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# 24. Biogenic Sedimentology of Radiolarian Assemblages in a Middle Eocene Diatom-rich Unit from the Eastern Equatorial Pacific: ODP Leg 199, Site 1219[1]

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## ABSTRACT

Quantitative analysis of radiolarian assemblages at Ocean Drilling Program Leg 199 Site 1219 provides new information on ocean temperature variations during a significant productivity event. This event (which occurs within radiolarian Zone RP-15) is marked by the accumulation of diatoms in association with highly diverse radiolarian faunas. The data collected for this present work include (1) counts of radiolarian diversity and (2) estimates of the abundance ratio of the radiolarian groups Spumellaria and Nassellaria. The radiolarian assemblages within the diatom-rich unit do not differ greatly from one another in their composition. There are, however, some long-term trends in faunal abundances, as indicated by changes in the nassellarian:spumellarian ratio. Particular changes in this ratio that possibly are related to the diatom event involve (1) the increase of the abundance of actinommids above the diatom-rich sediments and (2) the occurrence of abundance maxima of "robust" artostrobids at the beginning and during the terminal phase of diatom production. These changes can tentatively be interpreted as a reaction of specific radiolarian groups to the increase of diatom productivity in shallow waters. Taken together with the earlier onset of calcareous nannoplankton deposition, the diatom-rich unit can be interpreted as marking a short-term gradual change in sea-surface temperature, together with a change in the equatorial current sys-

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tem that involved the introduction of cold waters by lateral transport rather than the vertical upwelling of water masses derived from the southeastern regions of the Pacific Ocean.

## INTRODUCTION

Scientific ocean drilling in the central equatorial Pacific Ocean has concentrated on obtaining fundamental information about sedimentary successions and developing an overall biostratigraphic framework. As drilling techniques have improved, the research goals have changed somewhat—moving away from basic investigations and toward specialized objectives such as the reconstruction of changing climatic conditions and ocean-current patterns since the onset of sediment deposition. In addition to its general-interest objectives (those presented in the Ocean Drilling Program [ODP] Leg 199 *Scientific Prospectus*), Leg 199 focused on the sequence of calcareous and siliceous sediments in the area of the paleoequator during the early Tertiary (between 56 and 40 Ma) and on the evolution of biota there at that time. Of particular interest were (1) the effects of temperature on the position of the carbonate compensation depth and the stability of marine siliceous components and (2) the effects of the Late Paleocene Thermal Maximum on productivity. Previous drilling in this area was carried out during Deep Sea Drilling Project (DSDP) Leg 8 (Tracey, Sutton, et al. 1971), DSDP Leg 16 (van Andel, Heath, et al., 1973), and DSDP Leg 85 (Mayer, Theyer, Thomas, et al., 1985). Improved drilling techniques allowed the collection of high-recovery cores and almost undisturbed sediment sequences for most of Leg 199. In addition, multiple coring of several holes allowed continuous sedimentological analysis by letting gaps in the sediment record that were the result of drilling disturbances be filled with corresponding sediments from other holes at the same site.

Leg 199 Sites 1215–1222 (a north–south oriented transect) were drilled on 56-Ma basaltic crust; an exception was Site 1218, which was drilled on 40-Ma crust. The sedimentary record obtained from Leg 199 sites showed predictable variations from north to south. Significant thicknesses of sediment were intersected at the southern sites for those sites that were at the equator between 40 and 25 Ma. Three sites (Sites 1219, 1220, and 1221) contained signals of both southern and northern hemisphere positions (Shipboard Scientific Party, 2002).

The sediments studied from Leg 199 sites range in age from the late middle Eocene to the Eocene/Oligocene boundary. During that time, the ecological and productivity conditions changed from those characteristic of an oceanic, deepwater milieu to those that marked the change from siliceous to carbonaceous lithologies at the Eocene/Oligocene boundary. The drilled sediments spanned a 20-m.y. time period that covers the passage of the equator over the Inter-Tropical Convergence Zone (ITCZ). The sediments that were deposited contain accumulations of radiolarians, diatoms, and nannofossils that are characteristic of specific productivity conditions within the Eocene ITCZ. This paper is the result of a pilot study of 30 samples from Hole 1219A, from a diatom-rich unit that is both underlain and overlain by radiolarian-rich sediments.

## GEOGRAPHIC SETTING

Site 1219 is located at 7°48.019′N, 142°00.940′W, 3° north of the Clipperton Fracture Zone (Fig. F1). The drill site represents the southernmost location of a north–south oriented transect drilled on 56-Ma crust. The distance from Site 1219 northward to Site 1220 is ~400 km, and the distance to Leg 8 Sites 70 and 71 is ~300–400 km (Tracey, Sutton, et al., 1971).

Site 1219 was evidently situated in the southern hemisphere until 29 Ma (late Oligocene equator crossing); equatorial and tropical conditions existed there between the middle Eocene and the early Miocene (Shipboard Scientific Party, 2002). These conclusions are based on reconstruction of equator passage and paleogeographic position using a fixed hotspot model (Gripp and Gordon, 1990; Engebretson et al., 1985).

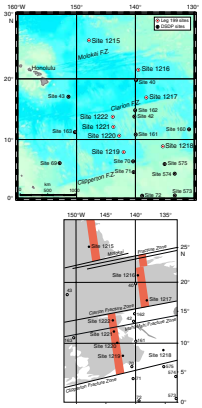
Site 1219 sediments contain numerous levels of diatom-bearing sediments that are related to the high-productivity events at 40 Ma and during the equator passage (Fig. F2). Neighboring sites are not included in this pilot study, either because of the scarcity of diatoms in the smear slides from Site 1220 or because of the poor sediment recovery at neighboring sites. Floral and faunal changes in the corresponding diatom-rich unit at Site 1218 will be compared with the present results in a separate study.

## SCIENTIFIC PURPOSE

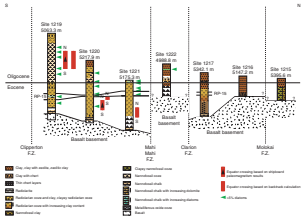
Previous investigations on siliceous organisms in the central equatorial Pacific Ocean have concentrated on radiolarian- and diatom-based biostratigraphic zonation, using as their basis sediments cored during DSDP and ODP legs and others obtained from box cores and piston cores (Moore, 1971; Dinkelman, 1973; Schrader, 1976; Fenner, 1984; Nigrini, 1985). Oceanographic research related to the occurrence of radiolarians and diatoms has focused on their lateral distribution relative to the present current system, sea-surface temperatures, temperature gradients, thermocline influences, salinity, and nutrient supply (comp. Blueford et al., 1990; Goll, 1976). Radiolarian depth zonations (Kling, 1979) have been obtained from different water masses and for low and high latitudes, and radiolarian associations have been recognized that represent specific temperature and bathymetric regimes (Petrushevskaya, 1971; Casey, 1993). Recent paleoceanographic research has investigated depositional patterns of siliceous and calcareous microorganisms and nannoorganisms with the purpose of delineating the spatial distribution of productivity zones and (in combination with ocean-climate models) of investigating the recycling of silica (Leinen, 1985; Ragueneau et al., 2000; Moore et al. 2001; Huber, 2002).

