Silicoflagellate biostratigraphy, Hole 1149A (ODP Leg 185, Nadezhda Basin, Northwestern Pacific).

Publisher:

ODP, Texas A&M University

Published version:

DOI:10.2973/odp.proc.sr.185.009.2003

Ludden, J.N., Plank, T., and Escutia, C. (Eds.)
Proceedings of the Ocean Drilling Program, Scientific Results Volume 185

4. SILICOFLAGELLATE BIOSTRATIGRAPHY, HOLE 1149A (ODP LEG 185, NADEZHDA BASIN, NORTHWESTERN PACIFIC)[1]

Francesca Lozar[2,3] and Massimo Mussa[2]

ABSTRACT

Silicoflagellate assemblages have been studied from Hole 1149A (northwestern Pacific, Ocean Drilling Program Leg 185) in a continuous record of pelagic clay from lithologic Unit I. The biostratigraphic framework of D. Bukry, adapted in this work, is calibrated to tropical and subtropical fossil floras. Four biozones and three subzones have been recognized (from the lower Pliocene *Dictyocha fibula* Zone to the Quaternary *Dictyocha aculeata aculeata* Zone), and their zonal boundaries have been calibrated to the magnetostratigraphic scale. In particular, the boundary between the *Dictyocha perlaevis delicata* and the *Dictyocha perlaevis ornata* Subzones approximates the Pliocene/Pleistocene boundary.

The identification of three closely spaced climatic events (the asperoid/fibuloid reversal at 75.11 meters below seafloor [mbsf], the sharp decrease in abundance of *Distephanus* sp. at 70.05 mbsf, and the last occurrence of *Distephanus boliviensis* at 68.46 mbsf) indicates the increased strength of the warm Kuroshio Current in the interval between 3.3 and 2.8 Ma, due to the final closure of the Central American Seaway and leading to the present-day hydrodynamic regime.

The beginning of the acme of *Mesocena quadrangula* at 37.01 mbsf (~1.1 Ma) also shows a sharp warming in surface waters.

---

[1] Lozar, F., and Mussa, M., 2003. Silicoflagellate biostratigraphy, Hole 1149A (ODP Leg 185, Nadezhda Basin, northwestern Pacific). *In* Ludden, J.N., Plank, T., and Escutia, C. (Eds.), *Proc. ODP, Sci. Results,* 185, 1–18 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/185_SR/VOLUME/CHAPTERS/009.PDF>. [Cited YYYY-MM-DD]

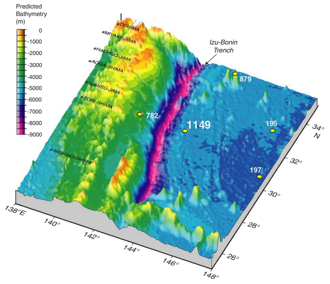
[2] Dipartimento di Scienze della Terra, Università degli Studi di Torino, via Accademia delle Scienze 5, I-10123 Torino, Italy. Correspondence author: **francesca.lozar@unito.it**

[3] CNR Istituto di Geoscienze e Georisorse, via Accademia delle Scienze 5, I-10123 Torino, Italy.

Initial receipt: 6 November 2001
Acceptance: 20 November 2002
Web publication: 31 March 2003
Ms 185SR-009

INTRODUCTION

Site 1149 was drilled in the northwestern Pacific during Ocean Drilling Program (ODP) Leg 185; it is located at 31.3°N, 143.3°E, on the Pacific plate in the Nadezhda Basin southeast of Japan in a water depth of ~5800 m. It resides among low abyssal hills on a slight high ~100 km east of the Izu-Bonin Trench, where the Pacific plate is flexed upward prior to its entry into the subduction zone (Fig. **F1**).


F1. Location of Site 1149, p. 14.

One of the objectives of drilling at Site 1149 was to obtain a reference site for the Cretaceous Pacific oceanic crust and its sedimentary cover being transported into the Izu-Bonin subduction zone, in order to compare the geochemical fluxes into the Izu-Bonin arc system with those of the Mariana arc, which show significant differences in key elements. Other goals of the drilling were to compare basement alteration characteristics to those in Hole 801C, to provide constraints on the Early Cretaceous paleomagnetic timescale (Plank, Ludden, Escutia, et al., 2000), and to provide constraints on mid-Cretaceous carbonate compensation depth (CCD) and equatorial circulation fluctuations in the western Pacific.

Besides the major goals of the leg, this study will provide new data on silicoflagellate biostratigraphy and paleoceanography in the late Neogene Pacific Ocean and will help to constrain some silicoflagellate bioevents with the geochronologic timescale of Berggren et al. (1995).

