221C-11X-3, whereas the last occurrence of Paleocene forms is at ~91 cm in the same section.

The Site 1221 P/E boundary interval appears remarkably similar to that recovered at Site 1220. Distinctive brown, pink, black, and dark brown layering can be correlated between the two sites 206 km apart.

Site 1222

Site 1222 (13°48.98'N, 143°53.35'W) forms a south-central component of the 56-Ma transect drilled during Leg 199 and is situated ~2° of latitude south of the Clarion Fracture Zone in typical abyssal hill topography. On the basis of regional magnetic anomalies, we anticipated basement age at Site 1222 to be equivalent to C25r or C25n (~56–57 Ma; Cande et al., 1989), slightly older than at Site 1219. At the outset of drilling at Site 1222, our estimate for total sediment thickness was ~115 m; based upon a fixed hotspot model (Gripp and Gordon, 1990, for 0- to 5-Ma Pacific hotspot rotation pole and Engebretson et al., 1985, for older poles) Site 1222 should have been located ~1° north of the equator at 56 Ma and ~4°N at 40 Ma. A nearby gravity core (EW9709-17GC) taken during the site survey cruise recovered more than 5 m of red clay with a late to middle Miocene age on the basis of radiolarian biostratigraphy (Lyle, 2000).

Two holes were drilled at Site 1222. Hole 1222A was drilled to basement, which was penetrated at ~98 mbsf. Hole 1222B recovered the APC-suitable portion of the sediment column (to ~60 mbsf). The sediment column at Site 1222 contains a sequence of lithologies significantly different to that seen at other Leg 199 sites. Site 1222 recovered a 97.8-m thick section dominated by clay-rich lithologies and chert. Unit I consists of an ~60-m-thick yellowish brown to dark gray brown clay with zeolites grading to radiolarian clay. A thin interval of diatomaceous clay occurs near 17 mbsf (Sections 199-1222A-3H-2 to 3H-4). Within the diatom ooze is an interval with unusual layers of laminated diatom ooze that contain a nearly pure diatom component. Laminations are mainly white to olive. Diatom frustules within some laminae contain significant pyrite making them appear very dark gray to black. A sharp contact exists at the base of the diatom ooze interval and the underlying clay of Subunit IA. In Hole 1222A, this contact also contains a large (5-cm diameter) botryoidal manganese nodule. Unit II consists of a thin (~2 m thick) dark brown to brown nannofossil clay grading downcore to yellowish brown nannofossil ooze. Very pale brown mottles are common. Nannofossil content (estimated from smear slides) gradually increases from 30% in the upper portion to 80% near the base of the unit. Unit III consists of an ~8-m-thick sequence dominated by clay with iron oxides and zeolites. Unit III is underlain by a thick (>30 m) poorly recovered sequence of massive chert that, in turn, overlies basement basalt.

Radiolarians provide the biostratigraphic framework for Site 1222. Planktonic foraminifers are completely dissolved in all samples investigated. Calcareous nannofossils of early Oligocene age occur in Unit II and of early Eocene age in chalk attached to a piece of chert occur just above basement. This large chert nodule is rimmed with very pale brown nannofossil chalk that provides

datums indicating an early Eocene age (NP10). The biostratigraphic distribution of radiolarians suggests massive reworking and mixed Pliocene assemblages in the uppermost two and a half cores, between ~0 and 21 mbsf. The following two cores, between ~21 mbsf and 40 mbsf, contain upper and lower Miocene radiolarian assemblages. Two cores between ~40 mbsf and 60 mbsf hold upper and lower Oligocene radiolarian assemblages. Nannofossils are present between ~55 mbsf and 60 mbsf, supporting the radiolarian biostratigraphy. This upper part of the section at Site 1222 appears to contain several breaks in sedimentation. A major hiatus occurs between the lowermost Oligocene and the middle Eocene, having a duration on the order of ~5–6 m.y.

It was possible to construct a continuous spliced record from Site 1222 down to 34.44 mbsf (37.88 mcd), below which it was possible to align most cores from the two drilled holes to each other, but without continuous overlap. Cores 199-1222A-7H and 199-1222B-7H, however, showed good overlap and allowed the splicing of an additional ~13 m from ~59 to 72 mcd.

The paleomagnetic data from lithologic Subunit IA, down to (~40 mbsf) are not interpretable, except for the very top of the Hole 1222A. A large group of ChRM directions show relatively high magnetic inclinations after demagnetization especially in the most clay-rich lithologic units. The cause of the steep inclinations is unclear and might be indicative of unrecognized deformation during the drilling. A preliminary correlation of the magnetic stratigraphy to the GPTS shows that at the very top of the section we were able to identify the bottom of polarity Chron C1n (Brunhes). Stratigraphically downward we identify Chrons from C6Cn to C11n. A long reverse magnetization Chron at the bottom of the section (~67–75 mcd) is thought to represent Chron C12r.

The pore water profiles from Site 1222 primarily reflect minor organic matter degradation and the dissolution of biogenic silica. Most of the dissolved chemical constituents show a lack of gradient with depth and values similar to or slightly higher than seawater.

OPERATIONS

Port Call—Honolulu

Leg 199 began at 2200 hr on 23 October 2001 when the first line was passed ashore at Pier 32A in Honolulu, Hawaii. At 0830 hr on 28 October, after 5 days of port call activities, the last line was released and the transit to the first site of the leg began.

Transit to Site 1215 (PAT-15D)

After clearing the harbor under the pilot's instructions, the vessel transited the Honolulu channel passing within a couple nautical miles of Diamond Head. After proceeding into the open ocean, the vessel speed decreased slightly because the transit direction was directly into a 6 m sea/swell. Toward the afternoon of 29 October, the wind and sea conditions began to moderate and the vessel motion decreased with a concomitant increase in speed. At 1945 hr on 30 October, the vessel speed was reduced to 5 kt and a 5-mi 3.5-kHz survey was made over proposed Site PAT-15D. The 625-nmi voyage to Site 1215 required 58.5 hr at an average speed of 10.7 kt.

Site 1215

At the conclusion of the 3.5-kHz survey, the thrusters were extended, and the vessel returned to the site coordinates using the global positioning system (GPS) interface to the dynamic positioning

system (DPS). At 2100 hr on 30 October, the vessel was over the prospective site and the drilling crew began the assembly of the BHA. A beacon was deployed at 2144 hr.

Hole 1215A

After the vessel settled on location, the corrected precision depth recorder (PDR) depth of 5399.4 meters below rig floor (mbrf) of (referenced to the dual elevator stool) was obtained. After the BHA was made up, the drill string was then deployed to a depth of 5042 mbrf, at which point the armature shaft of the forward M89 traction (drawworks) motor broke. A spare motor was installed, tested, and fully operational by 2400 hr on 31 October 2001.

Hole 1215A was spudded with the APC at 0145 hr on 11 July. The seafloor depth indicated by the recovery of the initial core was 5406.3 mbrf. Piston coring advanced to 69.2 mbsf where the formation became too indurated to continue with the APC system. APC coring resulted in 68.22 m of core recovered from a 69.2 m hole (98.6% recovery) (Table T1). Cores 4H through 9H were oriented with one Adara heat flow measurement attempted at 29.7 mbsf (Core 4H). Further heat flow measurements were not made because the cutting structure of the Adara shoe was damaged by chert, and it was obvious that additional runs in this formation would further deplete the limited stock of this hardware.

The XCB was deployed and advanced from 69.2 to 75.4 mbsf. Most of the 80 rotating min for this core were used to advance the last half meter. When the core barrel was retrieved, several basalt fragments were removed from the core catcher, indicating that the objective of coring into basaltic basement was achieved. The one XCB core in Hole 1215A advanced 6.2 m with a recovery of 0.05 m (0.8% recovery). Overall, 68.27 m of core was recovered from 75.4 m of cored section at Hole 1215A.

Hole 1215B

After Hole 1215A operations ceased, the bit was pulled above the seafloor, and the vessel was offset 20 m south of Hole 1215A. Hole 1215B was spudded with the APC at 0900 hr on 2 November. A seafloor depth of 5406.0 mbrf was inferred by the recovery in the initial core. Piston coring advanced to APC refusal at a depth of 57.0 mbsf with 58.23 mbrf

of core recovered (102.2% recovery). Cores 3H through 8H were oriented. The XCB was used to advance the hole from 57.0 to 82.8 mbsf. Contact with basement was confirmed when basalt fragments were removed from the core catcher of Core 11X. Only 0.72 m of core was recovered from the 25.8-m XCB-cored interval (2.8% recovery). Overall, the average recovery for Hole 1215B was 71.2% (Table T1).

After coring operations ceased in Hole 1215B, the drill string was recovered and the BHA was dismantled in preparation for the transit to Site 1216. The beacon was successfully recalled and recovered. After the drilling equipment was secured, the vessel departed for Site 1216 at 1430 hr on 3 November.

Site 1216

Transit to Site 1216 (PAT-26D)

The 534-nmi transit to proposed Site PAT-26D was accomplished in 50.3 hr at an average speed of 10.6 kt. The vessel encountered a moderate current during 5 November that reduced the daily average rate to 9.9 kt. At 1645 hr on 5 November, the vessel slowed to 6 kt, and the seismic

equipment was deployed. The seismic survey utilized the 80-in³ water gun and Teledyne hydrophone streamer. The first leg of the survey was an 11 nmi north-northwest to south-southeast traverse across the prospective location. A short crossing track from east-northeast to west-southwest concluded the survey. The 24-nmi survey required 4.2 hr at an average speed of 5.7 kt. Following the retrieval of the seismic equipment, the vessel came about and returned to site, at which time the thrusters were lowered and the DPS was activated. The vessel was on the GPS coordinates of the new location by 2130 hr on 5 November. The hydrophones were then lowered, and assembly of the BHA began. A beacon was deployed at 2141 hr on 5 November.

Hole 1216A

After the drill string was deployed to a depth of 5100 mbrf, a “mudline” core was attempted from 5105.4 m and resulted in a “water core,” indicating that the bit was >10 m above the seafloor. The next attempt was made at 5115.4 mbrf with the same result. A third attempt was made with the bit at 5125.4 m and a fourth from 5135.4 mbrf, both of which resulted in water cores. The driller then lowered the bit until the heave compensator appeared to activate, suggesting contact with a firm sea bottom at a bit depth of ~5167 mbrf. The sixth attempt at a mudline core was made with the bit at 5163.0 mbrf, and Hole 1216A finally was spudded with the APC at 1615 hr on 6 November. The seafloor depth that was indicated by the recovery of the first core was 5163.3 mbrf, 50 m deeper than the PDR depth. The usual suspects (misreading the PDR, miscounting the drill pipe, applying the wrong Matthew’s table correction, and improper addition) were reviewed, but no culprit could be found. The uncorrected depth obtained during the initial site survey was also consistent with the PDR reading. The only viable remaining reason for this depth discrepancy appeared to reside in the possible presence of a very strong side echo that mimed a seafloor return on the bathymetric record.

A total of 10 piston cores were taken at Hole 1216A (Table T1). The cores were oriented starting with 3H. The first four piston cores were full-stroke events. All the remaining piston core attempts, however, did not achieve the fully extended 9.5-m stroke of the piston corer, probably due to the prevalence of chert stringers. Cores 5H to 10H (37.7–54.3 mbsf) were obtained using the advance-by-recovery (ABR) method. With this method, the bit position for the next piston core is advanced only to a depth equal to the recovery of the previous core. No heat flow measurements were attempted because of the high probability of damage to the Adara cutting shoe by chert. APC operations in Hole 1216A resulted in 54.3 m cored with 55.11 m recovered (101.5%).

One XCB core (11X; 54.3–62.2 mbsf) was acquired before the hole was terminated. The XCB core advanced 7.9 m and recovered 1.36 m (17.2%). The total recovery at Hole 1216A was 56.5 m, representing 90.8% of the cored interval (Table T1).

Hole 1216B

After the bit cleared the seafloor, the vessel was offset 10 m east of Hole 1216A, and Hole 1216B was spudded with the APC at 0540 hr on 7 November. This was a single-core attempt made with the bit at 5158.0 mbrf (5 m shallower than the bit position of Core 1H). The single core recovered 9.75 m or 102.6%.

After coring operations concluded at Site 1216, the drilling equipment was secured, and the beacon was successfully recovered. The 24-hr transit to the next site (PAT-19A) transit to the next site began at 1545 hr on 7 November.

Site 1217

Transit to Site 1217 (PAT-19A)

The 271-nmi transit to proposed Site PAT-19A was accomplished in 25.2 hr at an average speed of 10.8 kt. At 1700 hr on 8 November, the vessel slowed to 5 kt, and a short 3.5-kHz survey was made from north to south across the site. Upon conclusion of the 1-hr survey, the vessel came about and returned to site as the thrusters were lowered and the DPS was activated. The vessel was on the GPS coordinates of the new location by 1815 hr. The hydrophones were lowered, and assembly of the BHA began. A beacon was deployed at 1848 hr. The corrected PDR depth was 5340.9 mbrf.

Hole 1217A

After the drill string was deployed to a depth of 5330 mbrf, an APC mudline core was attempted from 5335.9 mbrf and resulted in a water core. The driller then lowered the bit until the heave compensator appeared to activate suggesting contact with a firm sea bottom at a bit depth of ~5353 mbrf. The second attempt at a mudline core was made with the bit at 5349.0 mbrf and was successful (0630 hr on 9 November). The seafloor depth indicated by the recovery of the this first core was 5353.0 mbrf and was 12.1 m deeper than the PDR depth.

Hole 1217A was deepened to 99.2 mbsf before it was deemed necessary to switch to the XCB to achieve the objective of obtaining a sample of basement (Table T1). Two of the twelve APC cores (Cores 6H and 8H) did not achieve a full 9.5-m stroke, presumably the result of striking chert. Many of the fully advanced cores also experienced lateral suctioning (flow-in) of sediment below recovered chert nodules. The cores were oriented starting with Core 3H. No heat flow measurements were attempted because of the high probability of damage to the Adara cutting shoe by chert. Hole 1217A APC operations resulted in 99.2 m of cored section with 86.17 m of material recovered (86.9%).

XCB coring (13X through 17X) deepened the hole from 99.2 to 145.2 mbsf, with recovery consisting of chert fragments and a section of nannofossil chalk near basement. A small sample of basalt was obtained in the last core. XCB coring operations deepened Hole 1217A 46.0 m beyond the APC operations and recovered 3.77 m (8.2%). The total recovery for Hole 1217A was 89.94 m, representing 61.9% of the cored interval.

Hole 1217B

After the bit cleared the seafloor, the vessel was offset 10 m north of Hole 1217A. The bit was washed to 20 mbsf before we initiated APC operations. Hole 1217B was spudded with the APC at 1545 hr on 10 November. Seven piston cores were obtained over the interval from 20.0 to 86.5 mbsf (Table T1). Many of the cores had flow-in or disturbance below recovered chert nodules. All cores in Hole 1217B were oriented. The average recovery was 92.5%.

Hole 1217C

After coring operations in Hole 1217 ceased, the bit was pulled clear of the seafloor, the vessel was moved another 10 m north, and Hole 1217C was spudded at 0630 hr on 11 November. The bit was washed to 32 mbsf, where APC coring operations began. Five oriented cores were taken over the interval from 32.0 to 79.5 mbsf (Table T1). The average recovery was 98.6%, but many cores suffered from flow-in.

After coring operations ceased at Site 1217, the drilling equipment was secured, and the beacon was successfully recovered. The 24-hr transit to the next site (PAT-8) transit to the next site began at 1545 hr on 12 November.

Site 1218

Transit to Site 1218 (PAT-8C)

The 497-nmi voyage to proposed Site PAT-8C was accomplished in 47.0 hr at an average speed of 10.6 kt. At 0030 hr on 14 November, the vessel slowed to 5 kt, and a short 3.5-kHz survey was made from north to south across the site. Upon conclusion of the 45 min survey, the vessel came about and returned to site as the thrusters were lowered and the DPS was activated. The GPS receiver interface to the dynamic-positioning system was employed, and the vessel was over the coordinates of the new location by 0115 hr. A beacon was deployed at 0241 hr. The corrected PDR depth was 4848.0 mbrf.

Hole 1218A

After the drill string was deployed to a depth of 4811 mbrf, the driller then lowered the bit until the heave compensator appeared to activate, suggesting contact with a firm sea bottom at a bit depth of ~4840 mbrf. Hole 1218A was spudded with the APC at 1000 hr on 14 November. The seafloor depth indicated by the recovery of the initial core was 4837.3 mbrf, 10.7 m shallower than the PDR depth.

Hole 1218A was deepened to 188.7 mbsf (base of Core 20H) before it became necessary to switch to XCB operations to accomplish the deeper objectives of the hole. Cores 3H through 20H were oriented. All 20 piston cores fully stroked, but the core barrels for Cores 19H and 20H could not be pulled free with 80,000 pounds of overpull, and thus both were drilled over to release them from the sediment. The average recovery for the APC section was 102.8% (Table T1).

Ten XCB cores were taken over the interval from 188.7 to 276.8 mbsf (Cores 21X through 30X). A small sample of basalt was obtained in the last core, thus confirming basement contact. XCB coring deepened the hole 88.1 m and recovered 72.4 m (82.2% recovery). The total recovery of Hole 1218A was 266.4 m, representing 96.3% of the cored interval (Table T1).

Downhole Logging Operations (Hole 1218A)

To prepare Hole 1218A for logging, the drill string was pulled up to 78 mbsf and then lowered back to 277 mbsf. The hole was then displaced with 110 bbl of 8.9-lb/gal sepiolite mud, and the bit was placed at the logging depth of 85 mbsf. Logging rig-up operations began at 1130 hr on 16 November and, after some minor technical problems, were completed by 1645 hr. The triple combination (triple combo) tool was then run to the bottom of the hole (276.8 mbsf), and logging began at 2210 hr on 16 November.

Two passes were made with the triple combo tool in Schlumberger mode and a third pass in Lamont mode for multisensor gamma ray tool (MGT) data acquisition. Two passes were also made with the Formation MicroScanner-Sonic Velocity (FMS-Sonic) toolstring tool string. At the end of the second FMS-Sonic pass, the drill pipe was gradually withdrawn to a depth of 65 mbsf thus providing an extra 20 m of logged formation. In total, five logging runs were made with no bridges encountered, and the bottom of the hole was reached on all attempts. After logging operations, the

bit was pulled free of the seafloor at 1917 hr on 17 November and the vessel offset 20 m north of Hole 1218A.

Hole 1218B

In order to obtain a good stratigraphic overlap with cores from the first hole, the spud-in position for Hole 1218B was 3 m shallower than for Hole 1218A. Hole 1218B was spudded with the APC at 2050 hr on 17 November. Eighteen piston cores were obtained over the interval from 0 to 165.40 mbsf with orientation beginning on Core 3H. The average APC recovery was 102.1%. Heat flow measurements were obtained at 32.4 mbsf (Core 4H), 60.9 mbsf (Core 7H), 89.4 mbsf (Core 10H), and 108.4 mbsf (Core 12H). Following APC operations, 11 XCB cores were collected over the interval from 165.40 to 263.50 mbsf with an average recovery of 92.2%. Core 25X was drilled only 5 m instead of the usual 9.6 m in order to maintain a good stratigraphic overlap with cores from Hole 1218A. The total recovery of the hole was 259.25 m representing 98.4% of the cored interval.

Hole 1218C

Once the bit cleared the seafloor at 1654 hr on 19 November, the vessel was moved another 20 m north, and Hole 1218C was spudded at 1735 hr. The coring objective for the third hole was to fill the gaps in the compiled stratigraphic record of the first two holes. The hole was washed ahead to 55 mbsf and then piston cored to 163.5 mbsf. The average recovery from the 11 piston cores was 103.4%. All the cores were oriented. It was necessary to drill from 140.5 to 144.5 mbsf to maintain the required overlap with cores from Holes 1218A and 1218B. Heat flow measurements were made at 83.5 mbsf (Core 3H), 102.5 mbsf (Core 5H), and 121.5 mbsf (Core 7H).

After APC coring operations ceased, the hole was deepened with 10 XCB cores to a total depth of 256.8 mbsf (Table T1). The interval from 220.0 to 223.0 was drilled to maintain stratigraphic overlap with the cores from Holes 1218A and 1218B. XCB operations resulted in 90.3 m cored with 99.7% recovery. The total for the hole was 194.8 m cored and 198.05 m recovered (101.7%).

After drilling operations ceased, drilling equipment was secured, and the beacon was successfully recovered. The transit to the next site began at 1300 hr on 21 November.

Site 1219

Transit to Site 1219 (PAT-17C)

The 398-nmi voyage to proposed Site PAT-17C was accomplished in 36.0 hr at an average speed of 11.1 kt. After the vessel slowed to 5 kt at 0100 hr on 23 November, a short 3.5-kHz survey was made from east to west across the site. Upon conclusion of the 1-hr survey, the vessel came about and returned to site as the thrusters were lowered and the DPS was activated. The GPS receiver interface to the DPS was employed to situate the vessel over the coordinates of the new location by 0200 hr. A beacon was deployed at 0300 hr. The corrected PDR depth was 5084.4 mbrf.

Hole 1219A

After the drill string was deployed to a depth of 5071 mbrf, the driller further lowered the bit until the heave compensator appeared to activate, suggesting contact with a firm seafloor. The contact was at a bit depth of ~5075 mbrf. Hole 1219A was then spudded with the APC at 1200 hr, on 23

November, with the bit at 5071.0 mbrf. The seafloor depth indicated by the recovery of the initial core was 5074.5 mbrf. This depth was 9.9 m deeper than the PDR depth.

Hole 1219A was deepened to 224.5 mbsf with the APC before the XCB was deployed to accomplish the deeper objectives of the hole. Orientation began with Core 3H. All 24 piston cores were fully stroked events, but six core barrels (Cores 18H and Cores 20H through 24H) could not be pulled free of the sediment even with 80,000 pounds of overpull. The core barrels had to be drilled over to release them from the sediment. The active heave compensator (AHC) was engaged during drill-over operations for the majority of these cores. The average recovery in the APC section was 103.7% (Table T1).