The primary scientific goal of the present study is to describe and interpret the changes in radiolarian associations from the Zone RP-15 diatom-rich unit at Site 1219. The “radiolarites” underlying this unit are composed either of hard radiolarian chert that could not be penetrated, drilled, or recovered without problems or of soft brownish to pink radiolarian accumulations that are identified as radiolarites. These underlying radiolarian deposits range from middle to late Eocene in age and represent the overall signal of unique oceanic conditions described and modeled by Huber (2002). From an ecological standpoint, the radiolarian mass accumulations are a result of the evolutionary potential of radiolarians, the supply of silica into the ocean system, and the

F1. Leg 199 drill sites, p. 13.




F2. Diatom events, p. 14.



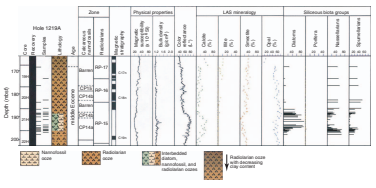
availability of nutrients. After the high temperatures of the early Eocene, radiolarians increased both in their diversity and in their individual abundance (hence in their biomass); the result was that everywhere at lower latitudes there was deposited a radiolarian-rich sediment interval (Zones RP-14 through RP-16). The mass accumulation rate of radiolarian silica is constant throughout this interval, suggesting that stable oceanic conditions existed for most of the middle Eocene. Within this radiolarian-rich interval is the diatom-rich unit that forms the subject of this present work; it represents an intercalation of particles produced by photoautotrophic phytoplankton and marks an important change in the eastern equatorial Pacific Ocean current system. This diatom-rich unit is related to a high-productivity belt deposited in the ITCZ during the equator crossing of Hole 1219A and nearby Site 1220. Backtracking and paleomagnetic investigations indicate that the southern sites of the transect crossed the equator at ~29 Ma. This timing favors the hypothesis that the diatom accumulation at Site 1219 is part of the southern productivity lobe of the ITCZ, which was moving southward and transporting the productivity signal in younger sediments of the southern sites. Above the diatom-rich unit are normal radiolarites that are almost lithologically identical to those from the middle Eocene; these occur up to the Eocene/Oligocene boundary.

This pilot study concentrates on the changes in biological associations from the onset to the end of the deposition of the diatom-rich unit. Because other siliceous organisms (e.g., sponges) are almost undetectable in the radiolarite, the analysis is limited to radiolarians. The main point of interest concerns the sedimentological or, possibly, biological relationship between spherical radiolarians (spumellarians) and monopylid radiolarians (nassellarians); this relationship has been used to interpret changes in water depth, temperature, and productivity at other times in earth history (Steiger, 1998). A secondary point concerns the question of whether the faunal development was induced by productivity or whether it was simply a long-term reaction of the radiolarians to gradual changes in oceanic conditions and the geographic location of the depositional area; this question is investigated by analyzing counts of subgroups on the family level or counts of groups of comparable morphotypes from base to top of the diatom-rich unit. Finally, the study tries to determine what were the major radiolarian assemblages, to identify the predominant species in these, and to estimate the degree to which compositional changes in the associations reflect alterations within the water column.

## METHODS

Thirty sediment samples were obtained from the diatom-rich unit. The disaggregated sediment was simply suspended in water on a slide and observed. This was sufficient to identify differences in radiolarian occurrences and to allow determination of the ratio of diatoms to radiolarians and the percentage of radiolarian families (Fig. F3). It must be stressed that the aim of the study was not to quantify fluxes of radiolarian and diatom tests to characterize paleoproductivity in this time interval but only to determine radiolarian maxima, typical radiolarian assemblages, and specific occurrences of taxon groups or growth forms above and below the diatom-rich unit (cf. Cortese and Bjørklund, 1999). Thus it was not necessary in this case to use sophisticated methods of radiolarian preparation (e.g., Locker, 1996) in order to obtain

F3. Vertical distributions of contents, Hole 1219A, p. 15.



randomly distributed individuals. The quantitative data set was based on a 300-point grid for the diatom:radiolarian ratio and on the counting of 300 radiolarian individuals in determining the percentages of radiolarian families.

## LITHOLOGIES OF DIATOMACEOUS SEDIMENTS AND RADIOLARITES AT SITE 1219

The diatom-rich unit occurs from the lower part of Sections 199-1219A-20H-4 through 22H-2. The interval of maximum diatom content is clearly revealed by a color change from reddish brown sediments dominated by radiolarians to grayish green diatomaceous sections. The color change is gradual in the lower part of the unit and more abrupt (but still gradual) in the upper part of the unit. The sediments are intensely bioturbated.

Preservation of diatom flora is moderate to poor because of intense dissolution of the tests (J. Fenner, pers. comm.). Dissolution of diatoms is species-selective (see discussion in Berger, 1976). Robust species of the Centrales group are predominant, whereas other taxa are almost impossible to identify, mostly because of their fragmented occurrence. In contrast to this, radiolarians are mostly well preserved, although dissolution features are present in delicate shells. Some of the robust radiolarians show rounded protuberances (e.g., the spines of the actinommids or periphaenas), and the ragged outlines of many spongodiscids is also evidence of dissolution. Artostrobids are typically dissolved at their collarlike base.

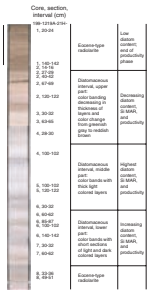
The radiolarian shells settled gently to the bottom, in water that may evidently have been moving slowly; afterward came bioturbation and compaction of the sediment. The reason for suggesting that there may have been slow-moving currents is that there is evidence in some places of both original layering and size-sorting of shells. This layering has been modified by differential compaction, forming small lenses in which grains are concentrated. The lenticular spaces of low grain density are filled with long-spined radiolarians and ornamented forms. Between the larger radiolarians, the rock matrix is composed of small radiolarians, diatoms, calcareous nannofossils, and clay.

The entire diatom-rich unit is composed of three parts. The basal part, above the color change from the reddish radiolarites to grayish to greenish diatom-radiolarian mixed lithologies, is characterized by thin-layered banding. The central part of the unit begins at a relatively abrupt color change, with thick color bands retaining the color of the basal part. The unit terminates with a gradational color change from greenish gray to reddish gray and reddish, returning to the normal Eocene-type radiolarite. The upper part of the unit still contains considerable numbers of diatoms in Core 199-1219A-20H.