The sedimentary section recovered at Site 1149 ranges from Lower Cretaceous to Pleistocene. The top of the section, recovered in Hole 1149A, consists of carbonate-free clay with common and discreet ash layers and dispersed ashes, containing relatively abundant and well-preserved assemblages of diatoms, radiolarians, silicoflagellates, ebridians, and sponge spicules (lithologic Unit I; 0–118.2 meters below seafloor [mbsf]) (Plank, Ludden, Escutia et al., 2000), and dark brown pelagic clays (Unit II; 118.2–179.1 mbsf) (Plank, Ludden, Escutia et al., 2000). Unit II clays are barren of any siliceous or calcareous microfossils but contain ichthyoliths. According to shipboard magnetostratigraphic data, Unit I in Hole 1149A ranges from late Miocene to Pleistocene age (Plank, Ludden, Escutia, et al., 2000); Unit II is still undated (ichthyolith biostratigraphy is in progress; F. Lozar, pers. comm., 2001).

This study deals with the biostratigraphic and paleoceanographic analysis of silicoflagellate assemblages recovered from Unit I in Hole 1149A. The silicoflagellates are a minor component of the marine phytoplankton, but their potential is good for biostratigraphic and paleoceanographic correlation in marine sediments deposited below the calcite compensation depth (CCD) and under upwelling conditions or high-nutrient water masses (Bukry, 1995).

MATERIAL AND METHODS

Studied samples are from lithologic Unit I. From Sample 185-1149A-12H-1, 135–141 cm, to its bottom (118.20 mbsf), Unit I is barren of silicoflagellates. Semiquantitative analyses of silicoflagellate assemblages was performed on 43 samples. Sample observation was performed under a polarizing light microscope at 400× magnification. Sample preparation was kept simple, and smear slides were prepared directly from the sediment samples using standard preparation techniques as for calcareous nannofossil analysis.

Abundance of biogenic particles, including silicoflagellates, radiolarians, diatoms, and sponge spicules, was estimated by comparing their abundance with the entire fine fraction (biogenic and abiogenic particles) following the method of Baccelle and Bosellini (1965). The following letter codes were adopted for total abundance:

V = very abundant (>50% of the fine fraction).
A = abundant (40% to 50% of the fine fraction).
C = common (20% to 40% of the fine fraction).
F = few (5% to 20% of the fine fraction).
R = rare (<5% of the fine fraction).
B = barren.

The presence of volcanic glass is recorded in the fifth column of the range chart (Table **T1**):

T1. Silicoflagellate distribution, p. 16.

N = absent.
S = present (<15% of the fine fraction).
A = abundant (>15% of the fine fraction).

The relative abundance of individual silicoflagellate species was tabulated in the range chart (Table **T1**) as follows:

A = abundant (>10 specimens per 50 field of view).
C = common (2–10 specimens per 50 fields of view).
F = few (1 specimen per 50–100 fields of view).
R = rare (1 specimen per 100–200 fields of view).
VR = very rare (1 specimen per 200–400 fields of view).

The last column in the range chart (Table **T1**) records the presence and relative abundance of aberrant silicoflagellate morphologies in the assemblages:

C = common (>1 specimen per 50–100 fields of view).
F = few (1 specimen per 50–100 fields of view).
R = rare (1 specimen per 100–200 fields of view).
N = absent.

Occurrence of other siliceous microfossil groups observed in the samples is also recorded in the range chart:

R = radiolarians.
D = diatoms.
S = silicoflagellates.
SP = sponge spicules.

All the species considered in this work and tabulated in the range chart are listed, ordered by generic epithets, in the **"Taxonomic Appendix,"** p. 13.

BIOSTRATIGRAPHY

Silicoflagellates belong to a small group of siliceous marine phytoplankton. Their siliceous skeleton is very susceptible to dissolution, and therefore their preservation is often hindered by diagenetic processes; moreover, their abundance is relatively low compared to that of other siliceous microfossils; both these reasons make their presence rare in the sedimentary record. Their paleogeographic distribution is often influenced by paleoceanography, driving adaptations of the paleocommunities to water masses and current systems that may control nutrient supply and temperature changes, giving origin to relatively well separated latitudinal bioprovinces. In recent years, a general biostratigraphic framework for temperate to warm waters at middle to low latitudes as been developed (Bukry, 1981b, 1983, 1985, 1995; Perch-Nielsen, 1985), whereas a different scheme is applicable to cold-water assemblages at high latitudes (Locker, 1995, and references therein). In general, the scheme used for Hole 1149A is that proposed by Bukry (1981b), but it differs in the identification of some datum levels because of the rarity or absence of some of the zonal markers used in Bukry's biozonation.

In the stratigraphic section recovered in Hole 1149A, four silicoflagellate biozones and three subzones have been recognized. Zones and particularly significant bioevents are described as follows in stratigraphic order.

Dictyocha fibula **Zone (Martini, 1971) Bukry, 1977**

Boundaries

Base = first occurrence (FO) of *Dictyocha neonautica,* not recorded in Hole 1149A.

Top = FO of *Dictyocha stapedia stapedia* in Sample 185-1149A-8H-4, 135–140 cm (67.05 mbsf).