XCB coring (Cores 25X through 27X) deepened the hole from 244.5 to 250.8 mbsf. A small sample of basalt was obtained in the last core confirming basement contact. XCB coring advanced 26.3 m and recovered 7.67 m (29.2%). The total recovery of Hole 1219B was 240.41 m representing 95.9% of the cored interval (Table T1).

Downhole Logging, Hole 1219A

To prepare the hole for logging, the drill string was pulled to 80.5 mbsf and then lowered back to 250.8 mbsf. The hole was then displaced with 100 bbl of 8.9-lb/gal sepiolite mud and the bit was placed at the logging depth of 83.3 mbsf. Logging then began at 1530 hr on 25 November.

The triple combo configuration with the MGT was deployed first. Two passes were made with the triple combo tool in Schlumberger mode followed by two passes in Lamont mode for MGT data acquisition. The triple combo configuration was followed by two passes of the FMS-Sonic toolstring. In all, six passes were made with no bridges encountered and the bottom of the hole was reached on all passes. Logging operations were completed by 1200 hr on 26 November.

Hole 1219B

After logging operations were completed, the bit was pulled free of the seafloor at 1230 hr on 26 November and the vessel was offset 20 m north of Hole 1219A. Hole 1219B was spudded with the APC at 1330 hr on 26 November. In order to obtain a good stratigraphic overlap with results from the first hole, Hole 1219B was drilled to 21 mbsf before piston coring was initiated. The plan for this hole was to deepen it with APC/XCB coring to ~240 mbsf. This depth objective was thwarted when the core barrel containing Core 16H could not be retrieved with the wireline. The piston core was fully-stroked and was pulled free of the sediment with a moderate amount of overpull (60 klb). However, the core barrel jammed in the BHA and could not be recovered in a routine manner. The Kinley Cutter was used to sever the wireline, after which the drill string and BHA, with the core barrel and Tensor tool, were recovered.

In light of the operational difficulties in Hole 1219B and the successes of both Hole 1219A and Site 1218, the shipboard party made a collective decision to abandon Site 1219 earlier than planned. This decision was made in order to target additional and more complete programs at forthcoming sites having lower and middle Eocene objectives. The vessel departed for the next site (PAT-9D) at 0445 hr on 27 November.

Sixteen piston cores were recovered at Hole 1219B with orientation starting on Core 1H. Heat flow measurements were obtained at 49.5 mbsf (Core 4H), 78.0 mbsf (Core 7H), and 116.0 mbsf (Core 11H). The average recovery in the Hole 1219B cores was 101.1% (Table T1).

Site 1220

Transit to Site 1220 (PAT-9D)

The 149-nmi voyage to proposed Site PAT-9D was accomplished in 13.3 hr at an average speed of 11.2 kt. At 1800 hr on 28 November, the vessel slowed to 5 kt and a short 3.5-kHz survey was made from east to west across the site. Upon conclusion of the 1-hr survey, the vessel came about and returned to site as the thrusters were lowered and the DPS was activated. The GPS receiver interface to the DPS was employed to situate the vessel over the coordinates of the new location by 1915 hr. A beacon was deployed at 2006 hr. The corrected PDR depth was 5234.4 mbrf.

Hole 1220A

After the drill string was deployed to a depth of 5215 mbrf, the driller lowered the bit until the heave compensator appeared to activate, suggesting contact with a firm seafloor. The contact was at a bit depth of ~5233 mbrf. Hole 1220A was spudded with the APC at 0500 hr on 29 November with the bit at 5229.0 mbrf. The seafloor depth that was indicated by the recovery of the initial core was 5229.1 mbrf. This depth was 5.3 m shallower than the PDR depth. Piston coring advanced routinely to 95.0 mbsf (Cores 1H through 10H) with excellent recovery (Table T1). Cores were oriented starting with Core 3H.

During the process of obtaining Core 11H, the overshot shear pin parted and the Tensor tool was recovered without the core barrel. The Tensor tool was set aside, and a second wireline trip with the sinker bars was made to retrieve the core barrel. Upon retrieval, the core barrel was momentarily stuck but quickly came free and was recovered. Core 12H was taken in the customary manner with a full bleed-off of pressure, indicating a full stroke. The sinker bars and Tensor tool were retrieved by the wireline but without the core barrel. The Tensor tool was laid down and the wireline jars were deployed to recover the core barrel. The core barrel could not be released by alternately applying overpull and upward impacts with the wireline jars. The effort was given up after 45 min, the overshot shear pin was intentionally parted, and the wireline was recovered. The drill string was then retrieved and the hole was terminated.

APC operations in Hole 1220A resulted in 114.0 m cored with 118.7 m recovered (average recovery of 104.1%).

Hole 1220B

After the BHA was redeployed, the vessel was offset 20 m west of Hole 1220A in preparation for the spudding of Hole 1220B. The drill string was deployed to a depth of 5215.5 mbrf, and Hole 1220B was spudded at 2215 hr on 30 November. After the bit was drilled to 34.0 mbsf, APC operations were initiated and the hole was deepened to 152.0 mbsf. The interval from 62.5 to 64.5 mbsf was drilled to maintain an appropriate stratigraphic overlap with Hole 1220A. The cored interval was 116.0 m with 126.8 m recovered (109.3% recovery). All piston cores were oriented. The Adara temperature tool was deployed at 53.0 mbsf (Core 2H), 83.5 mbsf (5H), and 102.5 mbsf (7H). The developmental methane tool (APCM) was deployed and appeared to have successfully obtained data.

Hole 1220B was deepened from 152.0 to 202.0 mbsf with XCB coring (Table T1) and penetrated basaltic basement with the last core (Core 20X). XCB operations deepened the hole 50.0 m and

recovered 17.8 m of sediment (35.6% recovery). The total recovery for the hole was 144.7 m, representing 87.1% of the cored interval.

Hole 1220B was terminated when the bit cleared the seafloor at 1530 hr on 2 December. The vessel was then offset 20 m west of Hole 1220B.

Hole 1220C

Hole 1220C was spudded at 1600 hr on 2 December. After the bit was drilled to 25.0 mbsf, one piston core was obtained spanning the O/M boundary (25.0–34.5 mbsf). The hole was then drilled from 34.5 to 60.0 mbsf, where continuous piston coring was initiated and the hole advanced to 145.5 mbsf. The APC cored interval was 95.0 m with 98.0 m recovered (103.2% recovery) (Table T1). All APC cores were oriented. Hole 1220C was deepened from 145.5 to 204.1 mbsf with XCB coring operations. Basaltic basement was reached with the last core (Core 17X). The XCB cored interval was 58.6 m with 18.13 m recovered (30.9%). The total recovery for the hole was 153.6 m, representing 75.6% of the cored interval (Table T1).

Following the end of coring operations in Hole 1220C, the drill string was pulled to the deck, the beacon was retrieved, and the drilling equipment, hydrophones, and thrusters were secured. The vessel departed location at 0930 hr on 4 December.

Site 1221

Transit to Site 1221 (PAT-10B)

The 144 nmi transit to proposed Site PAT-10B was accomplished in 17.0 hr at an average speed of 8.5 kt. The vessel did not proceed directly to PAT-10B because of strong winds (27–31 kt) and wind-driven seas (combined sea and swell >6 m). To avoid heavy pounding, the vessel pursued a course at a reduced speed that exposed the starboard quarter to the elements for most of the transit. The second half of the dogleg track required the vessel to steer almost directly into the seas. The vessel motion was moderate with maximum pitch and heave values measured at 6°. The modified track added 33 nmi to the transit.

At 0230 hr on 5 December, the vessel slowed to 4 kt, and a short 3.5-kHz survey was made from east to west across the site. Upon conclusion of the 42-min survey, the vessel came about and returned to site as the thrusters were lowered and the DPS was activated. The GPS receiver interface to the DPS was employed to situate the vessel over the coordinates of the new location by 0315 hr. A beacon was deployed at 0425 hr. The corrected PDR depth was 5197.4 mbrf.

Hole 1221A

After the drill string was deployed to a depth of 5157 mbrf, the driller lowered the bit until the heave compensator appeared to activate, suggesting contact with a firm seafloor. Hole 1221A was spudded with the APC at 1425 hr on 5 December. The seafloor depth that was indicated by the recovery of the initial core was 5186.6 mbrf. This depth was 10.8 m shallower than the PDR depth.

Piston coring in Hole 1221A advanced to the APC refusal depth of 110.6 mbsf with an average recovery of 102.8% (Table T1). Core orientation began with Core 3H. During piston coring, the heave of the vessel frequently exceeded 5 m and compromised the quality and recovery of the core. It was also difficult to land the APC assembly in the BHA without parting the overshot shear pin. Because of the excessive vessel motion combined with the deep water, it was also difficult to

ascertain whether the APC actually fired or was hydraulically pushed into the sediment after the shear pin parted during landing.

XCB operations began with Core 13X, and the interval from 110.5 to 115.6 mbsf was cored in 15 min. Most of the rotating time was consumed penetrating the first 2 m of this interval. Upon retrieval of the core, the core barrel became stuck in the BHA. Efforts to recover the core barrel by alternately applying overpull and upward impacts with the wireline jars were given up after 40 min. The overshot shear pin was intentionally parted, and the wireline recovered. The drill string was pulled out of the hole and tripped to a depth of 3572 m, where another attempt was made to recover the stuck core barrel. This effort was unsuccessful. The BHA reached the rig floor at 0215 hr on 7 December, and the core barrel was removed. Only 0.14 m of chert fragments were salvaged from the core catcher.

A fresh bit seal and lockable float valve were installed, and the BHA was redeployed. Concurrently, the vessel was offset 20 m south of Hole 1221A in preparation for spudding Hole 1221B.

Hole 1221B

Hole 1221B operations were designed to retrieve two cores near the mudline in an interval that contained the E/O boundary. Hole 1221B was spudded with the APC at 1400 hr on 7 December and advanced to 14.2 mbsf (two cores) with 102.3% recovery. The estimated seafloor depth that was calculated from the recovery of the first core was 5186.4 mbrf. The bit cleared the seafloor at 1505 hr on 7 December.

Hole 1221C

Hole 1221C was spudded with the APC at 1640 hr on 7 December, and the estimated seafloor depth that was calculated from the recovery of the first core was 5185.7 mbrf. This hole was spot cored (five cores) with the APC to a depth of 102.5 mbsf to recover material missed in Hole 1221A. The cored interval was 45.4 m with an average recovery of 96.3% (Table T1). The last three cores were oriented.

XCB coring (Cores 6X through 12X) deepened the hole from 102.5 mbsf to a basement contact at 157.3 mbsf. Abundant chert stringers adversely affected recovery. The average recovery over the 45.4 m cored interval was 43.7%. Upon completion of Hole 1221C, the bit was pulled to the seafloor at 1530 hr on 8 December. The vessel was then offset 20 m south in order to spud the last hole.

Hole 1221D

Hole 1221D plans were to drill ahead (in the interest of time) to 132.0 mbsf and then core to basement in the hope of recovery a second P/E boundary at this site. Hole 1221D was spudded with the XCB and a center bit at 1715 hr. After drilling ahead to 132 mbsf, the center bit was recovered and an XCB barrel was deployed. XCB coring advanced from 132.0 to 156.0 mbsf (Table T1). The interval from 144.8 to 151.0 mbsf was drilled ahead with a center bit to reduce penetration time. Basement contact was confirmed by the recovery of the basalt in the last core. The cored interval was 17.8 mbsf with 2.28% recovery. The drilled interval was 138.2 m.

After recovering the drill string, the vessel departed for the last site of the leg at 2100 hr on 9 December.

Site 1222

Transit to Site 1222 (PAT-12C)

The 107-nmi voyage to proposed Site PAT-12C was accomplished in 10.5 hr at an average speed of 10.2 kt. The vessel proceeded directly to the site without conducting a survey. The GPS receiver interface to the DPS was employed to situate the vessel over the coordinates of the new location by 0745 hr on 10 December. A beacon was deployed at 0845 hr. The corrected PDR depth was 5009.4 mbrf.

Hole 1222A

After the drill string was deployed to a depth of 4955 mbrf, the driller lowered the bit until the heave compensator appeared to activate, suggesting contact with a firm seafloor at ~5001 mbrf. The drill string was then picked up 5 m to position the bit at a depth of 4996 mbrf. Hole 1222A was spudded with the APC at 1815 hr on 10 December. The seafloor depth indicated by the recovery of the initial core was 5000.1 mbrf, 8.4 m shallower than the PDR depth.

Piston coring in Hole 1222A advanced to an APC refusal depth of 71.9 mbsf with an average recovery of 102.9% (Table T1). Orientation began with Core 3H. The hole was further deepened with four XCB cores until basement contact at a depth of 107.3 mbsf. The average recovery for the 35.4 m XCB cored section was 1.8%.

Hole 1222B

After coring operations were completed in Hole 1222A, the drill pipe was pulled out of the hole, and after the bit cleared the seafloor at 1735 hr on 11 December, the vessel was offset 20 east of Hole 1222A. Hole 1222B was spudded with the APC at 1910 hr, and coring advanced to refusal depth (64.4 mbsf; Table T1). As Core 7H was brought on deck, the time allotted for coring expired. The average recovery for the hole was 99.0%. Orientation started with Core 3H.

After coring operations ceased in Hole 1222B, the drill string was recovered, the BHA was disassembled into component parts and secured into the drill collar bays. During the recovery of the drill string, the beacon was successfully recalled. After the drilling equipment was secured, the drilling crew spent 1 hr cutting and slipping of the drilling line. The vessel departed for Honolulu at 1730 hr on 12 December.

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TABLE CAPTIONS

Table T1. Hole summary, Leg 199.

Table T2. Stratigraphic control around the Eocene/Oligocene boundary.

FIGURE CAPTIONS

Figure F1. Map of the central tropical Pacific showing (A) Leg 199 drill sites and DSDP drill sites in the region superimposed on bathymetry and (B) Leg 199 drill sites superimposed on the approximate position of magnetic Anomaly C25n (58.9–56.4 Ma), the target crust for the 56-Ma transect.

Figure F2. Chlorophyll contents in the Pacific equatorial region, from SeaWiFS satellite, September 1997–July 1998 composite. The high-productivity band along the equator is constrained to its position by ocean physics. Red = highest chlorophyll contents, dark purple = lowest chlorophyll.

Figure F3. Position and thickness of the equatorial sediment bulge in the equatorial Pacific Ocean. The thickest pile of sediments is displaced from the equator by the northwestward movement of the Pacific plate. Because of Pacific plate movement, Paleogene equatorial sediments lie beneath a relatively thin Neogene sediment column.

Figure F4. Sites along the 56-Ma Leg 199 transect, superimposed on model estimates of upwelling from a new early Eocene coupled ocean-atmosphere climate model. Lines with arrows = current streamlines at the approximate depth of the thermocline. Compare the upwelling pattern in this model with the chlorophyll distribution in Figure F2, an indicator of modern upwelling.

Figure F5. Compilation of benthic oxygen isotope data for the Cenozoic (Zachos et al., 2001a). Also shown is the time window investigated during ODP Leg 199 and the position of three major events targeted by the leg. P-E marks the position of the Paleocene/Eocene boundary and its associated thermal event. Oi-1 is approximately at the Eocene/Oligocene boundary and marks the first major Antarctic glaciation. Mi-1 is near the Oligocene/Miocene boundary and marks the beginning of the development of the Neogene cryosphere.

Figure F6. Lithologic summary for Leg 199. Individual units at each site are correlated to each other. The abundance of carbonate ooze in the Oligocene–upper Miocene sequence at Site 1218 suggests this site was above the CCD after the late Eocene. O/M = Oligocene/Miocene boundary, E/O = Eocene/Oligocene boundary.

Figure F7. LAS (300–2500 nm) determined concentrations for smectite and illite vs. depth for sites that contained an illite to smectite transition.

Figure F8. Illite–smectite transition plotted as a function of age and latitude. The transition most likely tracks the paleoposition of the ITCZ because it marks the switch from Asian dust sources (illite rich) to American sources (smectite rich).

Figure F9. Lithologic columns for Sites 1218, 1219, 1220 and 1221 showing where diatoms are common to abundant (>10% based on smear slide analysis). Diatoms are a significant constituent of sediments from all the southern sites during the RP15 radiolarian zone (upper middle Eocene). RP19 and 20 (basal Oligocene) is diatom rich, with the exception of Site 1219. At Site 1219, a pronounced peak in diatom abundance is found in upper Oligocene sediments. O/M = Oligocene/Miocene boundary, E/O = Eocene/Oligocene boundary, P/E = Paleocene/Eocene boundary.

Figure F10. Composite digital photographs of the late Eocene “pentachert” interval of Site 1218 plotted against gamma ray attenuation (GRA) bulk density (uncleaned data) in Sections 199-1218A-25X-1 and 25X-2, 199-1218B-25X-1, and 199-1218C-18X-3 and 18X-4. Five chert layers of early Paleocene age were recovered intact and can be observed through all holes drilled at Site 1218. The contacts of the radiolarite of Unit III and these lithified chert layers are gradational. More of these intact chert layers were observed in Cores 199-1218A-27X and 199-1218C-18X, 19X, and 20X.

Figure F11. Composite digital photographs of cores taken across the E/O boundary at Site 1218 using the shipboard GEOTEK digital imaging system. At Site 1218 (shallowest 42-Ma crust) it is clear that the Eocene–Oligocene carbonate transition is a two-step process. At Site 1219 (deeper 55-Ma crust) only one step can be observed.

Figure F12. A. Subsidence history of nonequatorial Leg 199 sites (1215, 1217, and 1221). Estimated calcite compensation depth (CCD) based on presence/absence of carbonate is also shown.

B. Subsidence history of equatorial Leg 199 sites (1218, 1219, and 1220). The estimated CCD based on presence/absence of carbonate is also shown.

Figure F13. Relative position of the paleoequator for the middle Eocene and late Oligocene based on data from Sites 1218, 1219, and 1220. The main oceanic magnetic anomalies as well as the major fracture zone are shown in blue. For each site, we have computed a mean declination and inclination for two different intervals, 26 and 39 Ma. Mean sites declination (less accurately oriented) have then been adjusted for the expected paleomagnetic pole for the Pacific plate of the appropriate age. The map was constructed using GMAP32 (Torsvik and Smethrust, 1989–1997).

Figure F14. Inferred paleolatitudes for Sites 1218, 1219, and 1220 based on mean paleomagnetic inclinations, using the dipole formula. Error bars represent the maximum difference obtained from different holes around their mean. Site 1218 has not produced data older than the Oligocene. Notice that Site 1219 crosses the equator much later than Site 1220. Data points at 0 Ma are the present-day latitudes of the studied sites.

Figure F15. Interstitial water profiles from Leg 199 sites. Profiles reflect the limited organic matter diagenesis and relatively high biogenic silica contents at these sites. Only Site 1219 has the “typical” Ca and Mg profile indicating an exchange of seawater Mg for basalt Ca during crustal alteration.

Figure F16. Shipboard ICP-OES analyses of sedimentary Si and Ca weight percent and mass accumulation rate (MARs). MAR is a product of sedimentation rate, elemental weight percent, and dry bulk density. Si largely represents biogenic silica, whereas Ca represents CaCO₃.

Figure F17. Summary of sedimentation rates derived from age-depth models at each of the Leg 199 drill sites. MAR is a product of sedimentation rate, elemental weight percent, and dry bulk density.

Figure F18. Shipboard ICP-OES analyses of sedimentary Al and P weight percent and mass accumulation rate (MARs). MAR is a product of sedimentation rate, elemental weight percent, and dry bulk density. Al represents detrital aluminosilicate deposition while P is delivered to the seafloor by primary productivity.

Figure F19. Si/Ti, Ba/Ti, and Al/Ti of Leg 199 sediments. Relatively constant Al/Ti suggests that the detrital sources had similar amounts of these elements. High Si/Ti reflects high biogenic opal deposition, whereas high Ba/Ti reflects high biogenic Ba burial.

Figure F20. Latitudinal transect of Si mass accumulation rate (MARs) for three time slices: early Oligocene (25–34 Ma), middle Eocene (38–45 Ma), and early Eocene (50–55 Ma). Si accumulation in the early Eocene is low and probably has a major contribution from detrital aluminosilicates. Middle Eocene Si accumulation is high, about double modern opal accumulation at the equivalent longitude. Early Oligocene Si accumulation resembles that of modern sediments (Lyle, 1992).

Figure F21. Latitudinal transect of Ca mass accumulation rate (MARs) for three time slices: early Oligocene (25–34 Ma), middle Eocene (38–45 Ma), and early Eocene (50–55 Ma). Ca MAR almost exclusively results from the deposition of CaCO₃. The early Oligocene pattern of Ca MAR is the only one that resembles the Neogene in both shape and magnitude. CaCO₃ is essentially absent from middle Eocene sediments along the 56-Ma transect but is present intermittently at the southern end of the transect. The early Eocene Ca MAR is about half of modern flux, and curiously, equatorial Ca MAR is significantly less than the off-axis flux.

Figure F22. Synthesis of magnetic stratigraphy from four Leg 199 drill sites. Depth scale in mcd is shown on the right of each column, and geographic coordinates are shown at the bottom of each column. Black = normal magnetic chrons, white = reversed magnetic chrons, gray = no polarity assignment possible. Crosses = intervals with no data, dashed lines = correlation between selected chrons to the GPTS (Cande and Kent, 1995).

Figure F23. Comparison of estimated ages of radiolarian zones (Sanfilippo and Nigrini, 1998) to age boundaries intercalibrated with magnetic reversal stratigraphy on Leg 199. Significant improvements of zone boundary ages have occurred because of Leg 199 shipboard studies.