Smear slides of older samples show that there is a precursor diatom event within Section 199-1219A-23H-4 (middle Eocene; radiolarian Zone RP-14; *Podocyrtis mitra* Zone) (cf. Sanfilippo and Riedel, 1985). Above Zone RP-15, the diatom content of late Eocene radiolarian sediments is 0%–5%, which does not represent a distinct diatom interval. The Zone RP-15 diatom episode is important because high numbers of calcareous nannoplankton are present. The sedimentologic overview (Fig. F3) demonstrates that calcareous nannoplankton occurs earlier than the diatoms that start just at the beginning of the *Podocyrtis cha-*

*lara* Zone in Section 199-1219A-24H-2. The alternating layers of diatom and radiolarian deposits are characterized by a distinct color banding (Fig. **F4**).

F4. Lithologic sequence of RP-15 diatom-rich interval, p. 16.



## BIOSTRATIGRAPHIC BOUNDARIES AND DURATION OF DEPOSITION OF DIATOM-RICH UNIT

The late middle Eocene radiolarites of Hole 1219A are composed of taxa belonging to radiolarian Zones RP-16 (*Podocyrtis goetheana* Zone), RP-15 (*Podocyrtis chalara* Zone), and RP-14 (*Podocyrtis mitra* Zone). Based on age calculations using data from the multisensor track (**Pälike et al.,** this volume), the diatom-rich unit was deposited ~1.8 m.y. ago (39.554–41.358 Ma).

Linear sedimentation rates for Hole 1219A of ~4.8 m/m.y. indicate the end of a 4-m.y. period of relatively fast sedimentation (Shipboard Scientific Party, 2002). Bulk mass accumulation rates (MARs) are very high at ~41 Ma. MARs of silica for Hole 1219A peak at 41 and 43 Ma, corresponding to both of the middle Eocene diatom intervals.

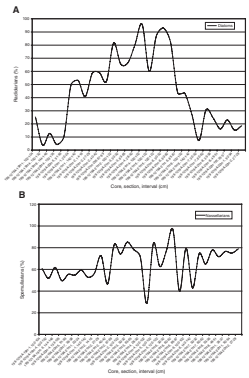
The basal part of the diatom-rich unit in Zone RP-15 corresponds to the base of the lower Si MAR peak, and the middle part of Zone RP-15 shows stepwise decreasing Si MAR. A similar trend can be recognized at Site 1218 and, with weaker intensity, at Site 1217 (Shipboard Scientific Party, 2002).

## QUANTITATIVE ANALYSIS OF RADIOLARIANS IN ZONE RP-15 DIATOM INTERVAL

The methodological approach to the particle analyses of the Zone RP-15 diatom interval depends strongly on preparation procedures that provide the basis for reproducible results. Considering the sedimentary fabric of the radiolarites described under **"Lithologies of Diatomaceous Sediments and Radiolarites at Site 1219,"** p. 5, the vertical distribution of the particles is influenced by reworking processes that are strong enough that high-resolution sampling would not yield more detailed information about the radiolarian deposition. Therefore, radiolarians were counted in the original sediment taken from suspended samples treated with hydrogen peroxide. The counting results are calculated as percentage of groups in the sample. Another problem with the counting procedure is the high dissolution rate and selective dissolution of the observed particles. The preservation of the diatomaceous sediments is characterized by the fact that diatoms are severely affected by dissolution, whereas radiolarians show specific dissolution features, restricting the possibility of comparing diatom accumulation and deposition of radiolarians. After counting, particles in the original sediment slides were prepared for identification of predominant taxa in the radiolarian assemblages.

The calculated results of radiolarian quantities vs. diatom content (Fig. **F5**) indicate that the diatom interval starts with a rapid decrease in the radiolarian content. Above the diatom maximum (at the boundary between narrower and wider color banding represented by darker gray layers), there is a stepwise decrease in the diatom content, correspond-

F5. Ratios of siliceous organisms, p. 17.



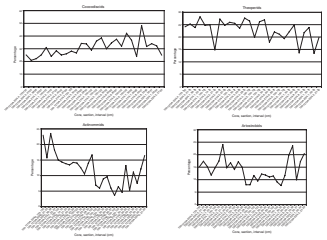
ing to a parallel stepwise reduction of the Si MAR, which indicates that diatoms are mostly responsible for the fluctuations in the Si MARs.

Radiolarian counts provide two important values:

1. The ratio of nassellarians to spumellarians indicates changes in the temperature regime.
2. The percentage of radiolarian families compared to the bulk fauna monitors significant form groups that possibly indicate evolutionary trends or more favorable conditions in the water column, such as changes in the food structure, light, or salinity.

Figures F5 and F6 show the results of nassellarian:spumellarian counting and radiolarian family counts. These raw data show trends in the radiolarian faunal distribution.

F6. Percentages of major radiolarian families, p. 19.



## RADIOLARIAN ASSEMBLAGES RECOGNIZED IN ZONE RP-15 DIATOM INTERVAL

Radiolarian counts demonstrate that recognizable assemblages in deposits underlying Zone RP-15 are different from those in deposits overlying Zone RP-15. Furthermore, the radiolarian assemblage composition obviously changes through the diatom interval, which possibly represents a linear faunal evolution pattern.

The radiolarian assemblage beneath the diatom accumulation is a coccodiscid–theoperid–artostrobid assemblage. The radiolarian assemblage in the uppermost section of diatom-rich sediments is a theoperid–coccodiscid–actinommid assemblage. There are also distinct faunal assemblage compositions in the lowermost sediments of Zone RP-15 and at the diatom maximum in the diatomaceous interval.

The coccodiscid–theoperid–artostrobid assemblage is characterized by large coccodiscid shells, mostly represented by *Lithocyclia ocellus E.* and various species of *Periphaena* and *Heliodiscus*. The artostrobid group is composed of smaller and robust forms represented by *Dictyoprora mongolfieri (E.)*.

The radiolarian assemblage from the uppermost part of the diatom interval, grading into the normal Eocene radiolarian sediment, is characterized by a reversal in the theoperid:coccodiscid ratio and a clear increase in actinommids. Artostrobids decrease above the diatom maximum.

## DETAILED FAUNAL CHANGE

The general pattern of radiolarian faunal change through the diatom interval is a change in the nassellarian:spumellarian ratio; there is an increase in nassellarian shells above the diatom maximum (Fig. F5). In detail, the radiolarian families reacted as follows (Fig. F6):

1. Actinommids increased above the diatom maximum to a point where spumellarians and nassellarians are equal during the latest stage of the event.
2. Higher contents of theoperids in the upper sections of the diatom interval indicate a minor decline in artostrobids.
3. The artostrobids show two maxima: a smaller peak at the base of the diatom event and a second peak above the diatom maximum

but in the diatom zone. The peak at the base of the interval probably represents a generally high artostrobid content, mostly represented by *D. mongolfieri (E.)*, which is interrupted by one sample with fewer specimens. The upper peak could also be seen as a sedimentologic effect but is located at the top of a gradual increase of artostrobids during the diatom event.

There is no dramatic change in the radiolarian composition during the Zone RP-15 diatom interval. The major groups, such as coccodiscids and theoperids, display a long-term trend that does not seem to be influenced by the diatom occurrences. It is difficult to interpret these findings. Actinommids comprise the only group that clearly contributes to the composition of the radiolarian assemblage as a reaction to the diatom event and probably represent faunal elements that originated in the upper parts of the water column (cf. Casey, 1993). Actinommids probably show minimum occurrences because of the diatom impact in the uppermost part of the water column. Other radiolarian groups, which are not affected by the diatom event, belong to tropical warm-water assemblages that, especially in the Eocene, were located in deeper bathymetric zones. The artostrobids seem to react in colder and deeper zones of the water column. In the literature, robust forms of this group are interpreted as belonging to cold-water upwelling faunal assemblages (Casey, 1993); therefore, it is of interest to recognize them at both the base and top of the diatom interval. Consequently, the artostrobids together with the diatoms could be interpreted as representatives of a cooling event, but they dominated only for short periods of time.

## CONSEQUENCES FROM FAUNAL ANALYSIS

Radiolarian counts from the diatom interval sequence indicate that the deposition of radiolarian shells at Site 1219 is probably not connected to the production of diatoms or the occurrence of a high-productivity event. The changing nassellarian:spumellarian ratio is either a result of a long-term trend of slight deepening of the oceanic environment or of a temperature change with cooling and subsequent warming of the entire water column in the equatorial area during the middle to late Eocene. Also, there are some observations that could be interpreted as reactions to the onset of both diatom deposition and a new oceanic circulation pattern (comp. Blueford et al., 1990). This reaction is illustrated in the vertical distribution of radiolarian groups and specific dissolution features in radiolarian shells traced from base to top of the diatom sequence.

The general Eocene-type radiolarian fauna is mostly composed of warm-water, tropical, low-latitude forms as interpreted by Casey et al. (1990). The lateral distribution of the middle Eocene radiolarites indicates a very broad tropical zone, where similar assemblages of radiolarians are deposited. The cosmopolitan radiolarian composition in the Central Pacific region is influenced by the open Isthmus of Panama during the Eocene. It is not possible to interpret a maximum zone of radiolarian production in this area. McGowran's (1989) interpretation of radiolarian development at the end of the early Eocene, after maximum temperature regimes (Zachos et al., 2001) and during the following cooling period, is reasonable. As long as radiolarians are used as indicators of increased productivity, the widespread occurrence of thick radiolarian deposits can be interpreted as a biologic reaction of siliceous

organisms in an oceanic environment without steep gradients but with a slight tendency toward cooling. The permanent El Niño model introduced by Huber (2002) supports this interpretation. Interruptions of the middle Eocene oceanic conditions in terms of temperature changes and availability of silica could immediately modify the geometry of the circulation system with a consequent change in the configuration of productivity areas. The three-lobed productivity zone of the ITCZ in the equatorial Pacific Ocean could have developed under these conditions, reaching shallow water levels, transporting cold-water biota (such as radiolarians from the southeastern Pacific area), and initiating the growth of diatoms. This picture does not take into account specific oceanic influences produced by limiting factors like Fe (cf. Ragueneau et al., 2000) or special wind systems.

The mass accumulation of diatoms is an indicator and part of the Zone RP-15 productivity event. The change in the oceanic circulation regime is documented by the occurrence of calcareous nannoplankton followed by diatoms that indicate maximum productivity for this 2-Ma interval. Only a few radiolarian groups, or even single taxa, reacted under these changing conditions. The artostrobids possibly represent such cold-water forms having bloomlike evolution episodes in the initial and terminal stages of the diatom productivity event. Another group of radiolarians, the actinommids, represent tropical warm-water faunas and are indicators of a warming phase after the diatom event when the former middle Eocene radiolarian assemblage composition returns.

It is possible that the elongated occurrence of the diatom mass accumulations (also found at Site 1218) belongs to the southern productivity lobe of the ITCZ in the middle Eocene. Site 1219 sediments continuously contain varying amounts of diatoms throughout the Oligocene. Greater diatom content coincides with the equator passage at ~29 Ma.

## SUMMARY

The primary results of this study on the depositional patterns of radiolarians during a diatom event in the equatorial Pacific Ocean during the middle Eocene are as follows:

1. Most radiolarian groups were not affected by the mass production of diatoms and the deposition in the area of the ITCZ, indicating major radiolarian taxa distribution in deeper marine tropical environments and a deep thermocline with temperatures similar to surface temperatures.
2. Changing environmental conditions are responsible for rapidly evolving distinct zones of higher productivity in the equatorial area. The Eocene radiolarian sedimentation, which is characterized by an extended marine zonation lacking steep gradients, is controlled by slight cooling of the circulation system and rich input of nutrients and silica after an extremely warm period (early Eocene).
3. Radiolarian assemblage compositions indicate that lateral transport, together with the increasing South Equatorial Current, induced an overprint from above, adding diatoms and shallow marine radiolarians (actinommids) to the faunal spectrum during and immediately after maximum diatom production.

4. Some specific forms of radiolarians ("robust" artostrobids; Casey, 1993) seem to react at the beginning and end of the diatom occurrence. Nassellarians, mostly occurring in intermediate zones between the warm- and cold-water levels at greater depths, could be specialized to collect food and silica from the sinking diatom tests, which are mostly dissolved at these bathymetric levels.

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## REFERENCES

Berger, W.H., 1976. Biogenous deep-sea sediments: production, preservation, and interpretation. *In* Riley, J.P., and Chester, R. (Eds.), *Chemical Oceanography* (Vol. 5): London (Academic Press), 265–388.

Blueford, J.R., Gonzales, J.J., and Van Scoy, K., 1990. Comparing radiolarian and diatom diversity and abundance from the northeast Pacific. *Mar. Micropaleontol.,* 15:219–232.

Casey, R.E., 1993. Radiolaria. *In* Lipps, J.H. (Ed.), *Fossil Prokaryotes and Protists:* Boston (Blackwell Scientific), 249–284.

Casey, R.E., Weinheimer, A.L., and Nelson, C.O., 1990. Cenozoic radiolarian evolution and zoogeography of the Pacific. *Bull. Mar. Sci.,* 47(1):221–232.

Cortese, G., and Bjorklund, K.R., 1999. Radiolarians from the cyclic Messinian diatomites of Falconara (Sicily, Italy). *In* De Wever, P., and Caulet, J.P. (Eds.), *InterRad VIII, Paris/Bierville 8–13 Septembre 1997*. Geodiversitas, 21(4):593–624.