Figure F24. Digital photograph of the record of the Oligocene–Miocene transition and Mi-1 glacial step at ODP Site 1218. Lithology and magnetic susceptibility records show the distinct cyclicity in carbonate content and physical properties observed around the O/M boundary. Together with unambiguous magnetostratigraphy and biostratigraphy, the cycle record contributes to the first high-resolution astronomical-calibrated chronology for the O/M boundary in the Pacific. Bioevents such as the first and last appearance datums of the clacareous nannofossil, *Sphenolithus delphix*, and the appearance datum of the foraminifer *Paragloborotalia kugleri* are identical within current resolution to these same events in the Atlantic Ocean. Hence, we have no doubt that the Site 1218 record will become a standard reference section for the Oligocene–Miocene interval in the Pacific that can be correlated precisely to Atlantic sites that typically lack unambiguous magnetostratigraphies.

Figure F25. MST, paleomagnetic, and biostratigraphic data from Site 1218 and Site 1219 plotted on a common timescale (developed mainly from paleomagnetic reversal datums that were composited from both sites after matching of lithologic cycles). Note the close correspondence between MST data from the two drill sites and calculated sedimentation rates. Biostratigraphic nannofossil datums and their uncertainty intervals agree well, whereas datums based on certain foraminifera do not agree. Gray-shaded boxes = ages of magnetic reversals (Cande and Kent, 1995). VGP = virtual geomagnetic pole. GRA = gamma ray attenuation.

Figure F26. Composite digital photographs showing the Eocene–Oligocene sequence at each site and composite gamma ray attenuation (GRA) bulk density, magnetic susceptibility, and color reflectance data. The lithologic change from carbonate-rich to carbonate-poor sediments is evident as a two-step decrease in GRA density and an increase in susceptibility at Site 1218.

Figure F27. Composite digital photographs of the E/O boundary during ODP Leg 199 using biostratigraphic (nannofossil and radiolarian) and magnetostratigraphic data. The position of the boundary (at the 33.7-Ma isochron) has been calculated through linear interpolation between paleomagnetic and/or biostratigraphic indications. E/O = Eocene/Oligocene boundary.

Figure F28. Composite digital photographs of the correlation and comparison of the E/O boundary sections recovered during Leg 199. At four of the five sites from which this interval was recovered, cores from Holes A, B, and C overlap to produce continuous complete sections. At Site 1219 only one hole penetrated the boundary, and a small coring gap is present in the section. Refer to Figure F27 for biostratigraphic datums. E/O = Eocene/Oligocene boundary.

Figure F29. Comparison of diatom events (>5% diatoms in the sediments) to estimated position of equator crossings in lower Oligocene–lower Eocene sediments from the 56-Ma transect. Equator crossings have been estimated by shipboard paleomagnetism and by using a fixed hotspot model of Pacific plate motion. Diatom events are not clustered at equator crossings. F.Z. = fracture zone.

Figure F30. Digital photographs of the P/E boundary sediments recovered at Sites 1220 and 1221. Lower Eocene calcareous chinks grade downcore into multicolored clay-rich lithologies. The last occurrence of Paleocene fauna is recorded at the base of the brown clay, and the first occurrence of Eocene assemblages is at the top of the dark brown clay. Calcareous fossils are barren to poorly preserved in the multicolored clay layers, and percentage CaCO₃ values are very low. FO = first occurrence, LO = last occurrence.

Figure F31. Digital photograph of the >63- μ m fraction of washed sample from across the P/E boundary. The following major grains are observed at each depth interval: Planktonic foraminifers (intervals 199-1220B-20X-2; 13–20, 28–35, 35–43, and 42–50 cm; 198.90–199.40 mbsf), pink brown grains and dolomite crystals (interval 199-1220B-20X-2; 50–57 cm; 199.40–199.47 mbsf), black grains and sediment lumps (interval 199-1220B-20X-2; 57–64.5 cm; 199.47–199.55 mbsf), large pinkish grains with many dolomite crystals (interval 199-1220B-20X-2; 65–72 cm; 199.55–199.62 mbsf), small pink brown grains with rare planktonic foraminifers and dolomite grains (interval 199-1220B-20X-2; 74–78 cm; 199.64–199.68 mbsf), and dolomite grains and rare benthic foraminifers (interval 199-1220B-20X-2; 77.5–85 and 85–95 cm; 199.68–199.85 mbsf).

Figure F32. Digital photograph of the stratigraphic distribution of benthic foraminifers in Section 199-1220B-20X-2 (198.90–199.85 mbsf). Red triangles at 199.68 mbsf = P/E boundary as represented by the benthic extinction event is shown by red triangles at 199.68 mbsf.

Figure F33. A. Composite digital photograph of shipboard ICP-OES analyses of Si, Al, Ti, Fe, and Mg on 2-cm bulk sediment scrapes across the Paleocene–Eocene (P/E) boundary from Sites 1220 and Sites 1221. Elevated concentrations of all these elements in the boundary interval reflect low CaCO₃. Different levels of elements through the interval reflect the distinct color bands.

Figure F33 (continued). B. Composite digital photograph of shipboard ICP-OES analyses of Ca, Sr, Ba, P, and Mn on 2-cm bulk sediment scrapes across the P/E boundary from Sites 1220 and Sites 1221. The difference in behavior between Ca and Sr reflects recrystallization. A strong Mn peak flanked by P and Ba peaks is characteristic of the boundary interval.

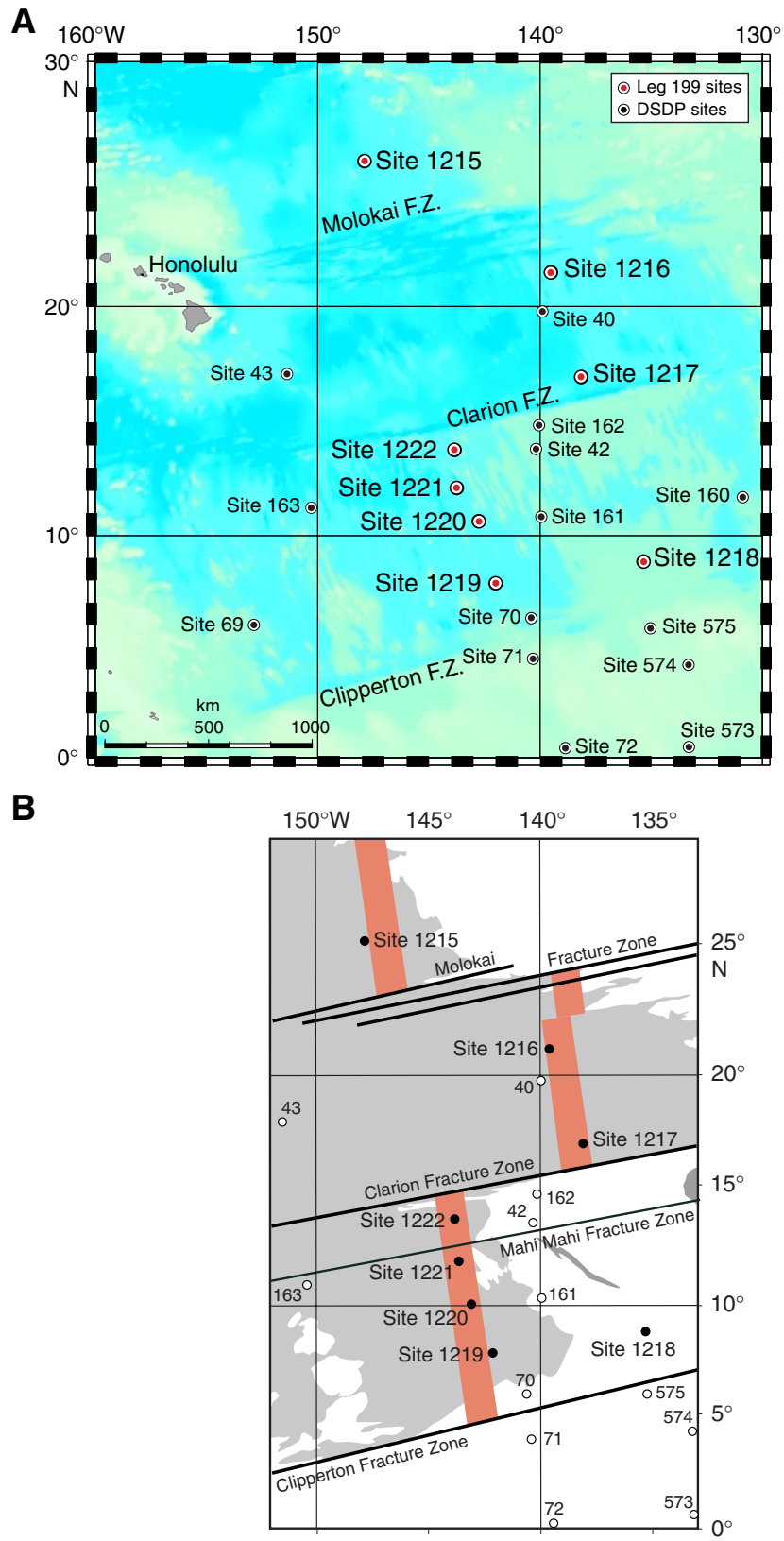
Table T1. Hole summary, Leg 199.

Hole	Latitude	Longitude	Water depth (m)	Number of cores	Interval cored (m)	Core recovered (m)	Recovery (%)	Interval drilled (m)	Time on hole (hr)	Time on hole (days)
1215A	26°01.7734'N	147°55.9906'W	5395.6	10	75.4	68.27	90.50	0	57.50	2.40
1215B	26°01.7626'N	147°55.9906'W	5395.3	11	82.8	58.95	71.20	0	32.00	1.30
		Site 1215 totals:		21	158.2	127.22	80.40	0	89.50	3.70
1216A	21°27.1629'N	139°28.7904'W	5152.5	11	62.2	56.47	90.80	0	31.00	1.30
1216B	21°27.1702'N	139°28.7859'W	5147.2	1	9.5	9.75	102.60	0	11.25	0.50
		Site 1216 totals:		12	71.7	66.22	92.40	0	42.25	1.80
1217A	16°52.0133'N	138°05.9981'W	5342.1	17	145.2	89.94	61.90	0	45.00	1.90
1217B	16°52.0175'N	138°06.0007'W	5342.1	7	66.5	61.49	92.50	20.0	15.00	0.60
1217C	16°52.0234'N	138°06.0012'W	5342.1	5	47.5	46.82	98.60	32.0	19.25	0.80
		Site 1217 totals:		29	259.2	198.25	76.50	52.0	79.25	3.30
1218A	08°53.3667'N	135°22.0002'W	4826.3	30	276.8	266.42	96.30	0	90.00	3.80
1218B	08°53.3777'N	135°21.9995'W	4827.6	29	263.5	259.25	98.40	0	45.65	1.90
1218C	08°53.3885'N	135°21.9997'W	4827.6	21	194.8	198.05	101.70	62.0	44.10	1.80
		Site 1218 totals:		80	735.1	723.72	98.50	62.0	179.75	7.50
1219A	7°48.0097'N	142°0.9390'W	5063.3	27	250.8	240.41	95.90	0	82.42	3.40
1219B	7°48.0186'N	142°0.9397'W	5063.3	15	137.0	138.55	101.20	21.0	40.33	1.70
		Site 1219 totals:		42	387.8	379.01	97.70	21.0	122.75	5.10
1220A	10°10.6008'N	142°45.4917'W	5217.9	12	114.0	118.68	104.10	0	37.75	1.60
1220B	10°10.6001'N	142°45.5028'W	5217.9	20	166.0	144.65	87.10	36.0	54.50	2.30
1220C	10°10.6002'N	142°45.5148'W	5217.9	17	153.6	116.12	75.60	50.5	42.00	1.80
		Site 1220 totals:		49	433.6	379.45	87.50	86.5	134.25	5.60
1221A	12°01.9987'N	143°41.6514'W	5175.3	13	115.6	113.81	98.50	0	47.00	2.00
1221B	12°01.9880'N	143°41.6524'W	5175.1	2	14.2	14.53	102.30	0	12.80	0.50
1221C	12°01.9873'N	143°41.6513'W	5175.1	12	100.2	54.07	54.00	57.1	24.42	1.00
1221D	12°01.9762'N	143°41.6519'W	5175.1	4	17.8	2.28	12.80	138.2	29.50	1.20
		Site 1221 totals:		31	247.8	184.69	74.50	195.3	113.72	4.70
1222A	13°48.9780'N	143°53.3477'W	4988.7	12	107.3	74.64	69.6	0	33.83	1.40
1222B	13°48.9776'N	143°53.3368'W	4990.7	7	64.4	63.77	99.0	0	23.92	1.00
		Site 1222 totals:		19	171.7	138.41	80.6	0	57.75	2.40
		Leg 199 totals:		283	2465.1	2196.92	89.1	416.8	819.30	34.10

Table T2. Stratigraphic control around the Eocene/Oligocene boundary.

Control points	Age (Ma)	Depth (mcd)	Accumulation (m/m.y.)	E/O depth (mcd)	E/O depth (mbsf)	E/O position in core
Site 1217						
Base C13n	33.545	29.88				
Top C15n	34.655	32.83	2.7	30.29	30.03	199-1217A-4H-5, 53 cm
Site 1218						
Top NP21	32.900	238.68				
Base NP21	34.000	245.03	5.8	243.30	219.84	199-1218C-17X-CC, 1 cm
Site 1219						
Base C13n	33.545	176.92				
Top C15n	34.655	182.84	5.3	177.75	152.42	199-1219A-17H-4, 58 cm
Base C16n.2n	36.341	190.99	4.8	177.67	152.34	199-1219A-17H-4, 50 cm
Site 1220						
Base C13n	33.545	76.97				
Top C15n	34.655	82.67	5.1	77.77	70.13	199-1220A-8H-3, 63 cm
Site 1221						
Base C13n	33.545	8.11				
Top C15n	34.655	10.65	2.3	8.46	9.02	199-1221A-1H-7, 2 cm

Notes: E/O = Eocene/Oligocene. The mcd and mbsf depths of the E/O boundary (set at 33.7 Ma) are extrapolated from the rates and datum points given in the Age, Depth, and Accumulation columns.