Dinkelman, M.G., 1973. Radiolarian stratigraphy: Leg 16, Deep Sea Drilling Program. *In* van Andel, T.H., Heath, G.R., et al., *Init. Repts. DSDP,* 16: Washington (U.S. Govt. Printing Office), 747–813.

Engebretson, D.C., Cox, A., and Gordon, R.G., 1985. *Relative Motions between Oceanic and Continental Plates in the Pacific Basin*. Spec. Pap.—Geol. Soc. Am., 206.

Fenner, J., 1984. Middle Eocene to Oligocene planktonic diatom stratigraphy from Deep Sea Drilling sites in the South Atlantic, equatorial Pacific, and Indian Oceans. *In* Hay, W.W., Sibuet, J.-C., et al., *Init. Repts. DSDP,* 75 (Pt. 2): Washington (U.S. Govt. Printing Office), 1245–1271.

Goll, R.M., 1976. Morphological intergradation between modern populations of *Lophospyris* and *Phormospyris* (Trissocyclidae, Radiolaria). *Micropaleontology,* 22(4):379–418.

Gripp, A.E., and Gordon, R.G., 1990. Current plate velocities relative to the hotspots incorporating the NUVEL-1 global plate motion model. *Geophys. Res. Lett.,* 17:1109–1112.

Huber, M., 2002. Straw man 1: a preliminary view of the tropical Pacific from a global coupled climate model simulation of the early Paleogene. *In* Lyle, M., Wilson, P.A., Janecek, T.R., et al., *Proc. ODP, Init. Repts.,* 199, 1–30 [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA. [**HTML**]

Kling, S.A., 1979. Vertical distribution of polycystine radiolarians in the central North Pacific. *Mar. Micropaleontol.,* 4:295–318.

Leinen, M., 1985. Techniques for determining opal in deep-sea sediments: a comparison of radiolarian counts and x-ray diffraction data. *Mar. Micropaleontol.,* 9:375–383.

Locker, S., 1996. Quantitative radiolarian slides prepared from soft marine sediments. *Micropaleontology,* 42(4):407–411.

Mayer, L., Theyer, F., Thomas, E., et al., 1985. *Init. Repts. DSDP,* 85: Washington (U.S. Govt. Printing Office).

McGowran, B., 1989. Silica burp in the Eocene Ocean. *Geology,* 17:857–860.

Moore, T.C., 1971. Radiolaria. *In* Tracey, J.I., Jr., Sutton, G.H., et al., *Init. Repts. DSDP,* 8: Washington (U.S. Govt. Printing Office), 727–775.

Moore, T.C., Jr., Rea, D.K., Lyle, M., and Liberty, L.M., 2002. Equatorial ocean circulation in an extreme warm climate. *Paleoceanography,* 17(1):51–56:10.1029/2000PA000566.

Nigrini, C., 1985. Radiolarian biostratigraphy in the central equatorial Pacific, Deep Sea Drilling Project Leg 85. *In* Mayer, L.A., Theyer, F., Thomas, E., et al., *Init. Repts. DSDP,* 85: Washington (U.S. Govt. Printing Office), 511–551.

Petrushevskaya, M.G., 1971. Radiolaria in the plankton and recent sediments from the Indian Ocean and Antarctic. *In* Funnell, B.M., and Riedel, W.R., *The Micropalaeontology of Oceans:* Cambridge (Cambridge Univ. Press), 319–329.

Ragueneau, O., Tréguer, P., Leynaert, A., Anderson, R.F., Brzezinski, M.A., DeMaster, D.J., Dugdale, R.C., Dymond, J., Fischer, G., Francois, R., Heinze, C., Maier-Reimer, E., Martin-Jézéquel, V., Nelson, D.M., and Quéguiner, B., 2000. A review of the Si cycle in the modern ocean: recent progress and missing gaps in the application of biogenic opal as a paleoproductivity proxy. *Global Planet. Change,* 26:317–365.

Sanfilippo, A., and Riedel, W.R., 1985. Cretaceous radiolaria. *In* Bolli, H.M., Saunders, J.B., and Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy:* Cambridge (Cambridge Univ. Press), 573–630.

Schrader, H.-J., 1976. Cenozoic planktonic diatom biostratigraphy of the southern Pacific Ocean. *In* Hollister, C.D., Craddock, C., et al., *Init. Repts. DSDP,* 35: Washington (U.S. Govt. Printing Office), 605–671.

Shipboard Scientific Party, 2002. Leg 199 summary. *In* Lyle, M., Wilson, P.A., Janecek, T.R., et al., *Proc. ODP, Init. Repts.,* 199: College Station TX (Ocean Drilling Program), 1–87. [**HTML**]

Steiger, E., 1998. Die Radiolarien des Campans der kalkalpinen Gosau (Lattengebirge, Bayern) [Ph.D. dissert.]. Ludwig Maximilians Univ., Munich.

Tracey, J.I., Jr., Sutton, G.H., et al., 1971. *Init. Repts. DSDP,* 8: Washington (U.S. Govt. Printing Office).

van Andel, T.H., Heath, G.R., et al., 1973. *Init. Repts. DSDP,* 16: Washington (U.S. Govt. Printing Office).

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science,* 292:686–693.

**Figure F1.** Location of Leg 199 drill sites. Site 1219 is situated north of the Clipperton Fracture Zone (F.Z.) on 56-Ma-old crust at seafloor depths of >5000 mbsl (Shipboard Scientific Party, 2002).