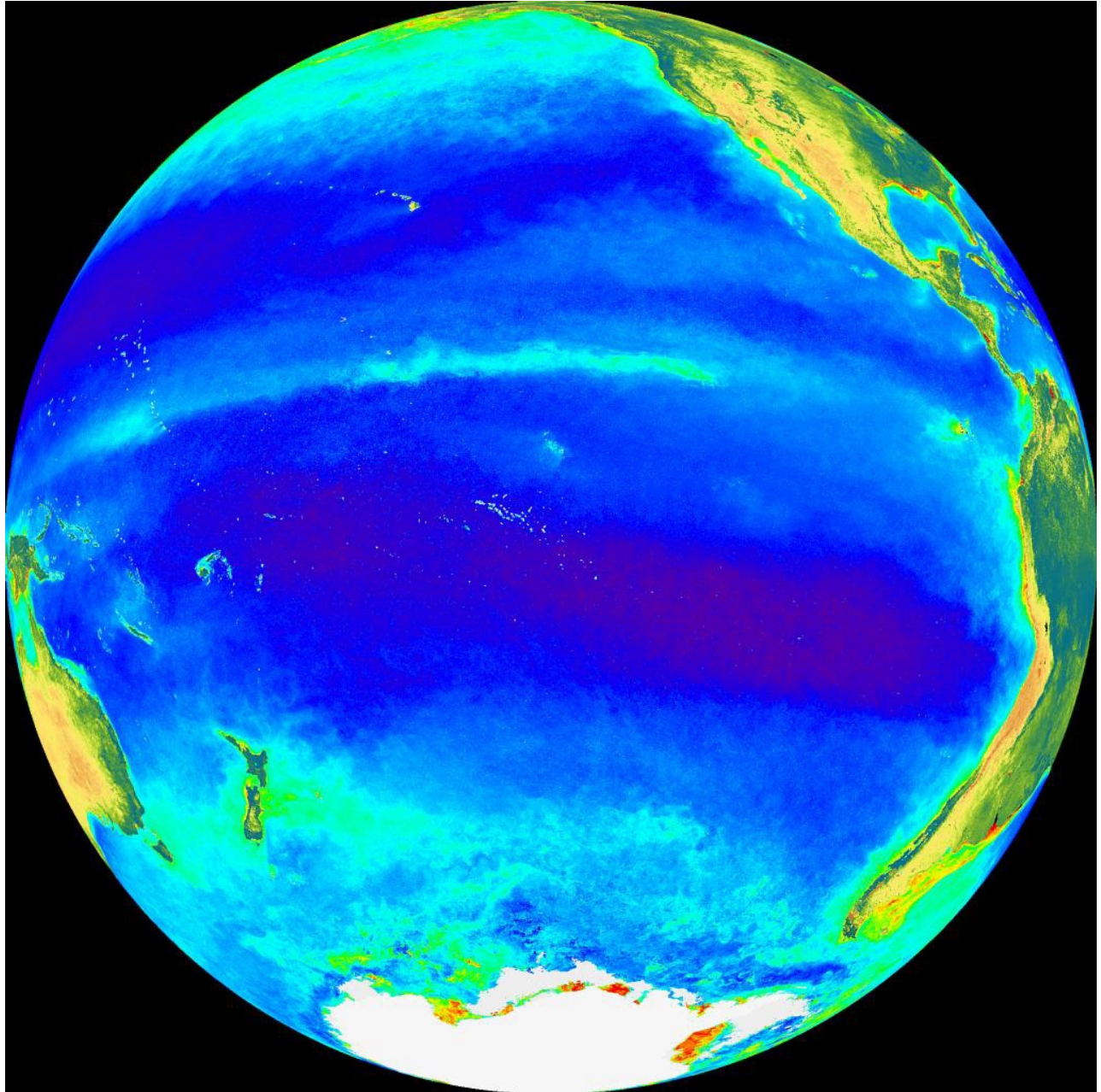


Figure F2

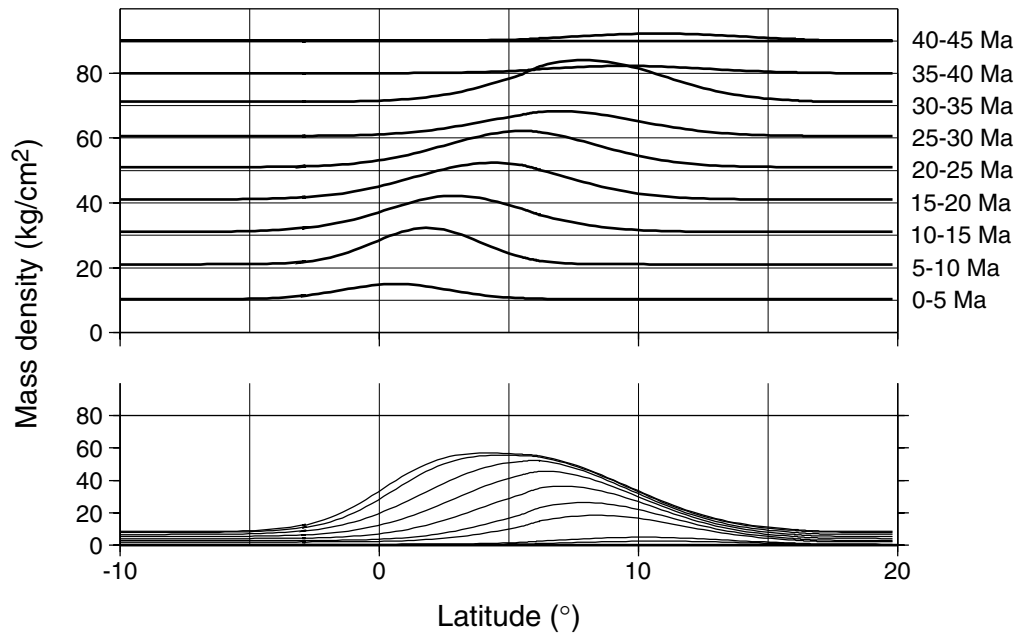


Figure F3

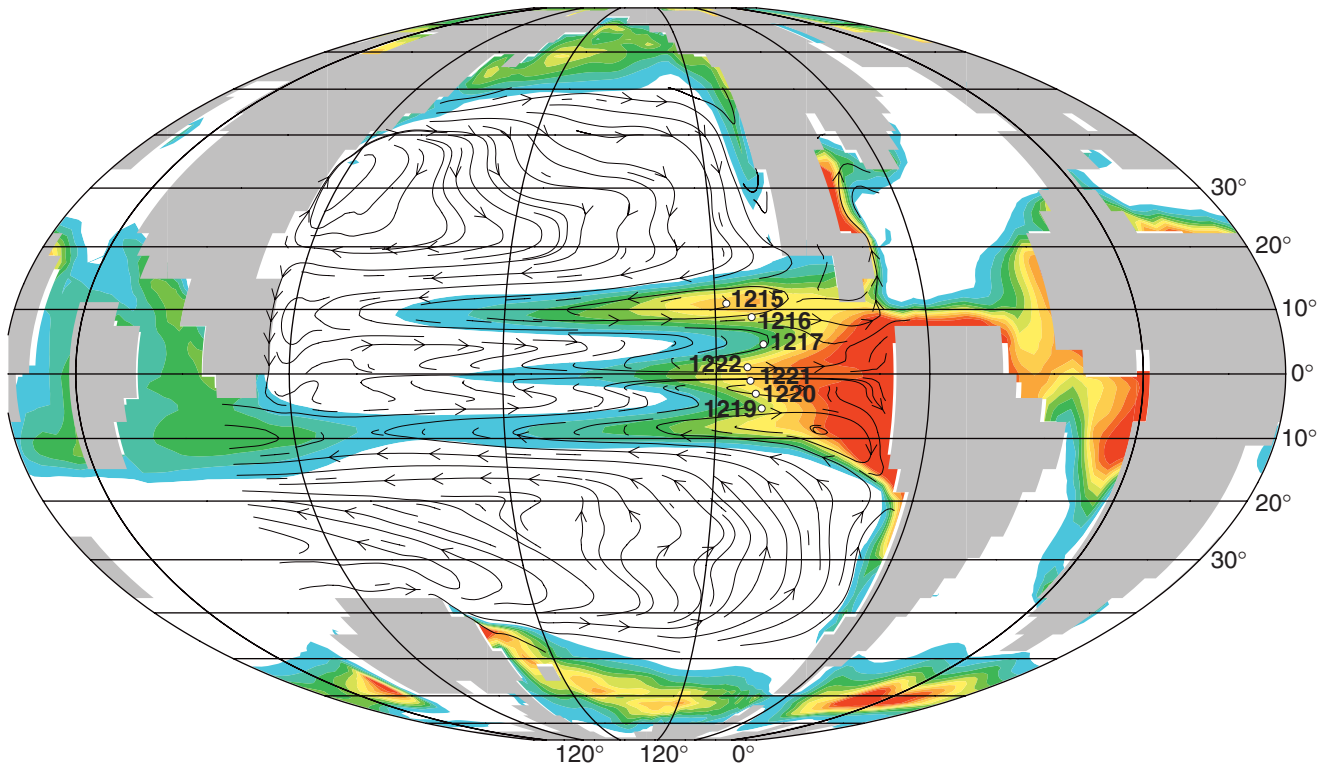


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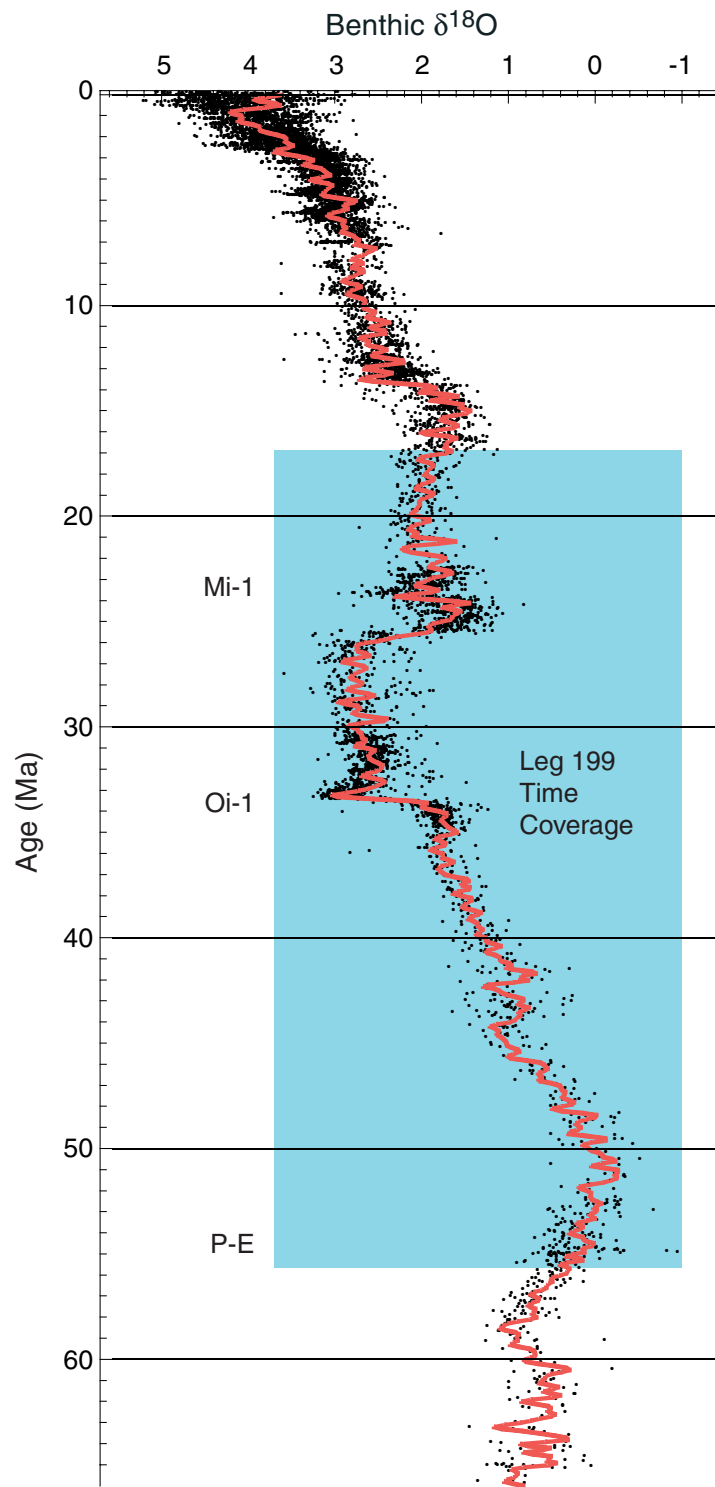


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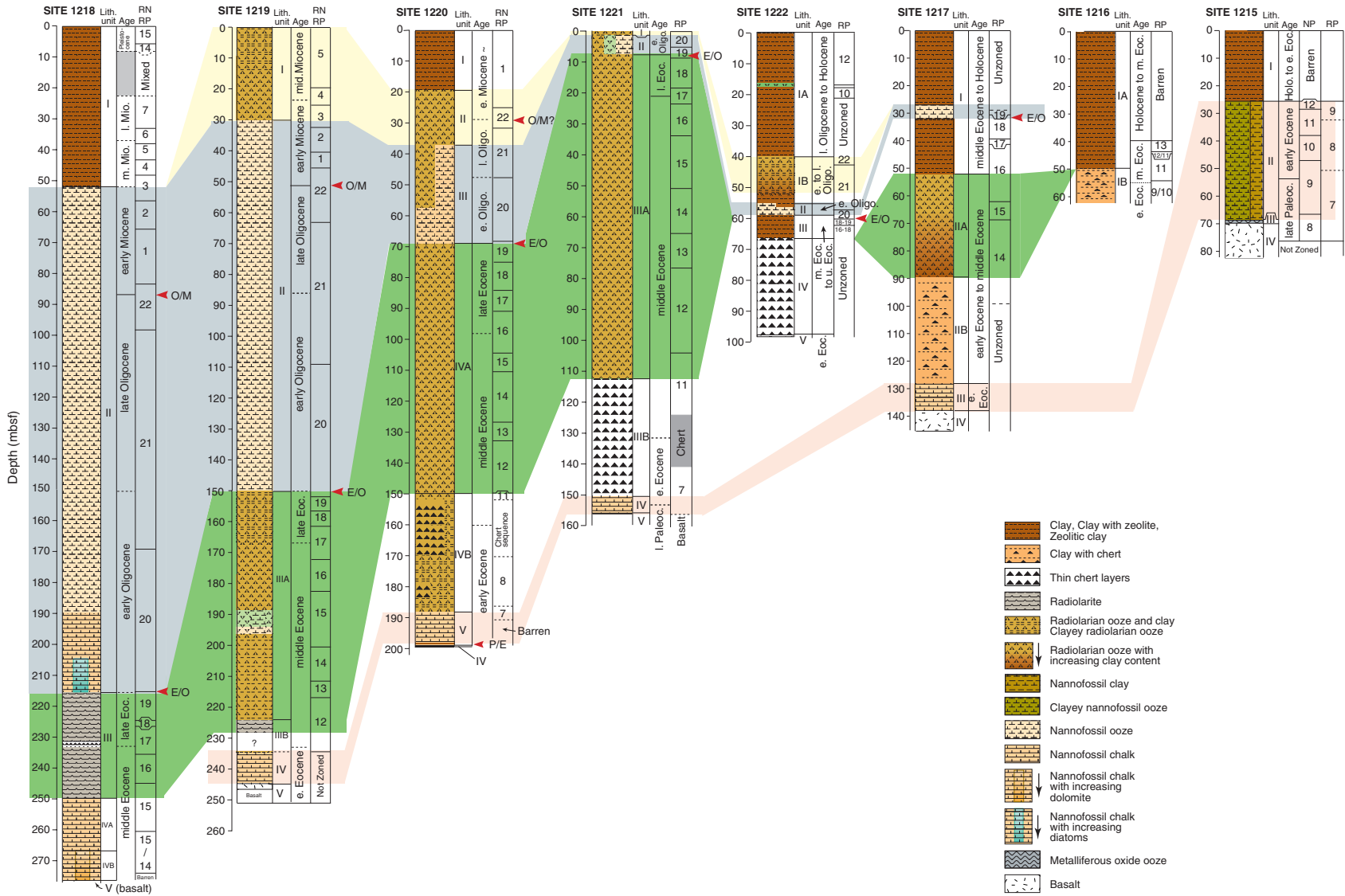


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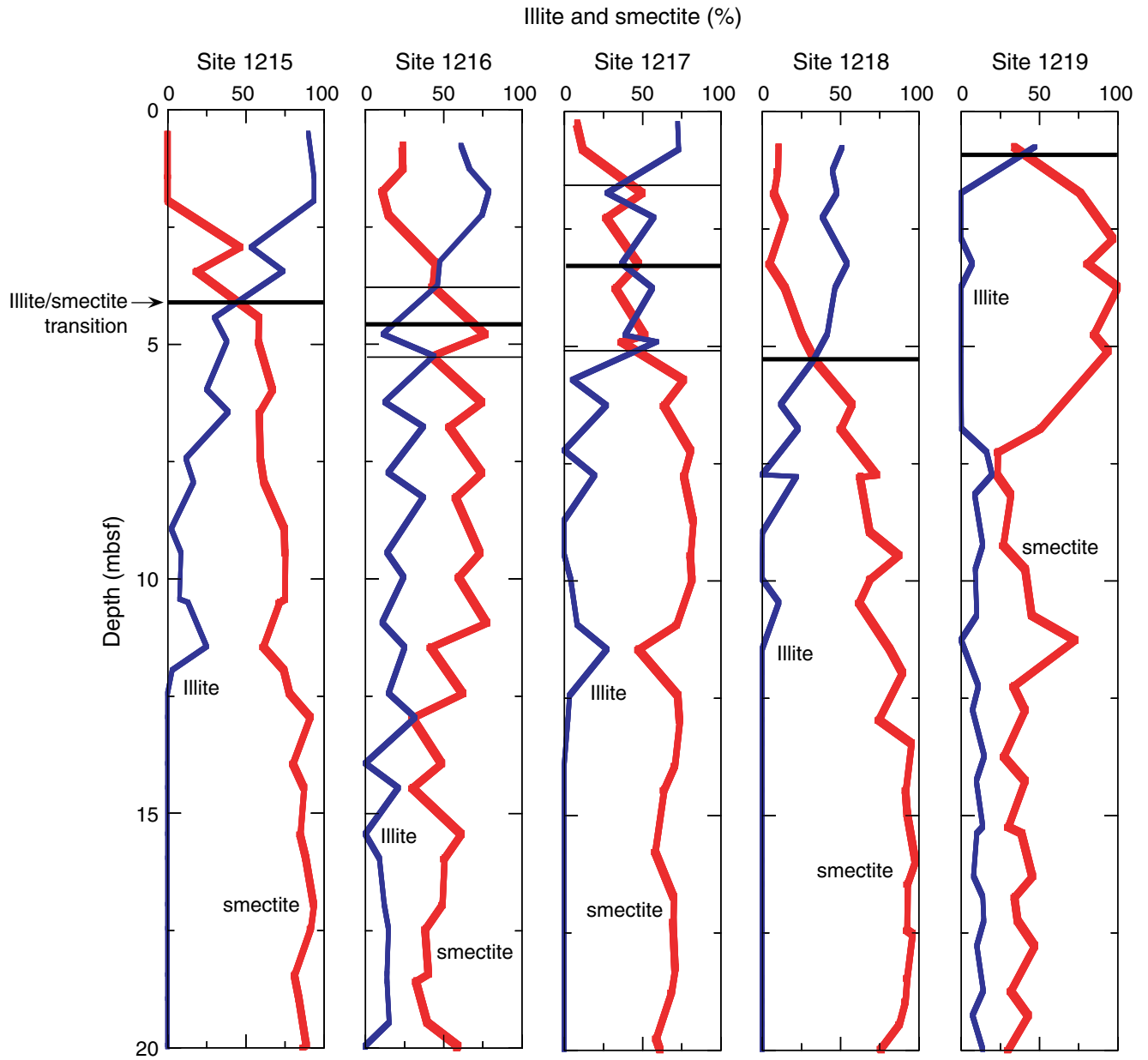


Figure F7

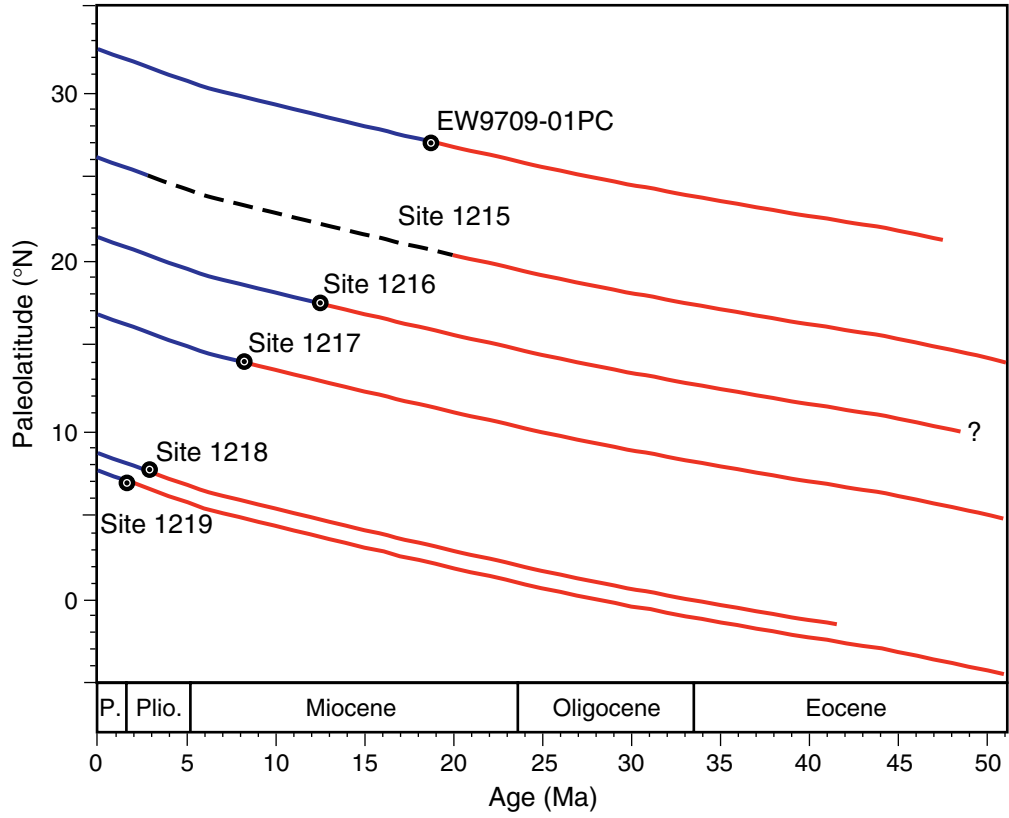


Figure F8

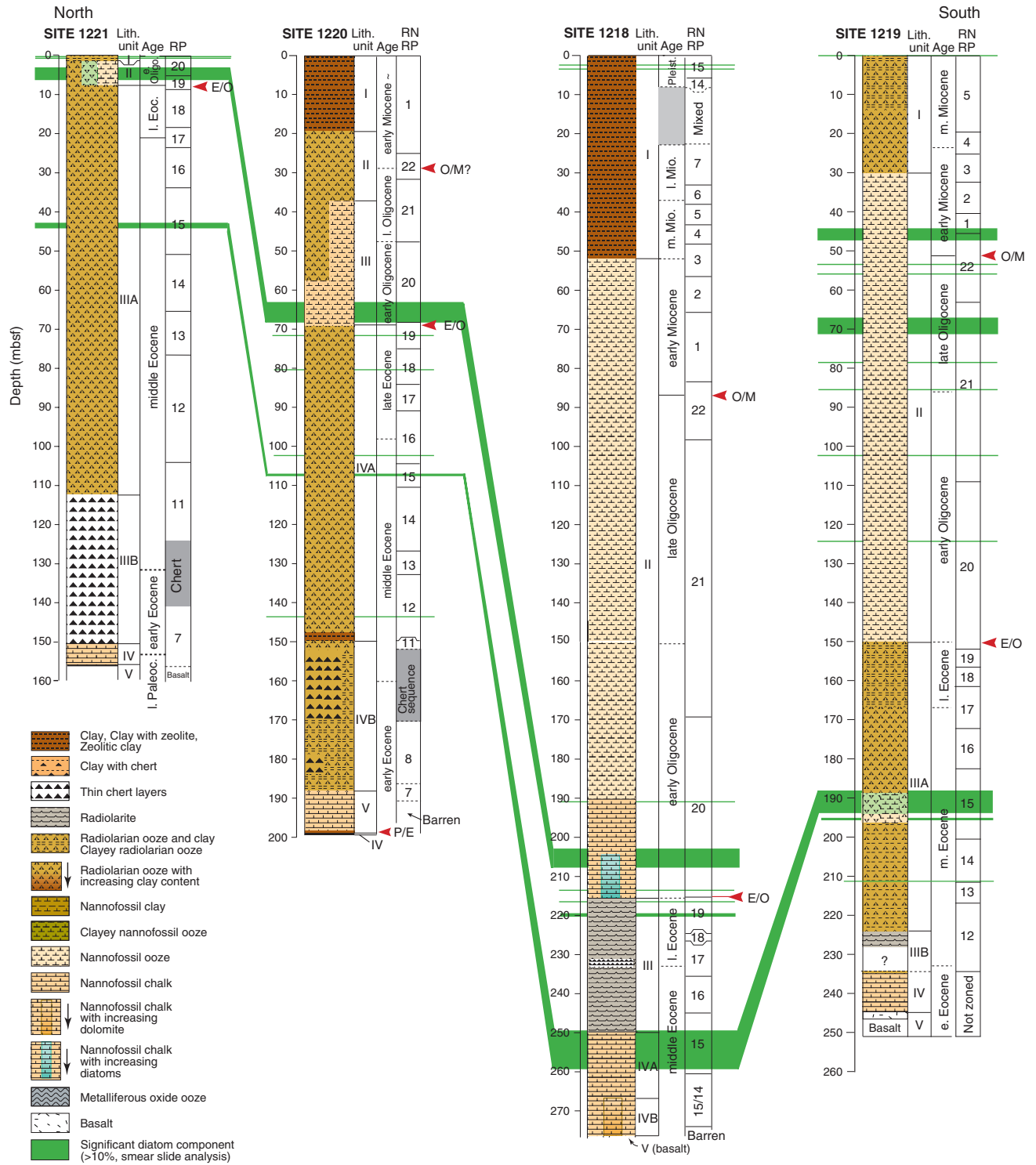


Figure F9

Site 1218
8.9°N, 135.4°W
4827.2 mbsl

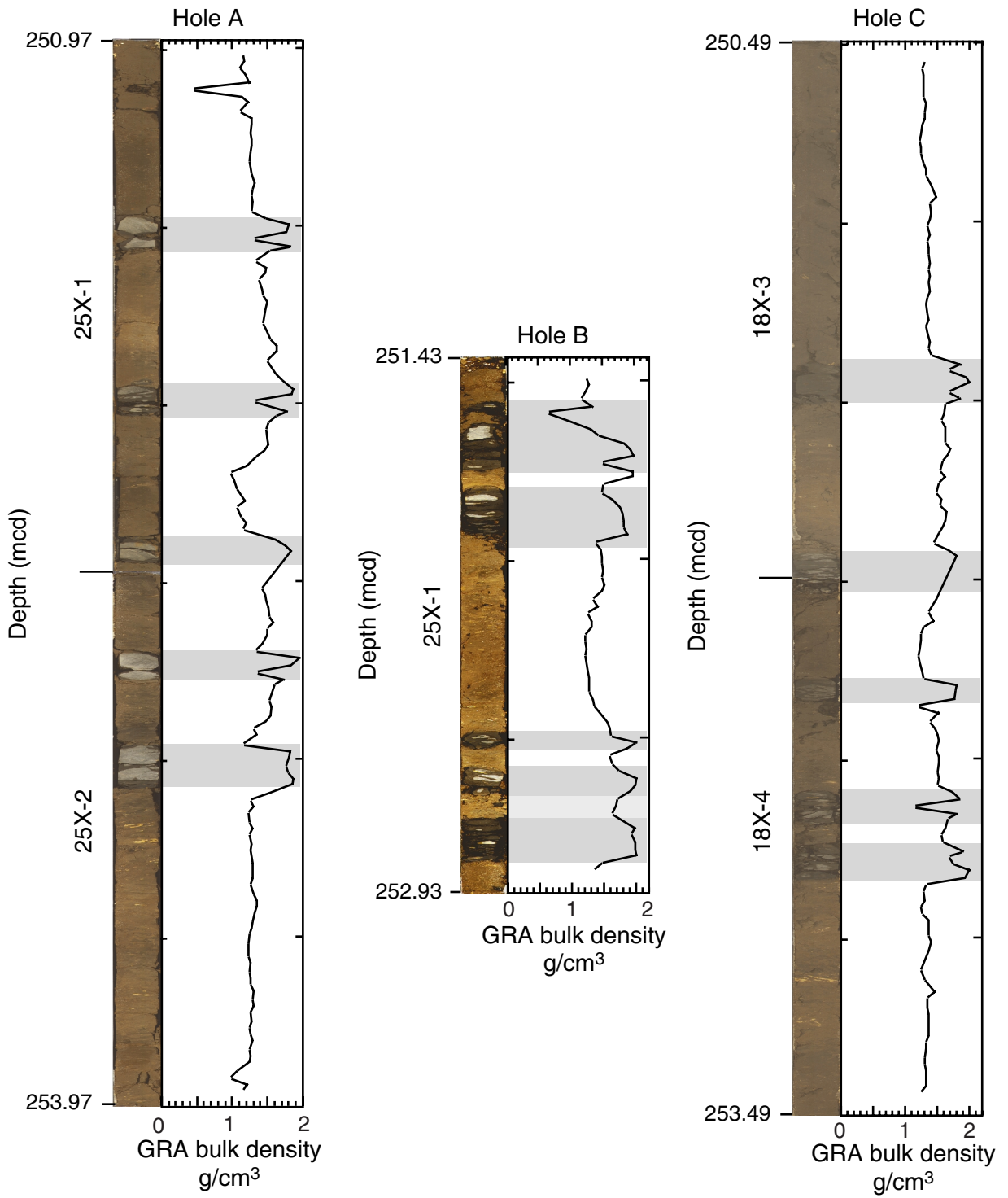


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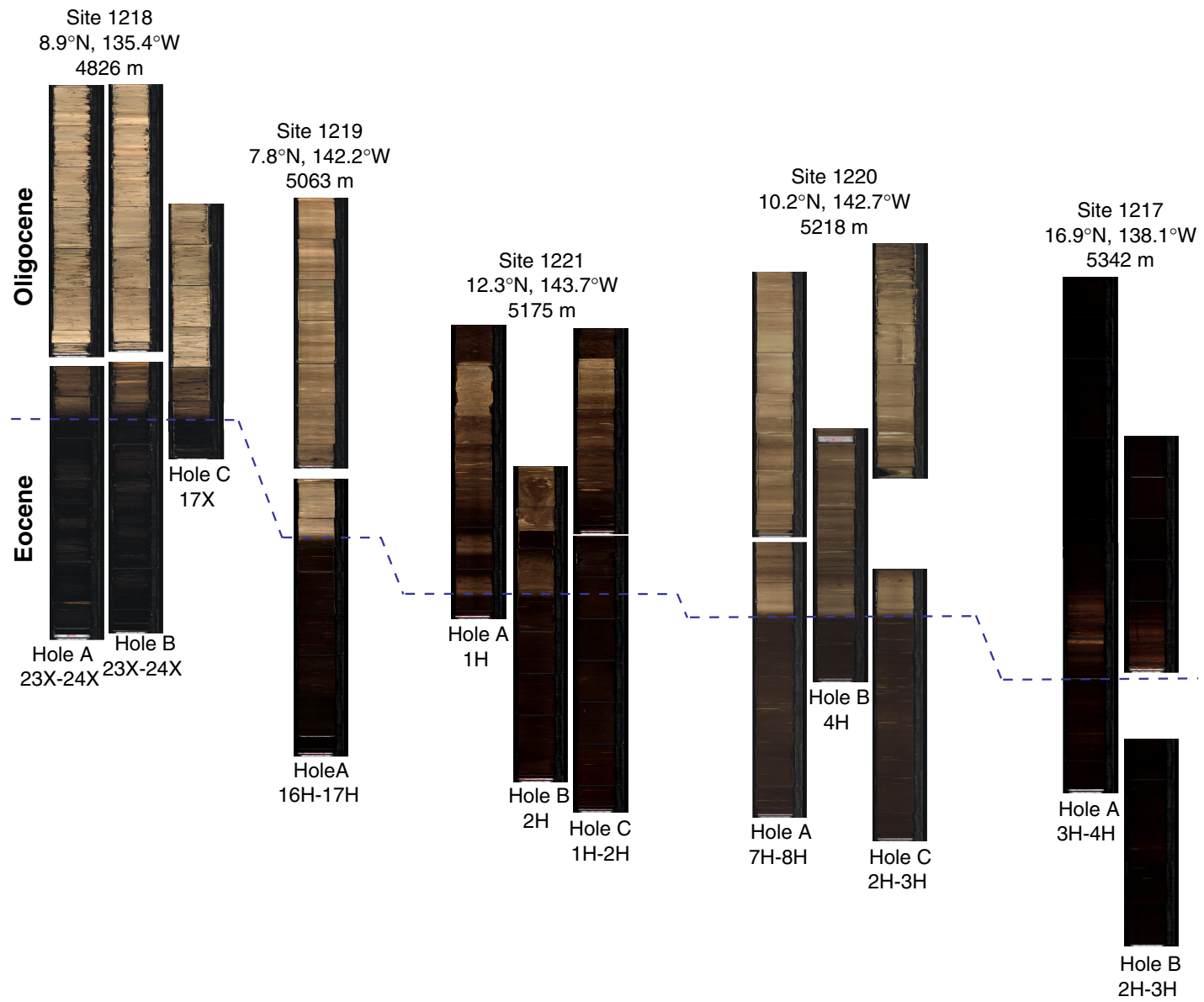


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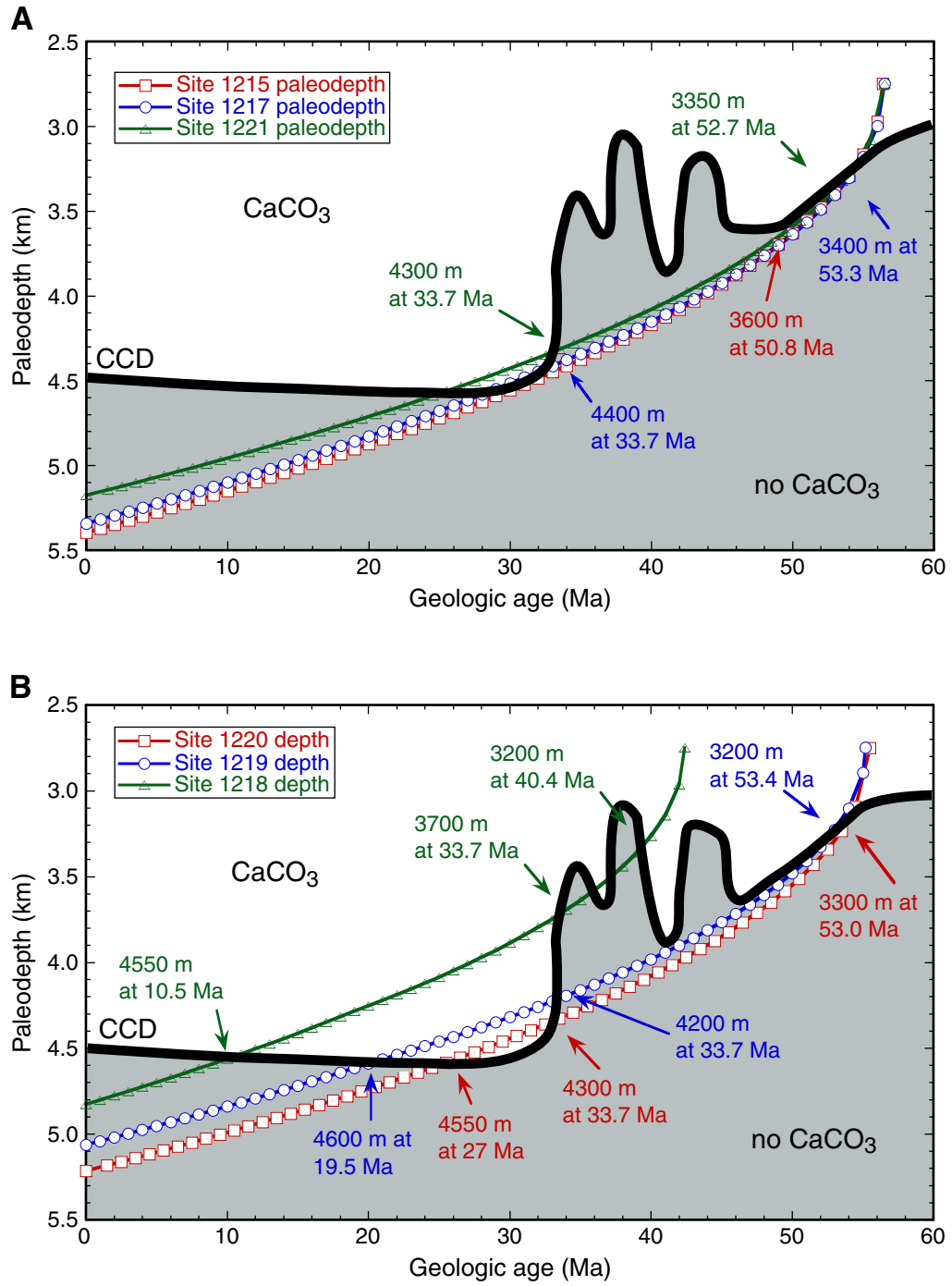


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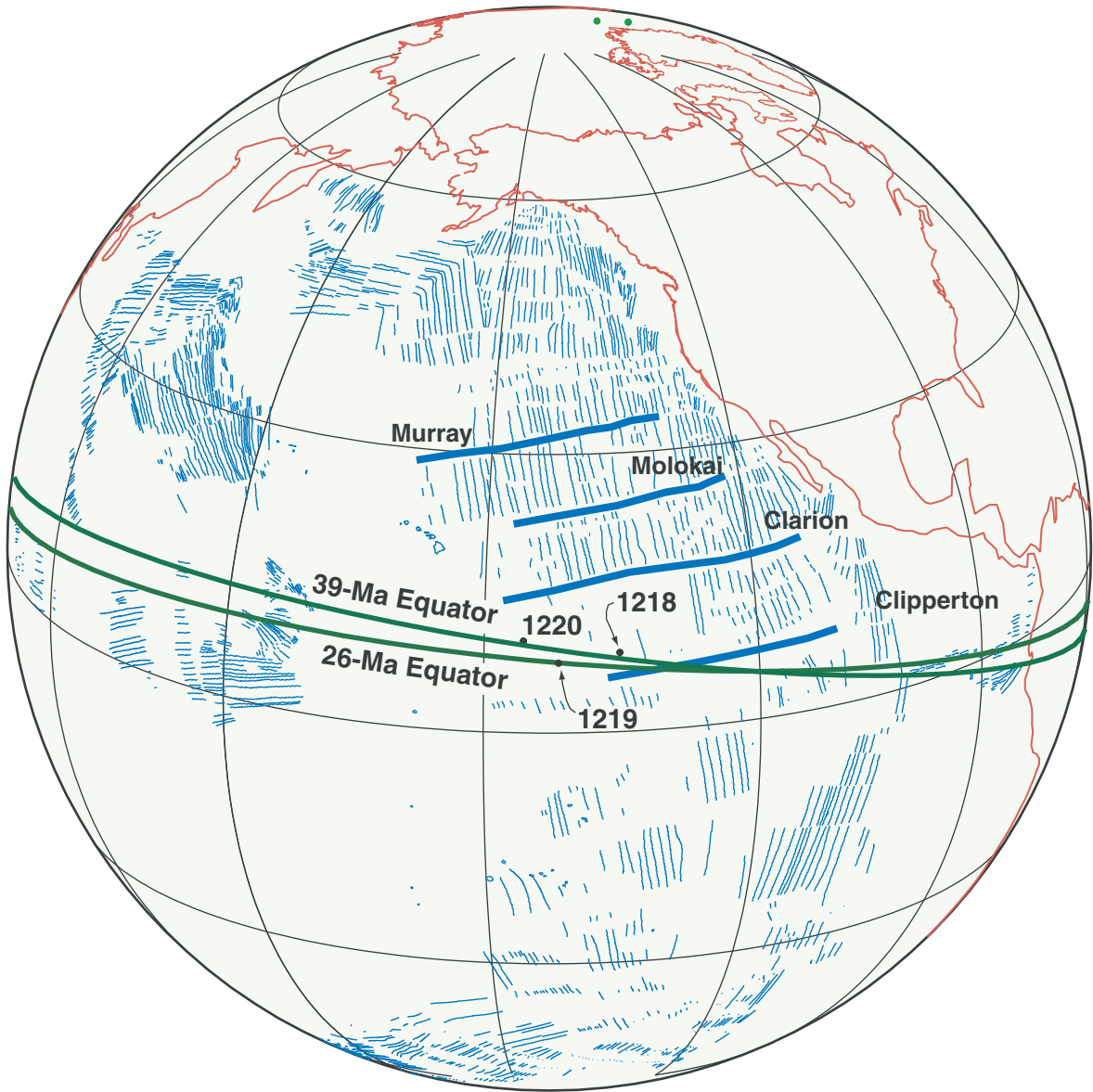


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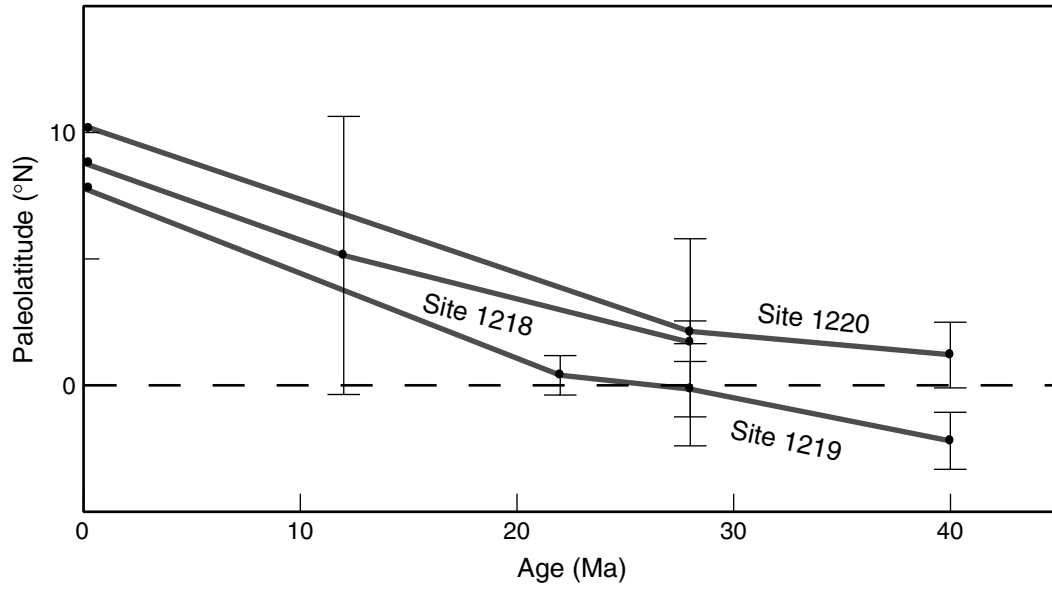


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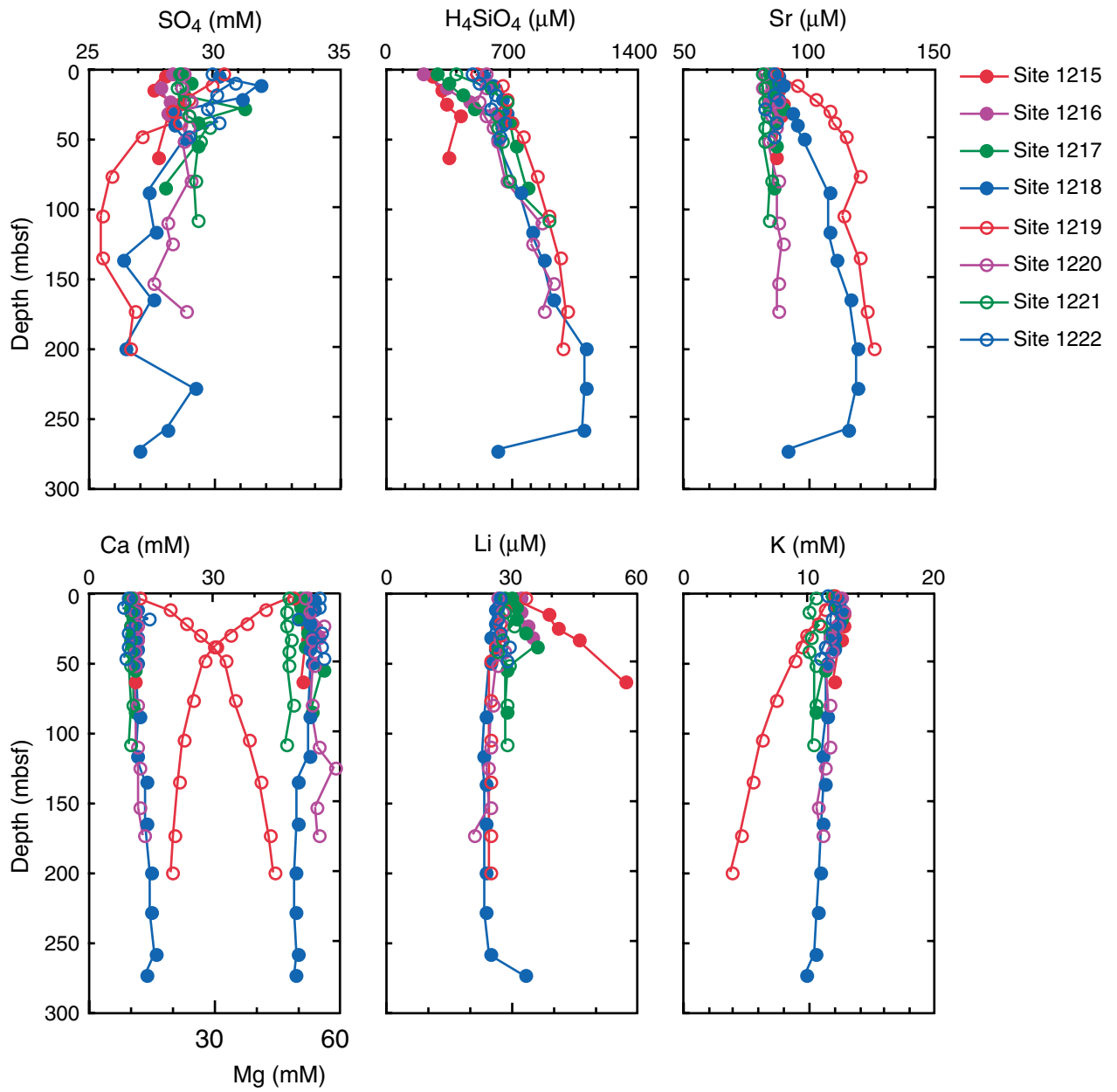


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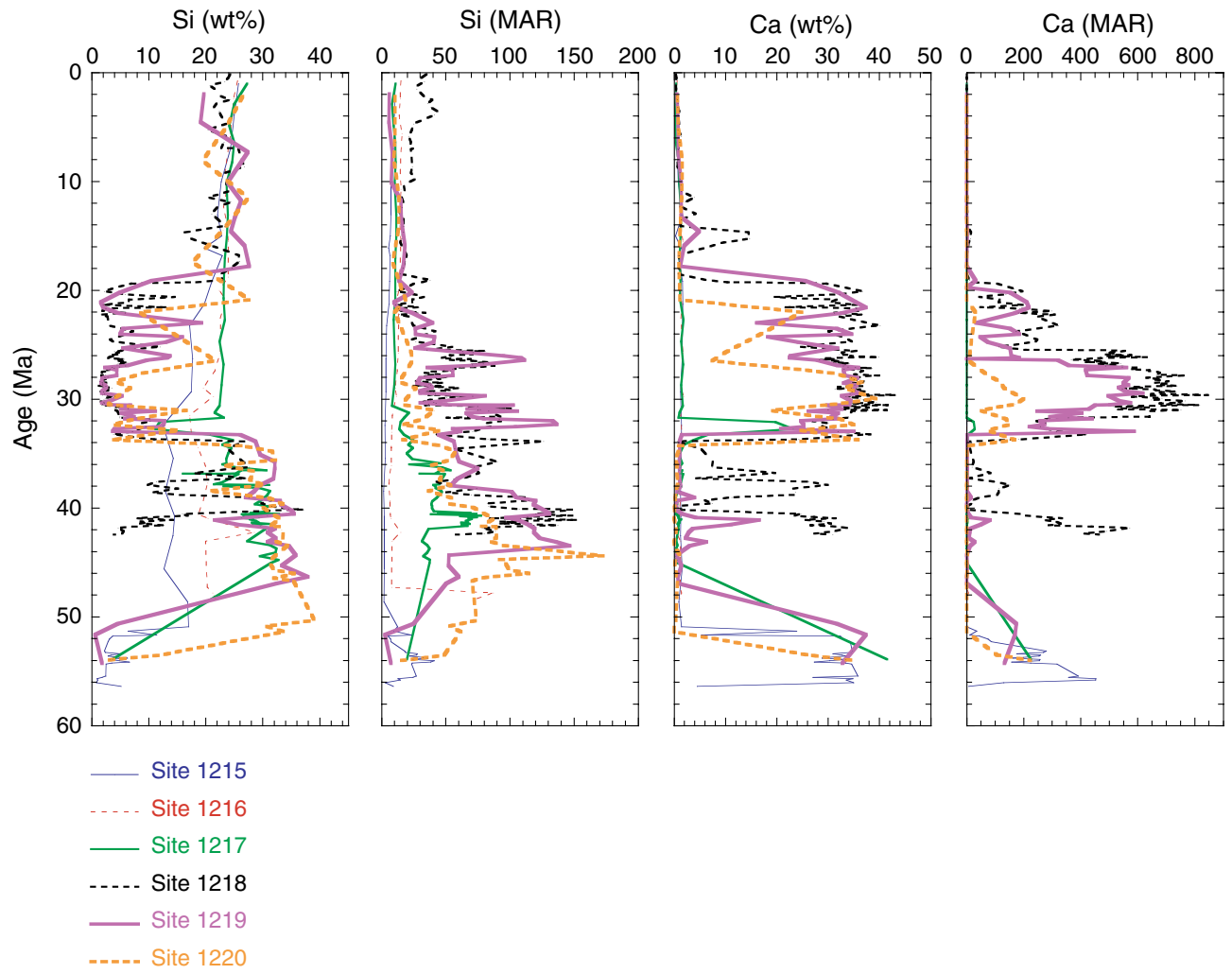