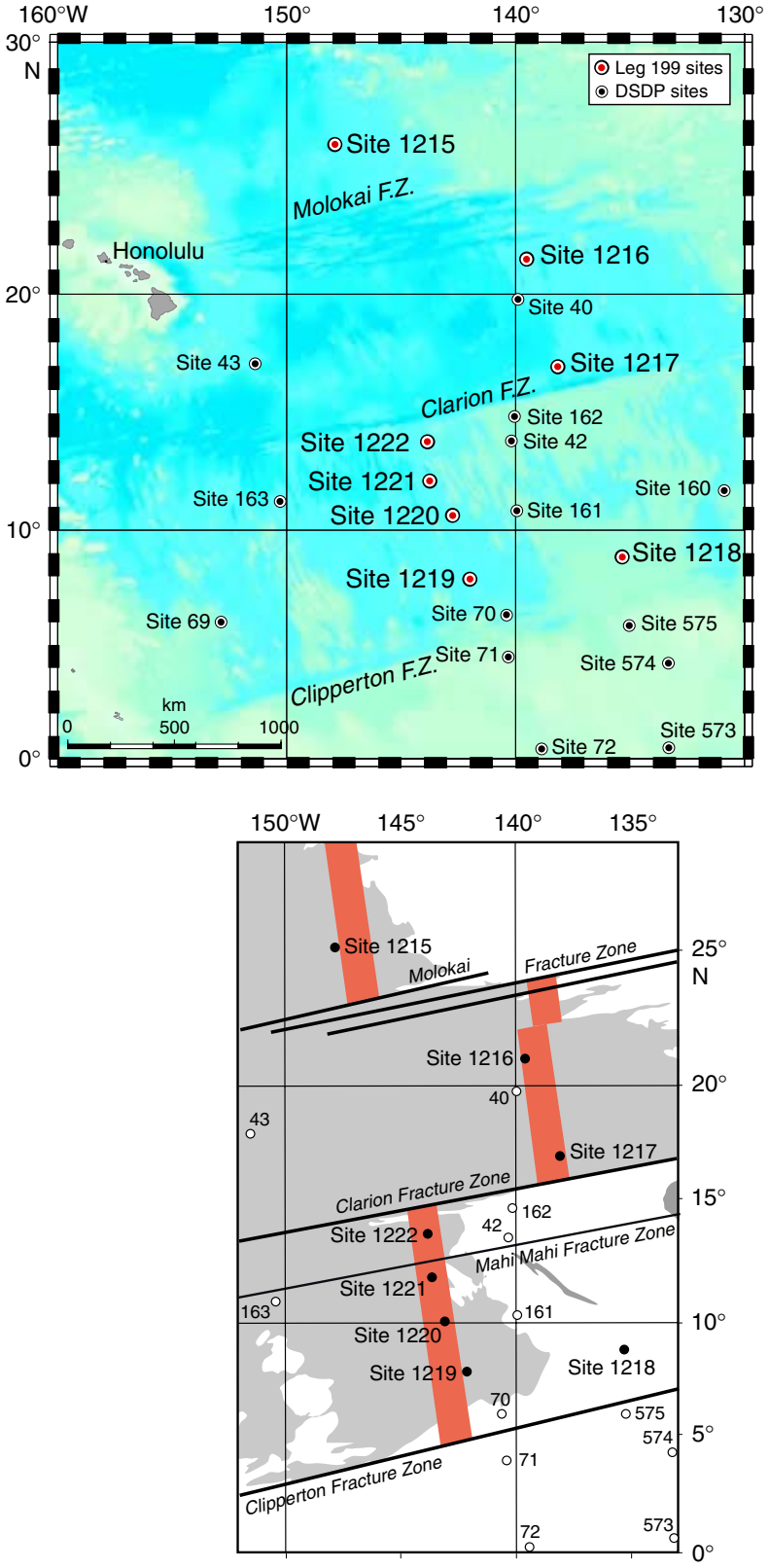

**Figure F2.** Occurrence of diatom events (>5% diatoms) observed in smear slides compared to the estimated positions of the equator crossing in Leg 199 dill sites (Shipboard Scientific Party, 2002). Site 1219 shows two diatom levels—one in the Middle Eocene and one during the Oligocene—along with the equator crossing of the site ~29 m.y. ago. F.Z. = Fracture Zone. N = nassellarians, S = spumellarians.

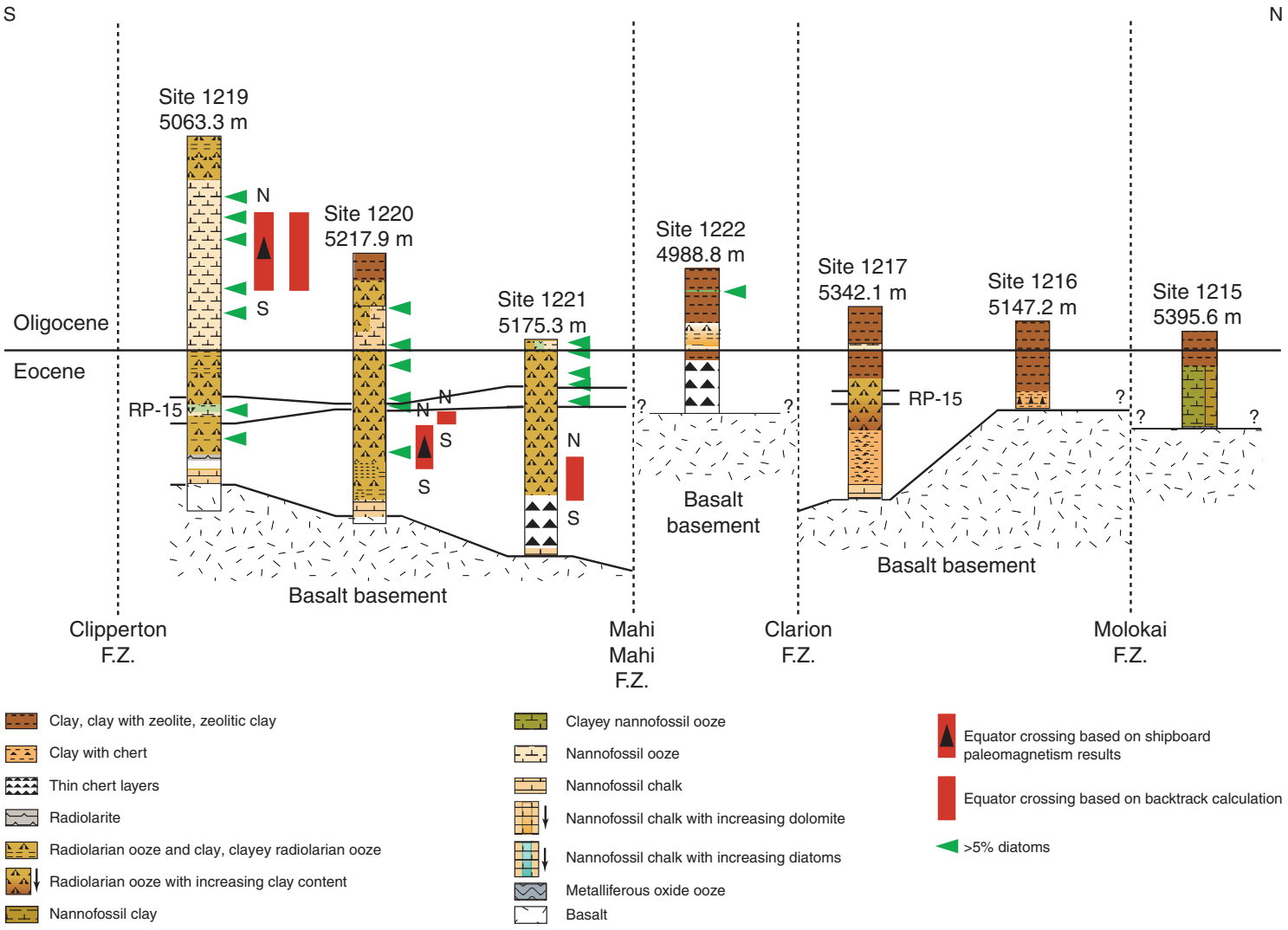

**Figure F3.** Hole 1219A between Cores 199-1219A-22H and 19H, containing vertical distributions of contents of siliceous biota, mineralogy, color reflectance, and physical properties as well as biostratigraphic zonations (Shipboard Scientific Party, 2002).