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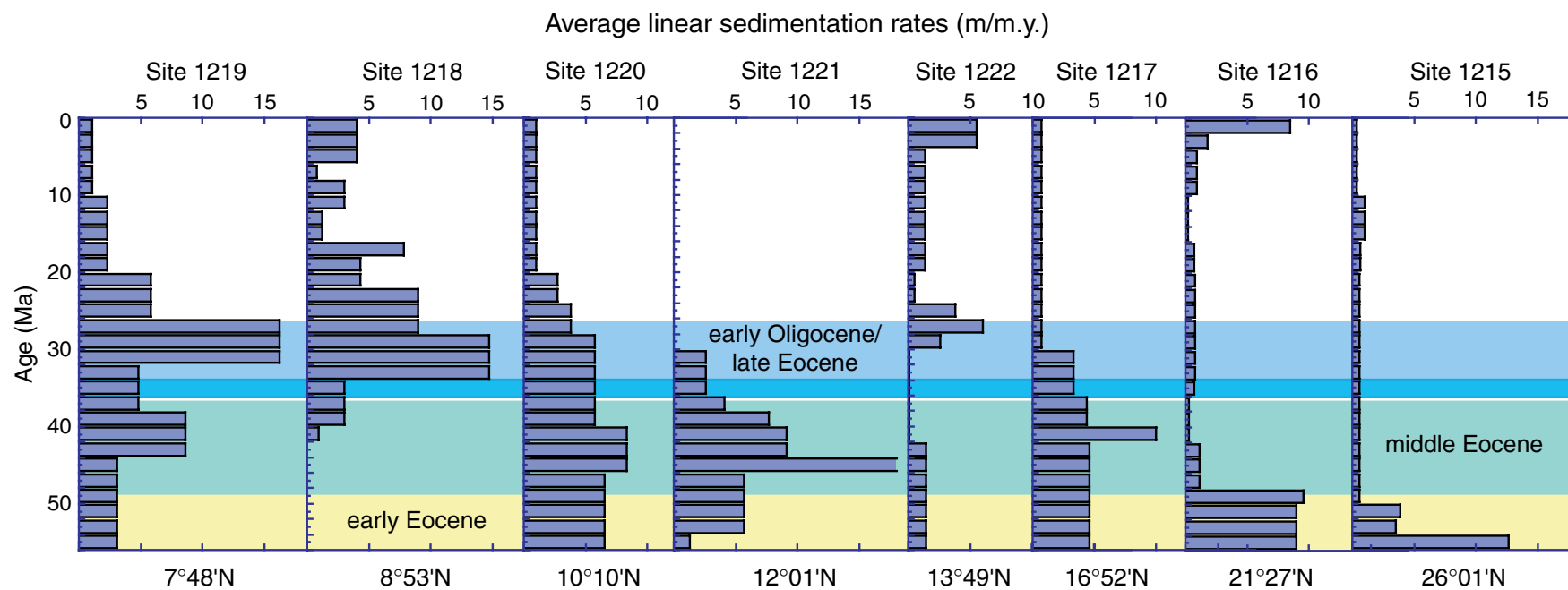


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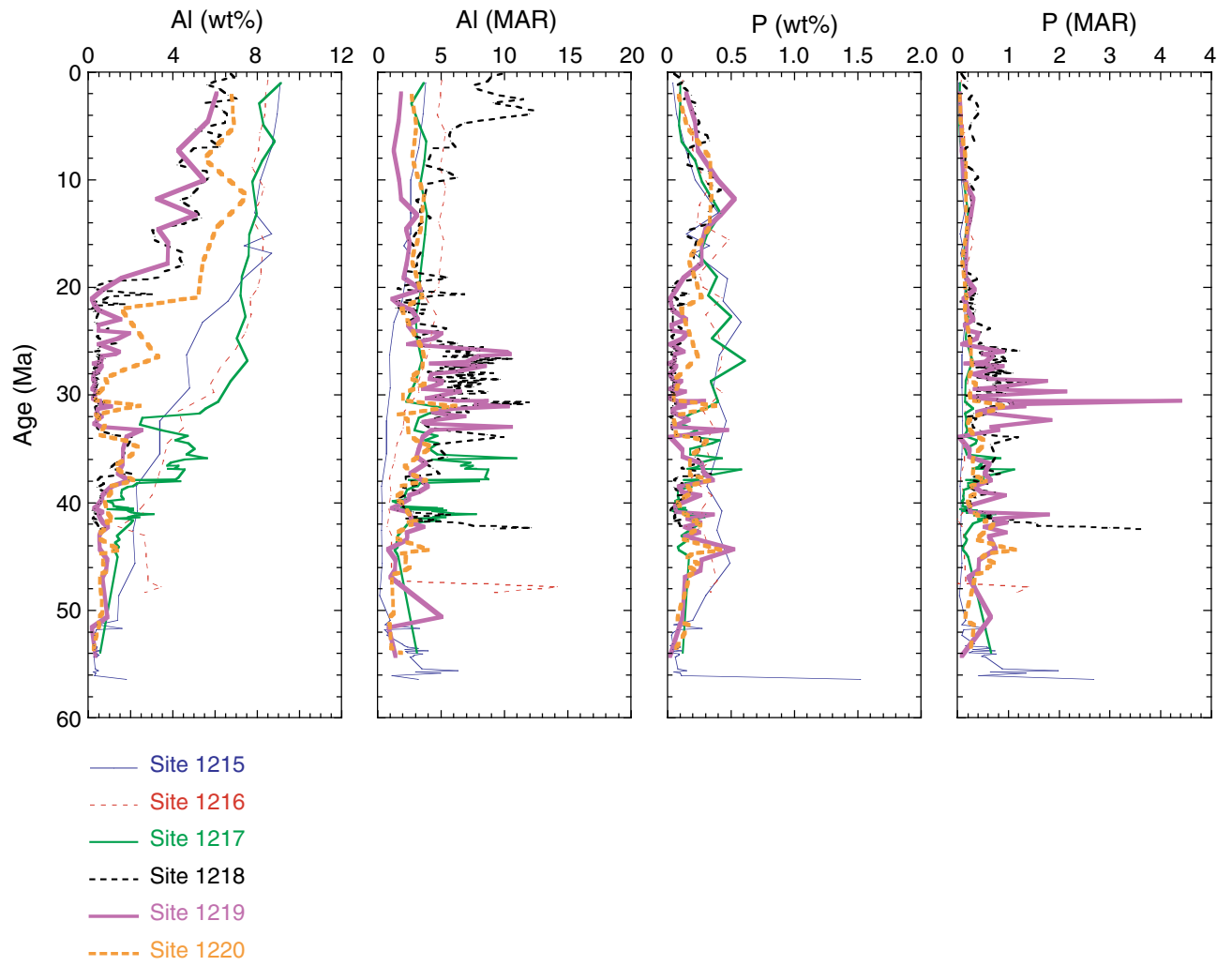


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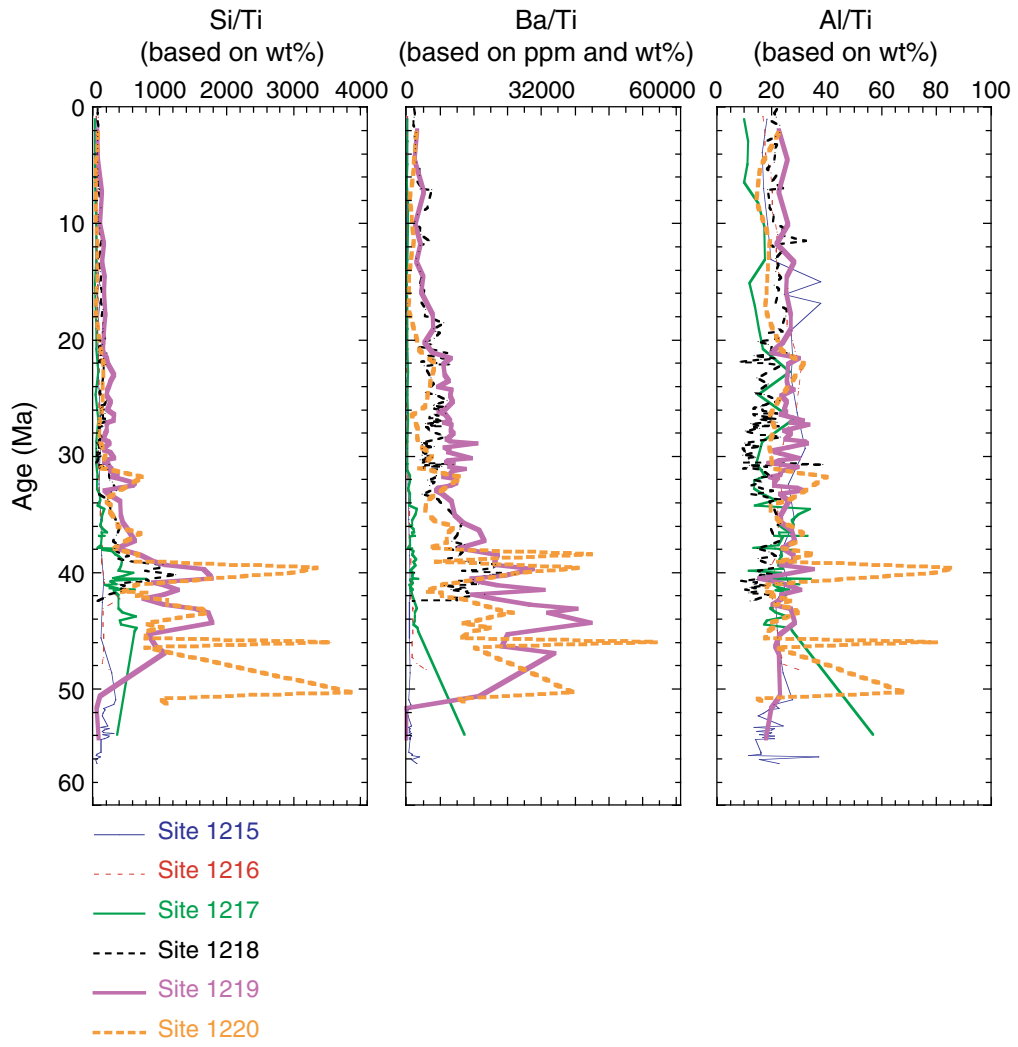


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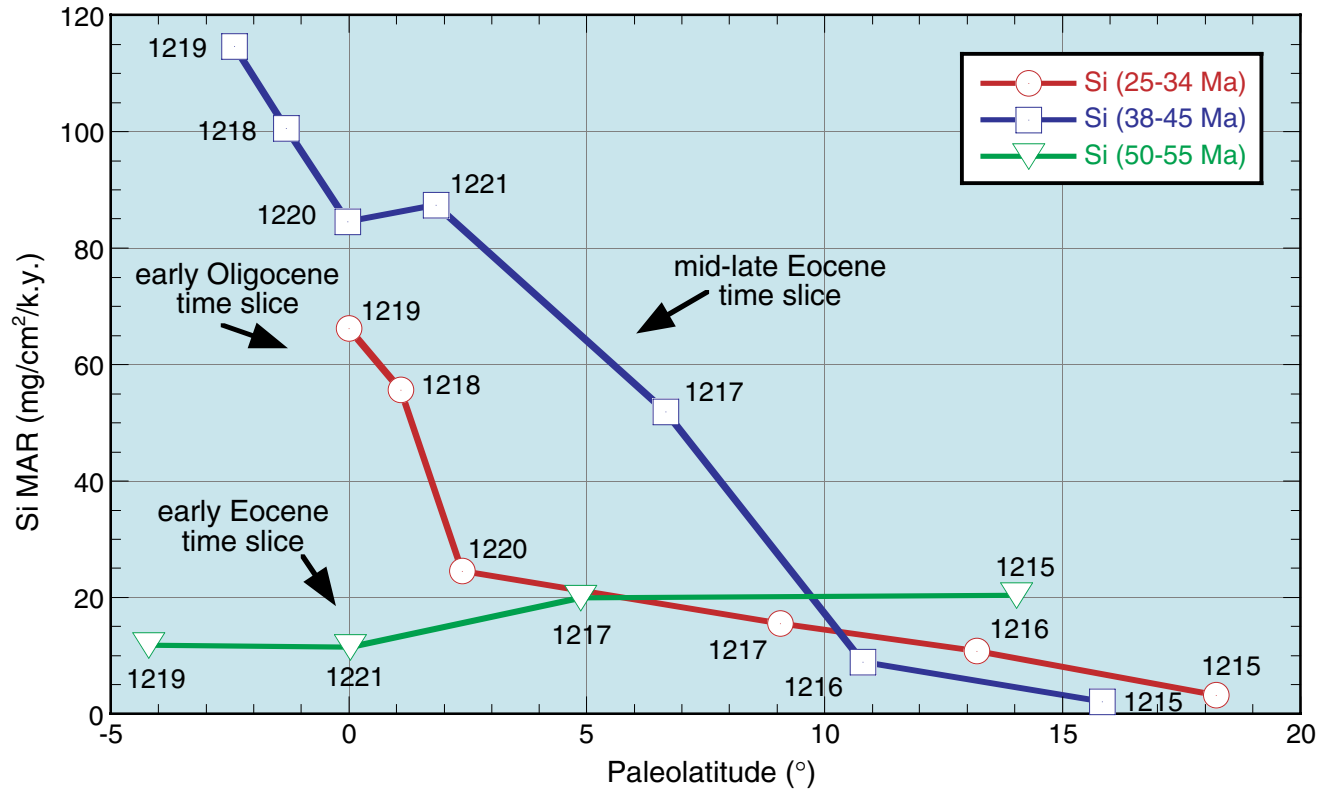


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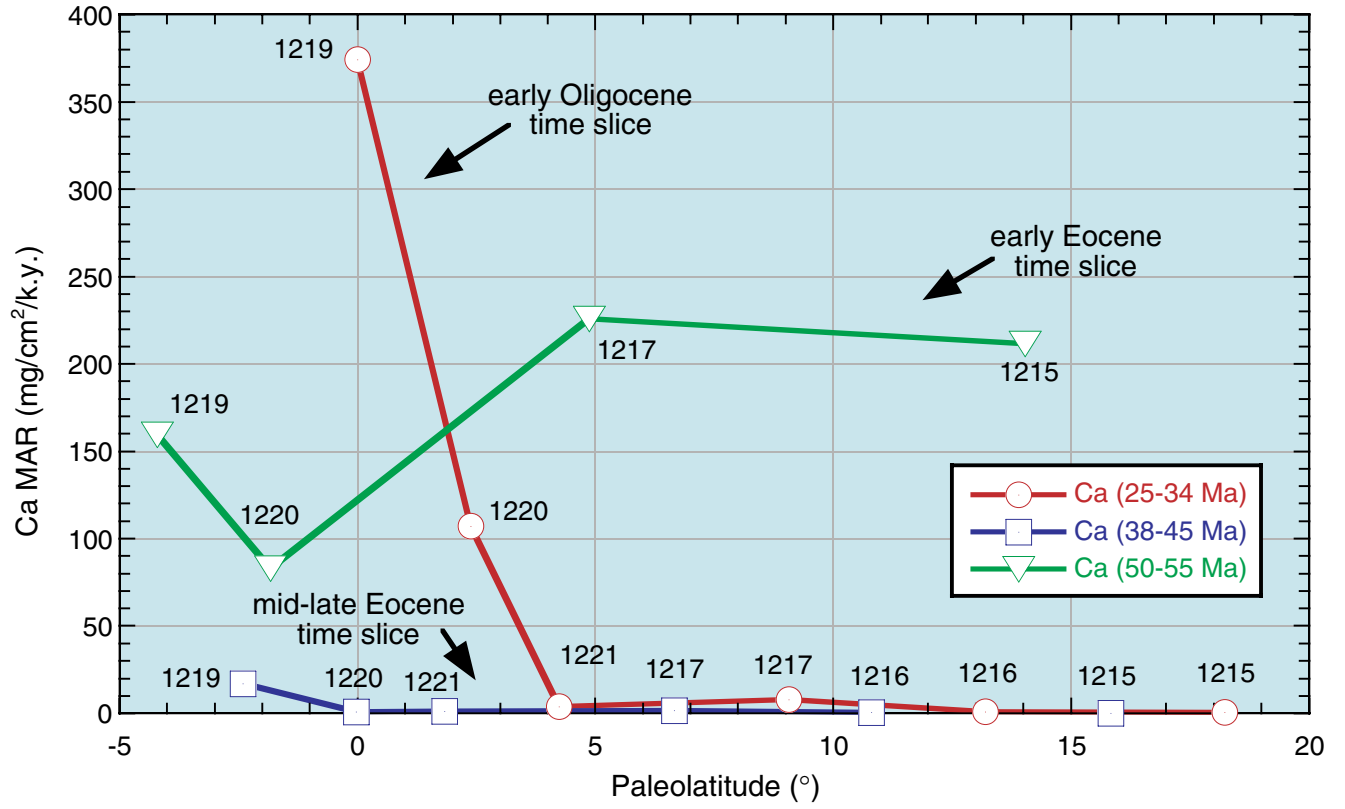


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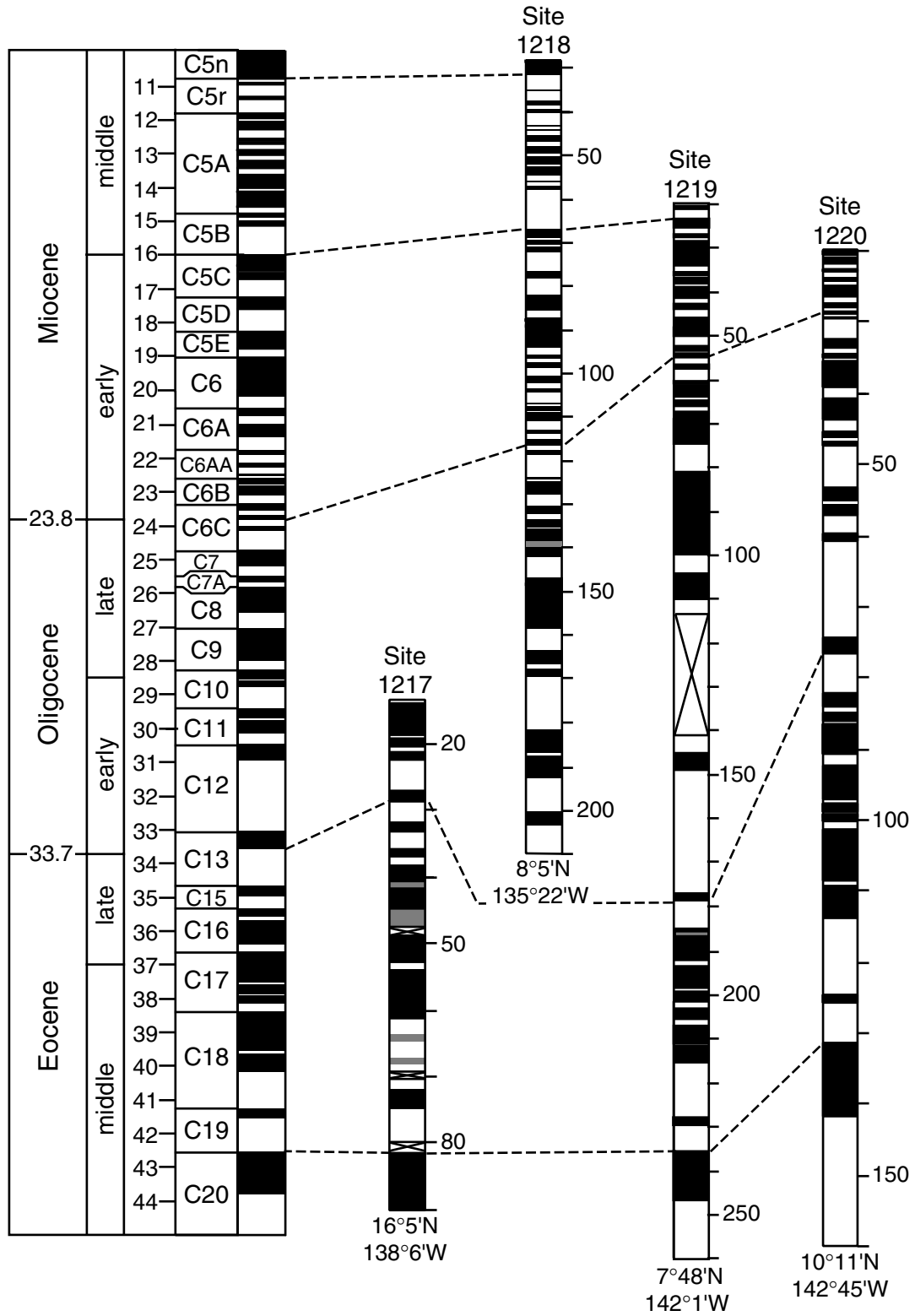