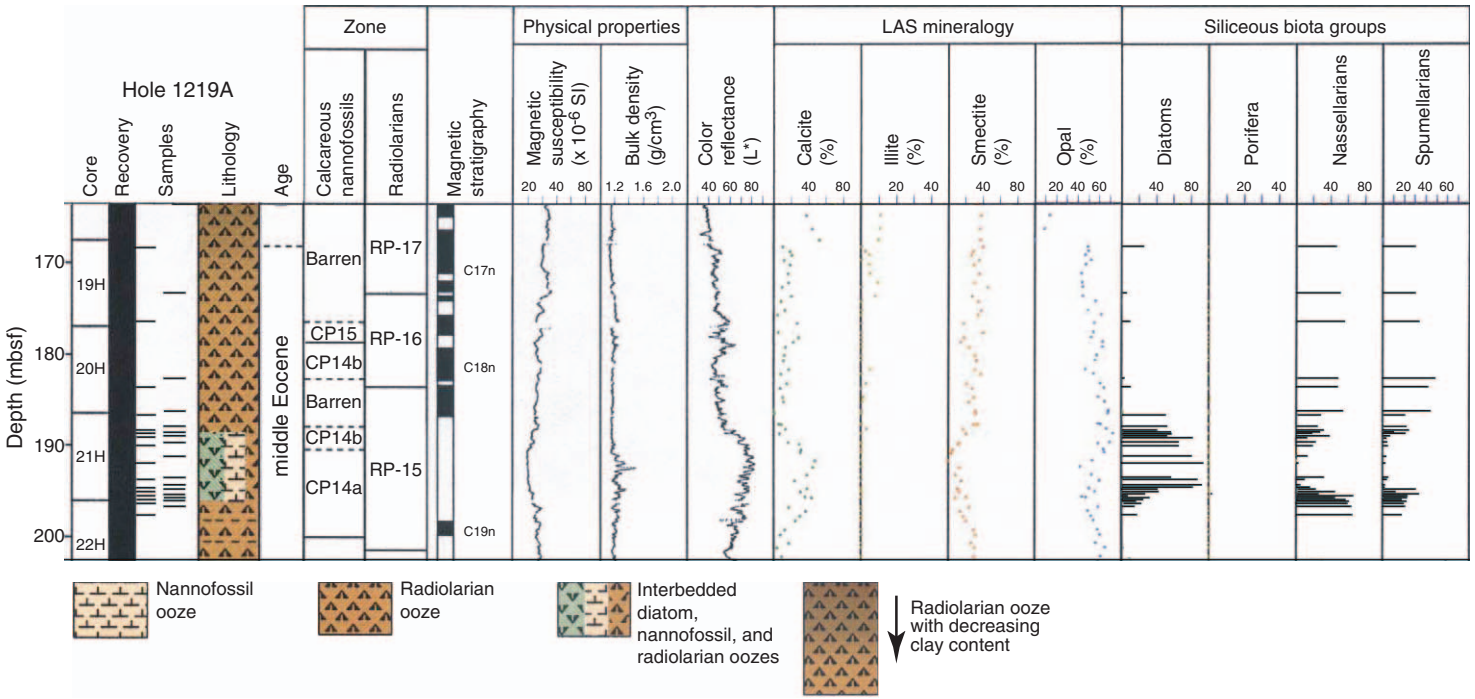

**Figure F4.** Lithologic sequence of the Zone RP-15 diatom-rich interval. Composite core images clearly show color changes and banding representing three diatom-rich intervals and their interpretation with respect to productivity and Si mass accumulation rates (Shipboard Scientific Party, 2002). MAR = mass accumulation rate.

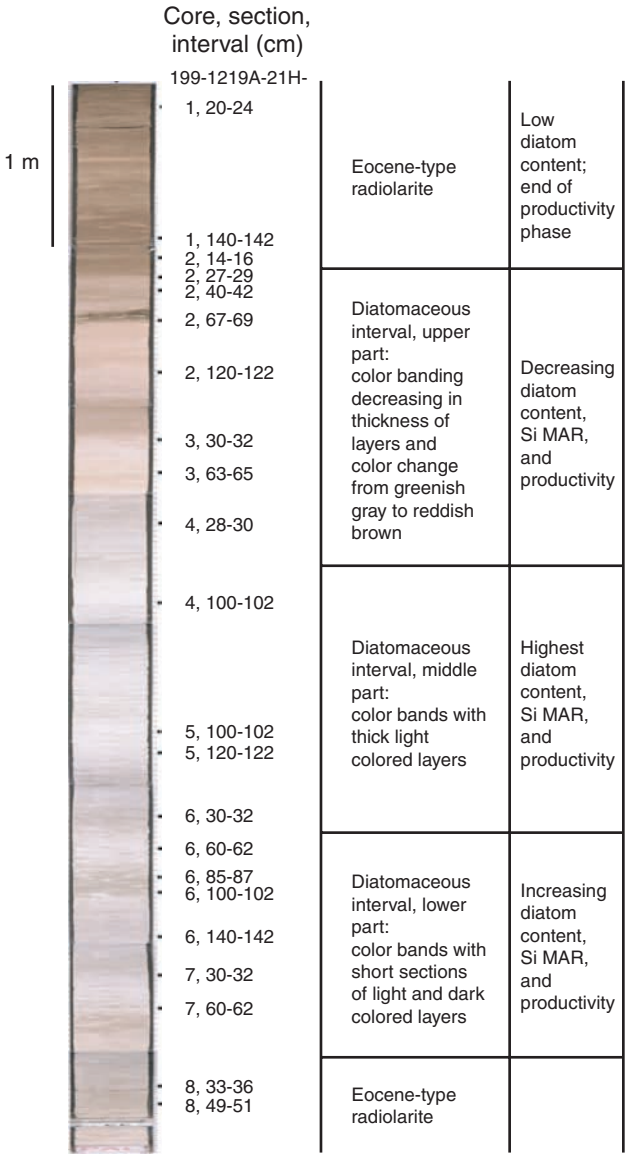

**Figure F5.** Ratios of siliceous organisms between Cores 199-1219A-22H and 19H. **A.** Diatom:radiolarian ratio shows the general trends of diatom development and stepwise reduction in Core 199-1219A-21H. **B.** Impression of radiolarian fluctuations during the diatom interval, mostly reflecting the high occurrences of artostrobids in the samples. (Continued on next page.)

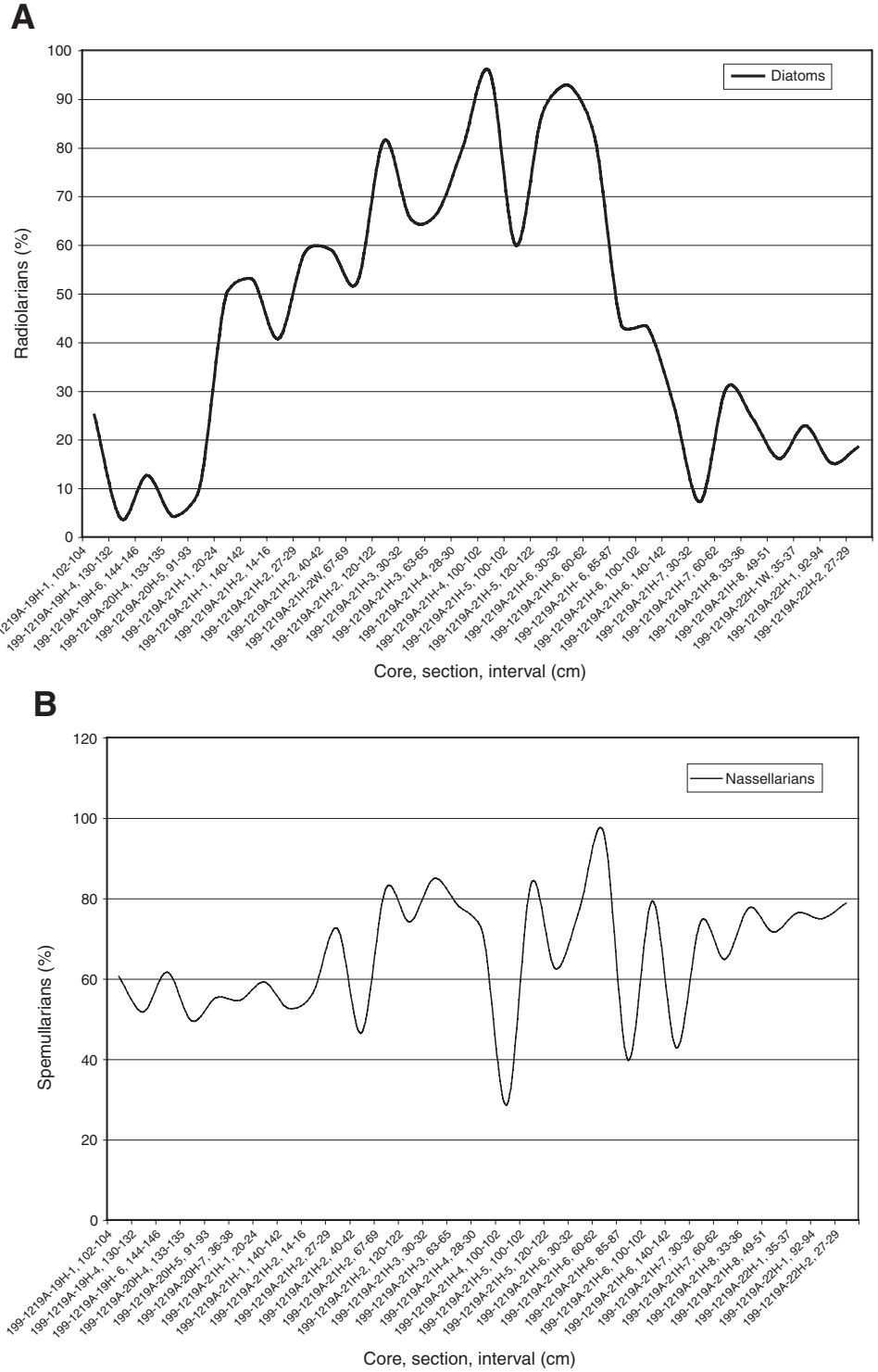

**Figure F5 (continued). C.** General shift of the nassellarian:spumellarian distribution compared to diatom quantities. Because of the increase of actinommids, the nassellarian:spumellarian ratio equals during the final phase of the diatom interval.

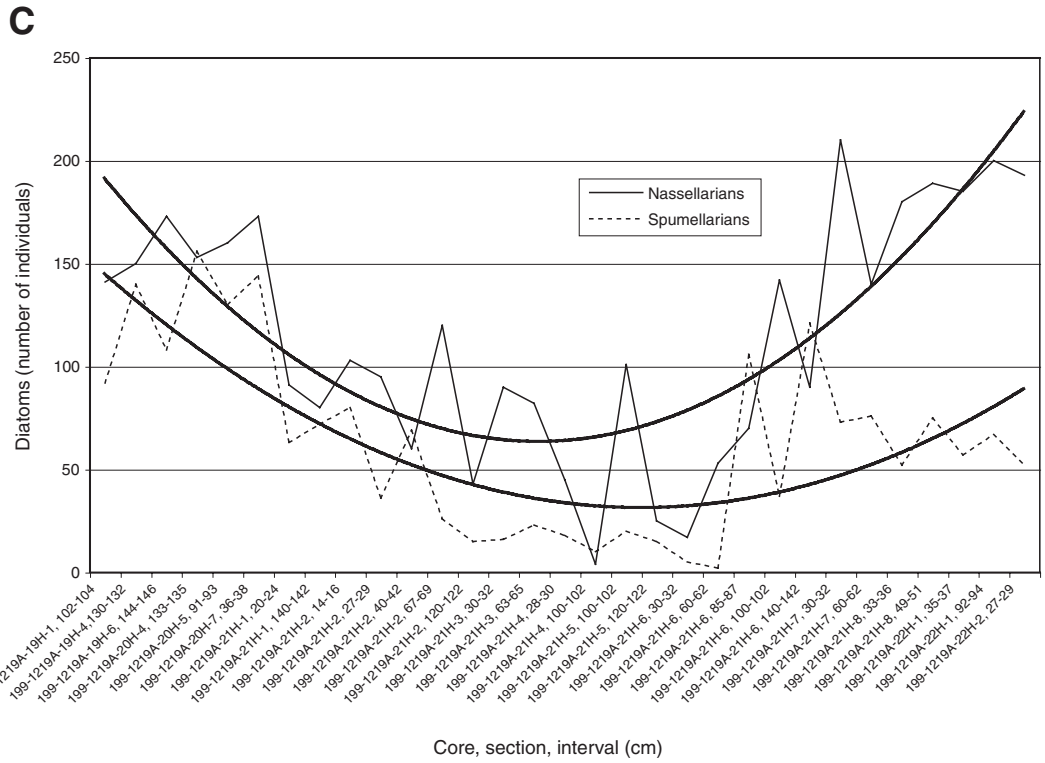

**Figure F6.** Percentages of major radiolarian families in the Zone RP-15 diatom-rich unit. Coccodiscids are distributed without general trend, the theoperid content slightly increases, and actinommids seem to react as a response to the diatom deposition. Artostrobids probably also depend on the occurrence of diatoms, with maximum contents at the beginning and in the terminal phase of diatom deposition.