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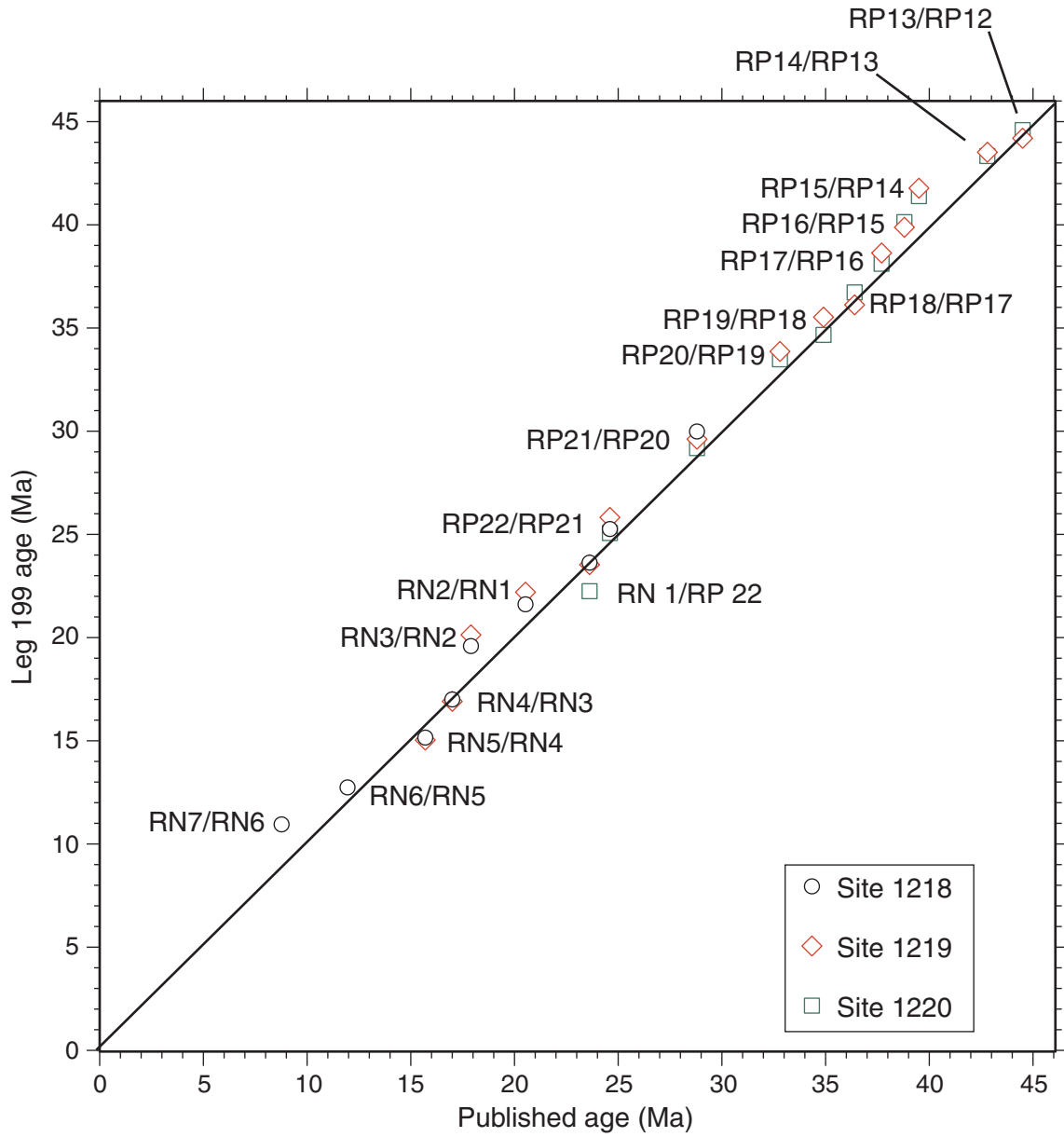


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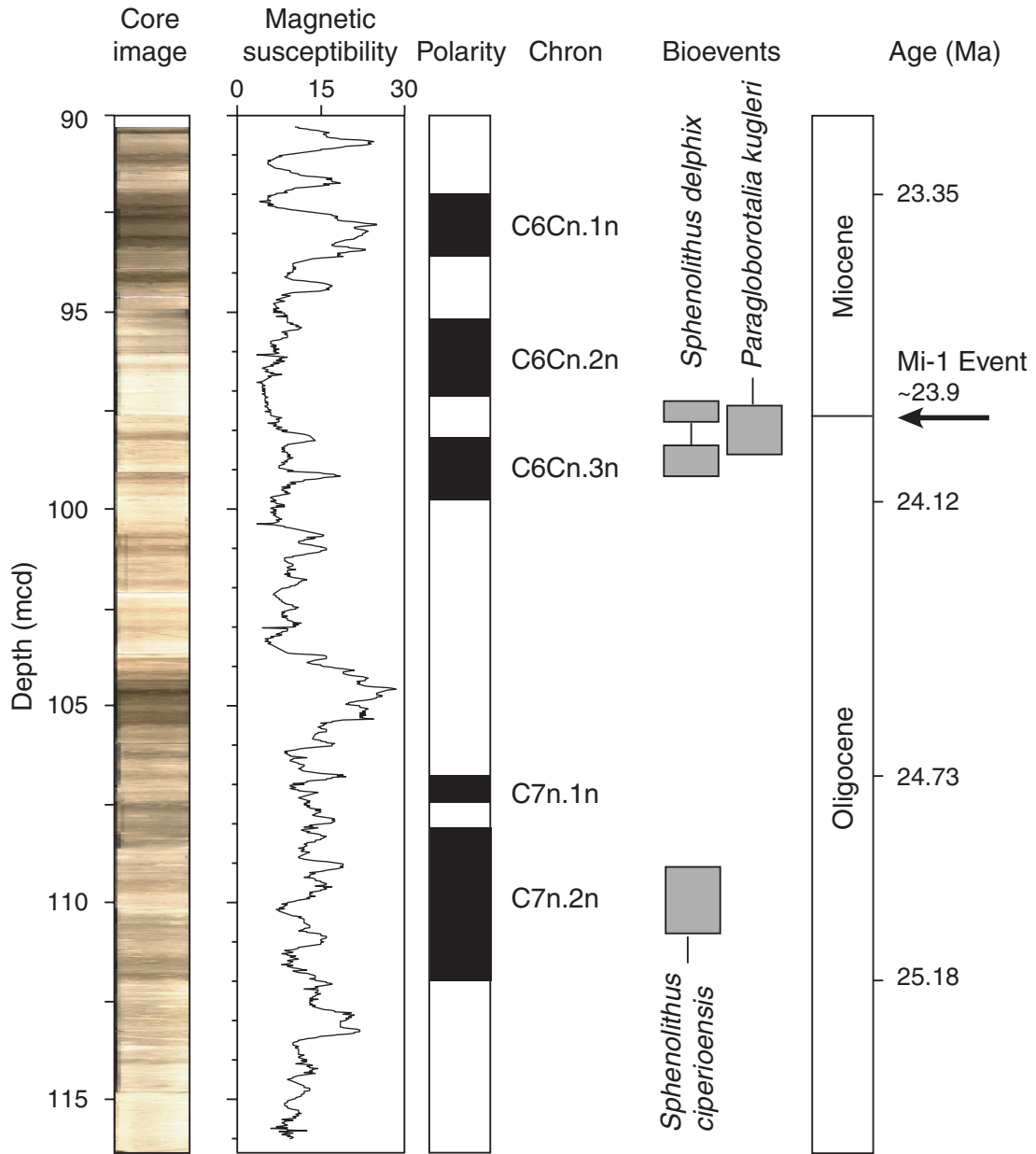


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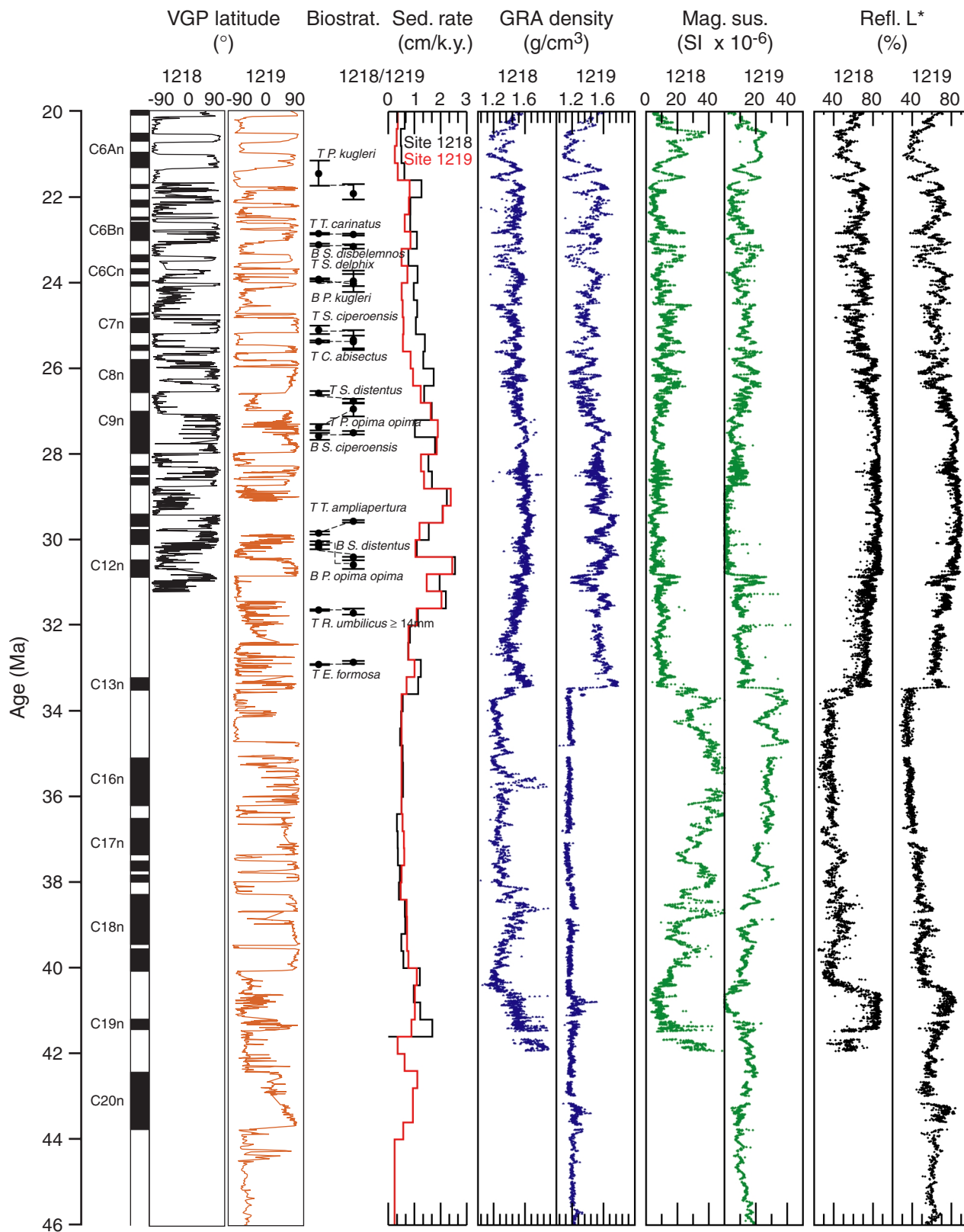


Figure F25

Site 1218
8.9°N, 135.4°W
4826 m

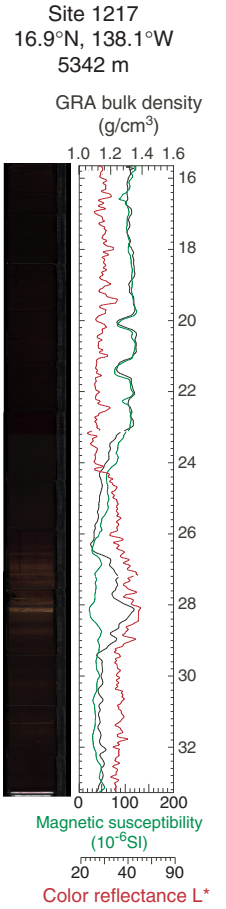
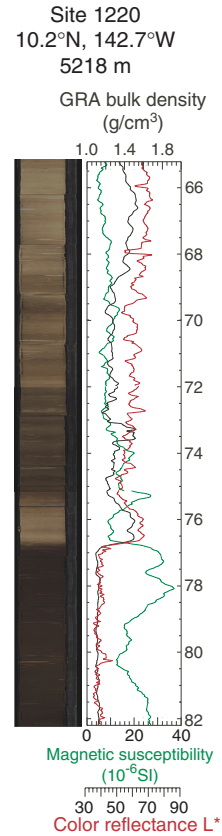
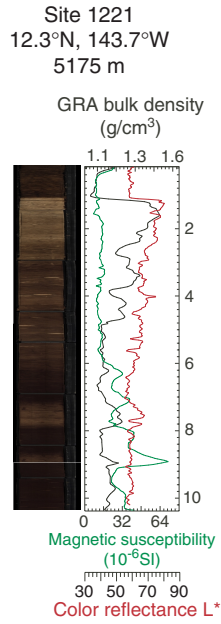
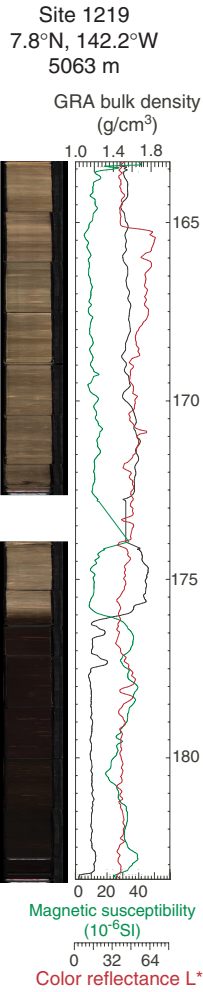
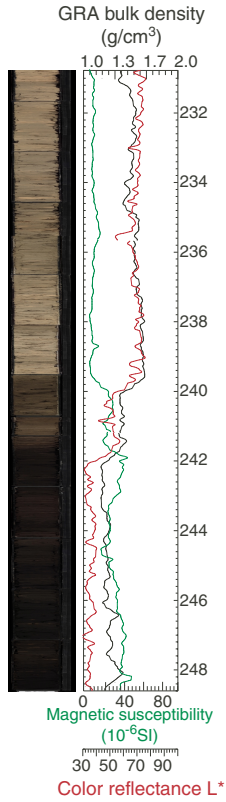


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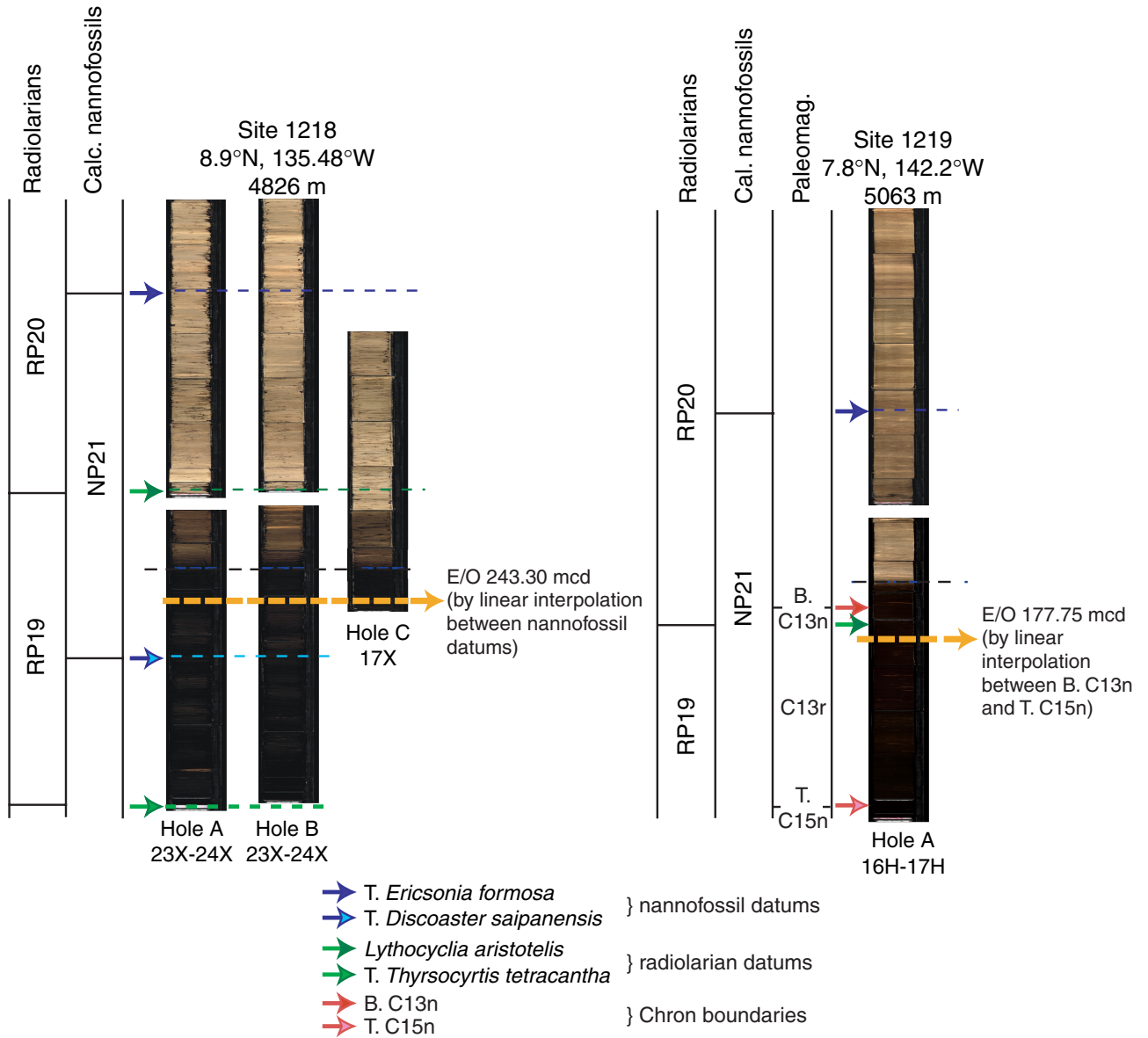


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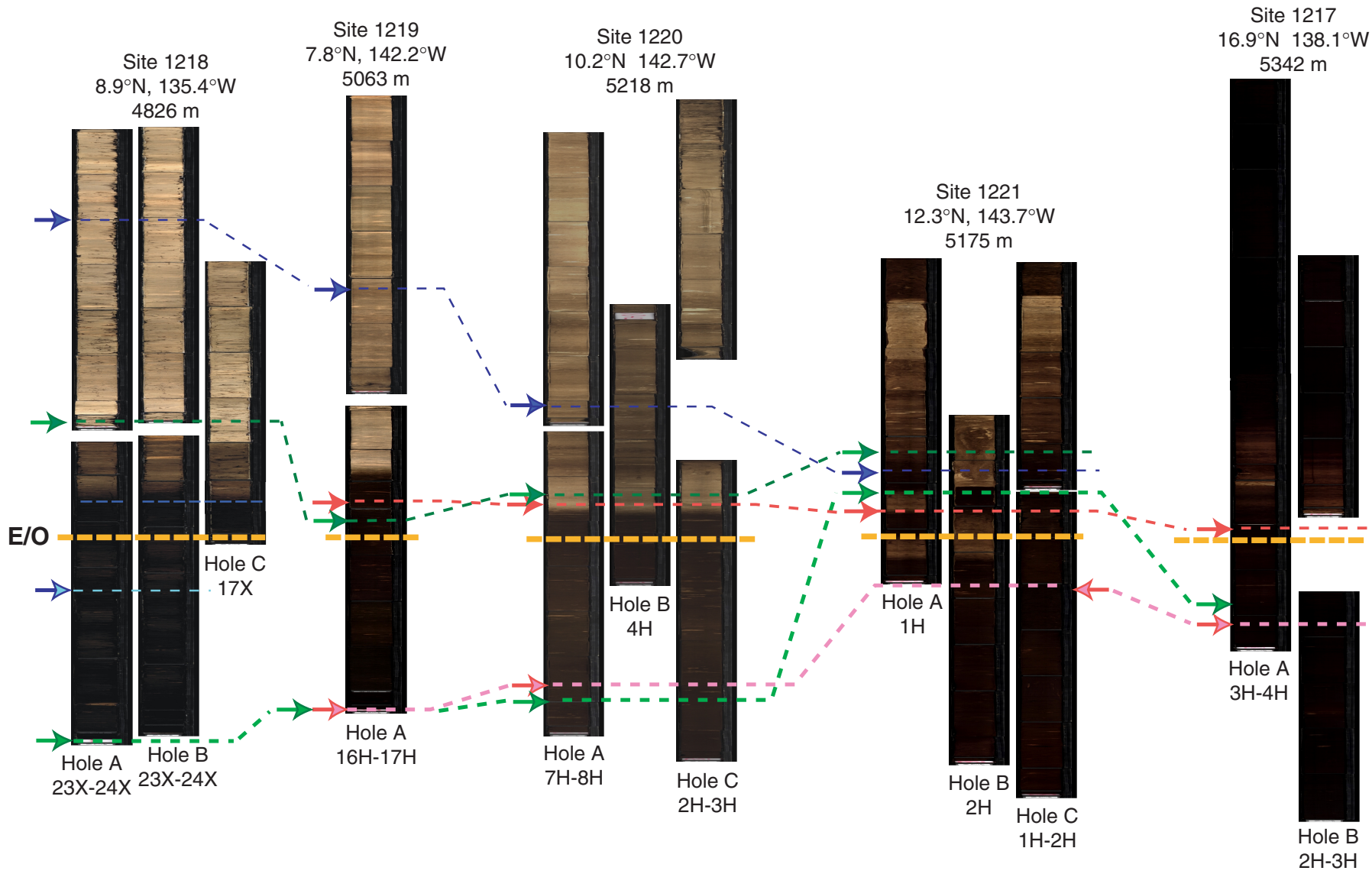


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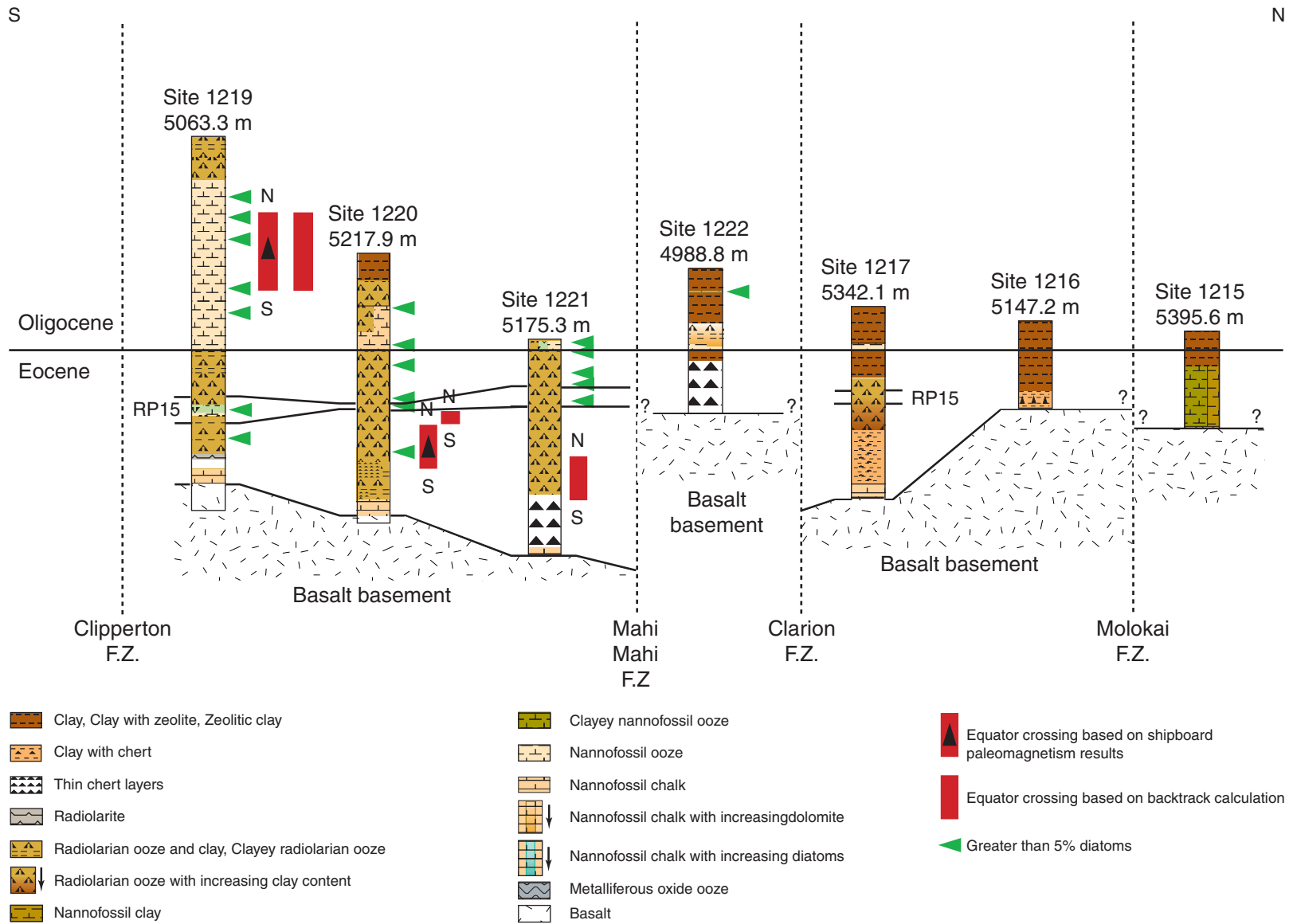


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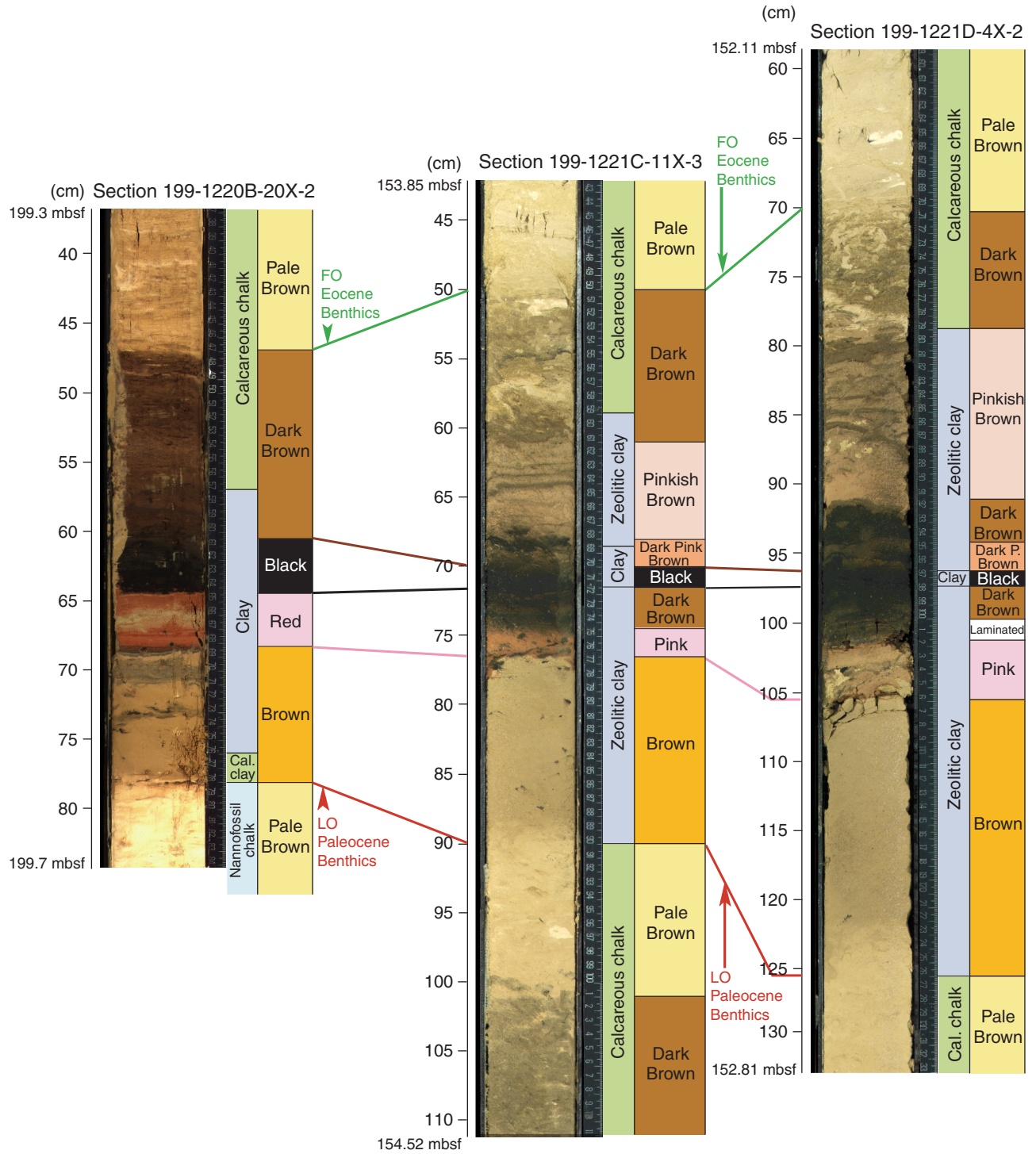


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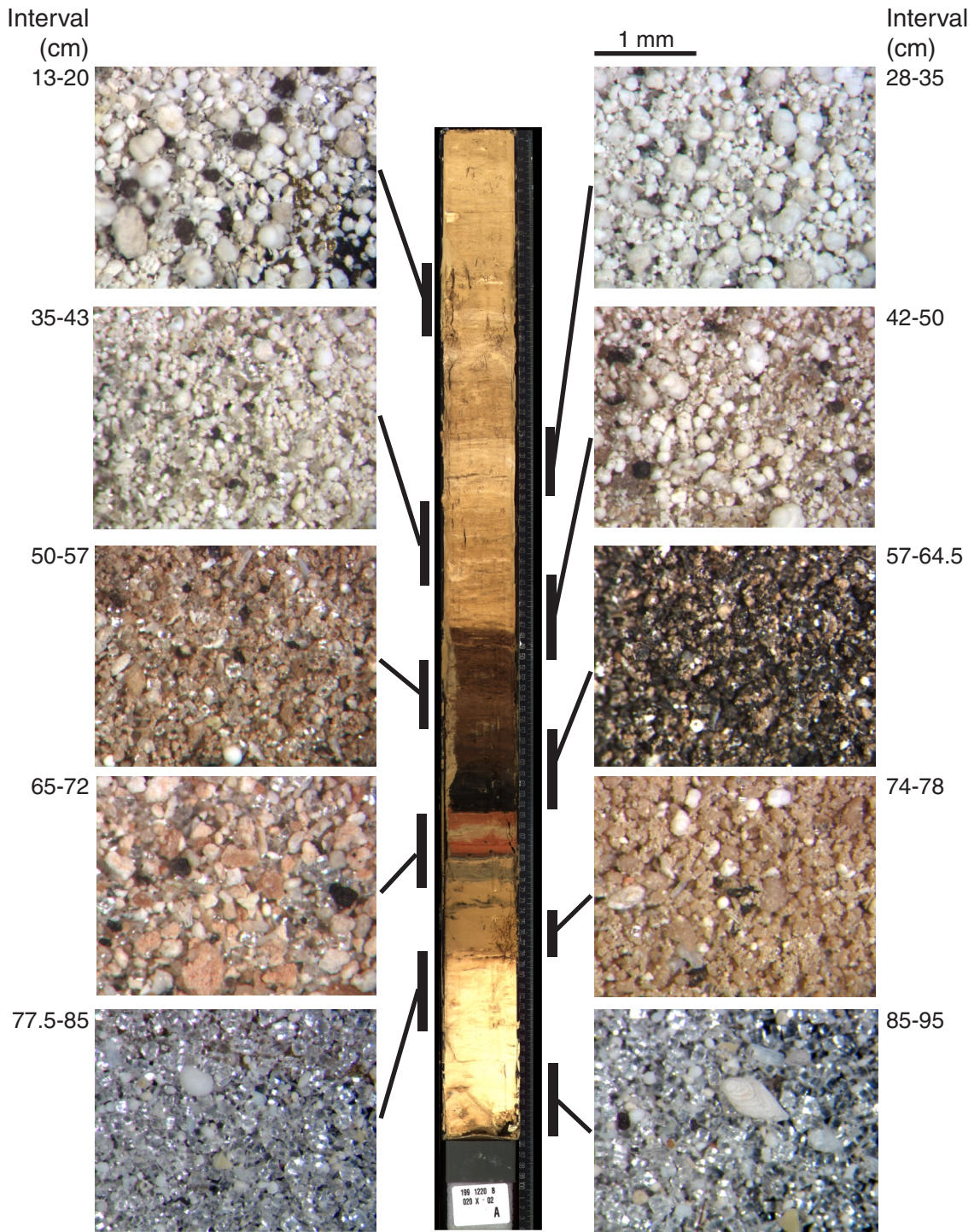


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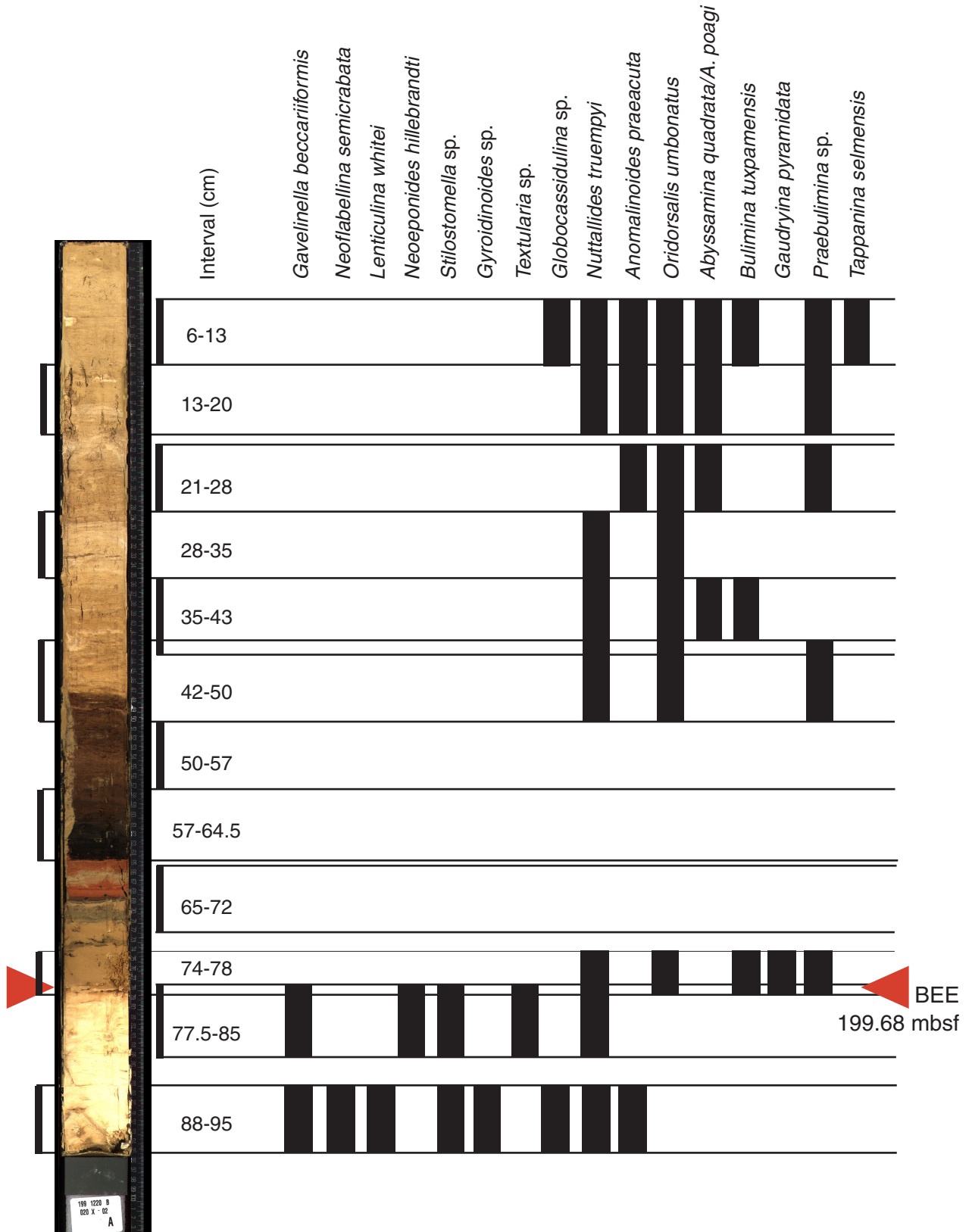


Figure F32

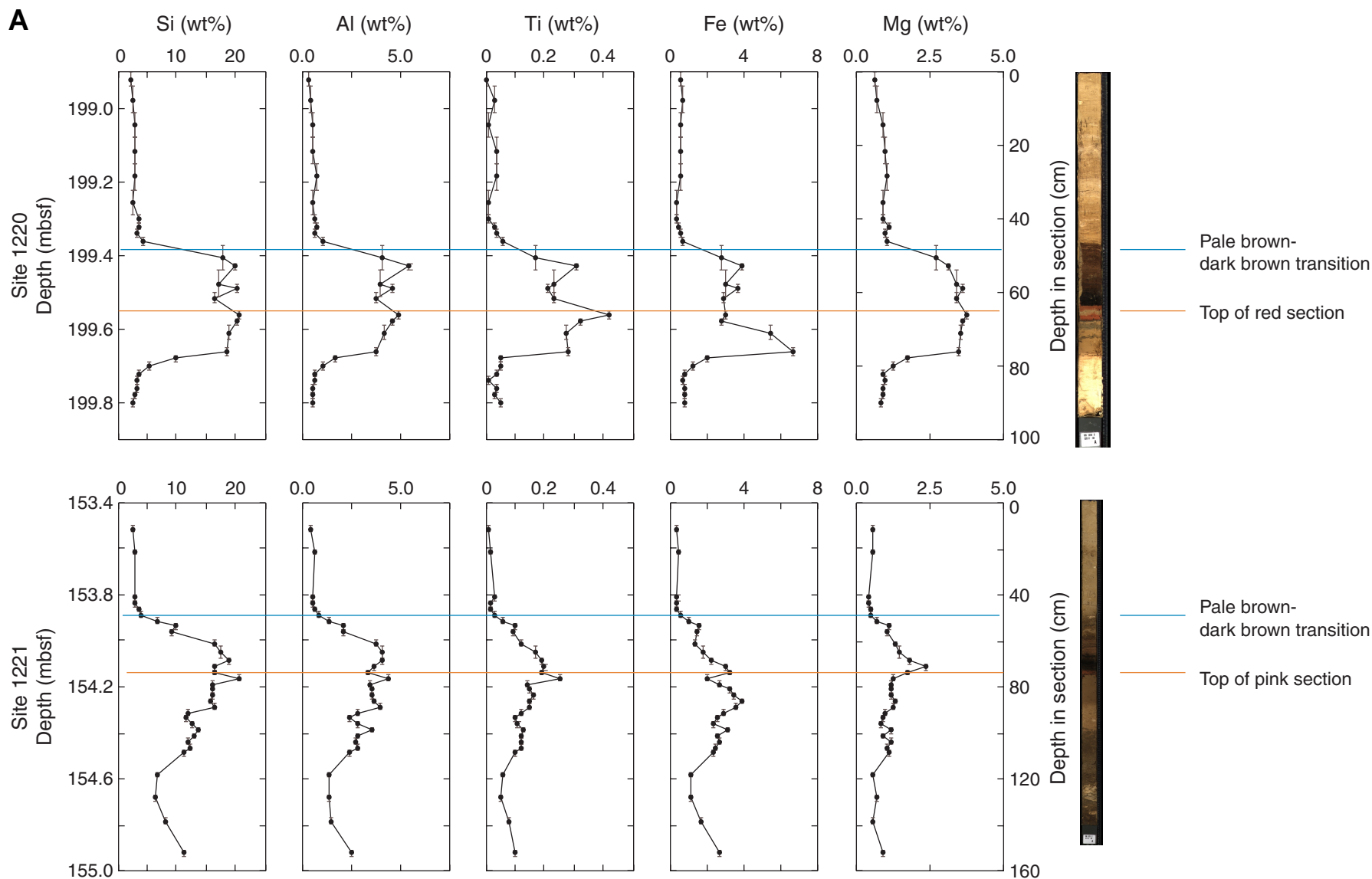


Figure F33

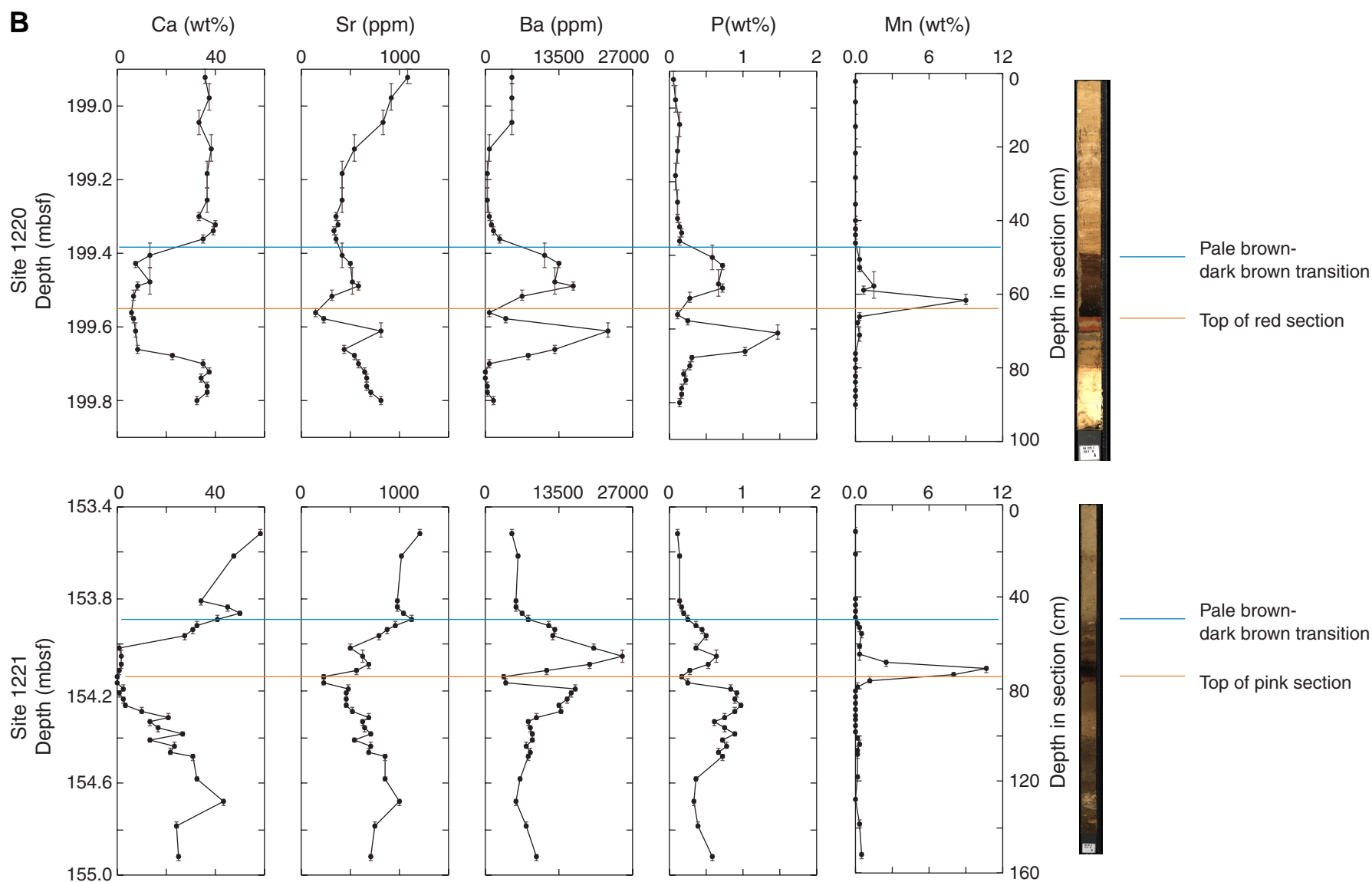


Figure F33 (continued)