Fossil Assemblage

Dictyocha aspera aspera, D. fibula, Dictyocha perlaevis perlaevis, Dictyocha brevispina brevispina, Dictyocha brevispina ausonia, Dictyocha stapedia aspinosa, Dictyocha pulchella, Dictyocha longa, Dictyocha calida calida, Distephanus speculum speculum, Distephanus crux s.l.*, Distephanus speculum minutus, D. boliviensis, Distephanus speculum pentagonus, Mesocena circulus, Mesocena elliptica,* and *Corbisema triachanta.*

Comments

D. fibula s.l. and *D. aspera,* together with *D. speculum speculum* are the most common taxa in this interval. *D. fibula,* the zonal marker, is the dominant species in most of the assemblages.

Bukry (1983, 1995) subdivides this zone into three subzones, from bottom to top: *D. neonautica, D. pulchella,* and *Dictyocha angulata* Subzones. The *D. neonautica* Subzone, defined as the interval between the FO and last occurrence (LO) of the marker species, is missing in Hole 1149A; this is compatible with our record, since the upper Miocene part of the section is barren of siliceous microfossils. The scattered occurrence of *D. pulchella* allows the identification of the homonymous subzone, spanning from the LO of *D. neonautica* to the LO of the marker species in the original definition (Bukry, 1983). The LO of *D. pulchella* is present in Sample 185-1149A-8H-5, 126–132 cm (68.46 mbsf), just below the FO of *D. stapedia stapedia,* indicating the base of the homonymous zone. The *D. angulata* Subzone, defined as the interval of common occurrence of the marker species above the LO of *D. pulchella* and below the FO of *D. stapedia stapedia* (Bukry, 1983), is not identified in the studied material. Two hypotheses may justify this result: the *D.*

angulata Subzone is very short (or condensed) in Hole 1149A and the sampling spacing (~1.5 m) did not allow its identification, or the subzone is missing because a hiatus occurs. This second hypothesis is not supported by the paleomagnetic data, which show a continuous and well-documented record of chronozones. The absence of *D. angulata* could also be ascribed to rarity of this marker species in our material. Unfortunately, Bukry (1982, 1983, 1984) has already pointed out that the upper boundary of the *D. pulchella* Subzone is troublesome, since *D. pulchella* has rarely been recorded also in the overlying *D. stapedia stapedia* Zone (Bukry, 1983).

In Hole 1149A then, only the *D. pulchella* Subzone is identified, and it corresponds to the upper part of the *D. fibula* Zone.

Two significant climatic bioevents occur in this zone: (1) from 75.11 mbsf the assemblage (dominated by *Dictyocha* species with the apical bar oriented along the minor axis [asperoid] in the interval below) is dominated by *Dictyocha* species with apical bar oriented along the major axis (fibuloid); this event is classically known as the asperoid/fibuloid reversal; (2) at ~75–70 mbsf we observe the decrease in abundance of *Distephanus* ssp., particularly the last occurrence of *D. boliviensis,* recorded in the upper part of the zone in Sample 185-1149A-8H-5, 126–132 cm (68.46 mbsf).

The presence of few Miocene taxa, such as *M. elliptica* and *C. triachanta,* is problematic. The presence of *C. triachanta* could be related to reworking, as suggested also by Bukry (1982) for samples from Deep Sea Drilling Project (DSDP) Site 503 from the same biozone. The same hypothesis is suggested for the presence of *M. elliptica,* a Miocene species, in Sample 185-1149A-11H-1, 136–142 cm (91.06 mbsf).

The presence of *D. calida calida* and *D. stapedia aspinosa,* both common taxa of the overlying *D. stapedia stapedia* Zone, confirms Bukry's observation (1983, 1984) and supports an extended range for these two species, at least in the Pacific Ocean.

Dictyocha stapedia stapedia Zone (Bukry, 1977)

Boundaries

Base = FO *D. stapedia stapedia* in Sample 185-1149A-8H-4, 135–140 cm (67.05 mbsf).

Top = acme beginning of *M. quadrangula* in Sample 185-1149A-5H-3, 131–137 cm (37.01 mbsf).

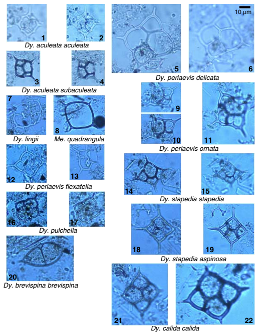
Fossil Assemblage

D. fibula, D. perlaevis perlaevis, D. stapedia aspinosa, D. calida calida, D. stapedia stapedia, Dictyocha perlaevis flexatella, D. perlaevis ornata, D. perlaevis delicata, Dictyocha calida ampliata, Dictyocha lingii, D. speculum speculum, D. crux s.l., *D. speculum minutus, D. speculum pentagonus, M. circulus, M. quadrangula, C. triachanta* (Pls. **P1**, **P2**).

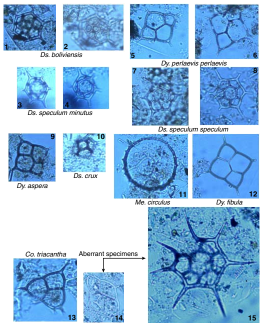
Comments

D. stapedia stapedia and *D. calida ampliata* are the most common taxa in this biozone; *D. calida calida* and *D. fibula* are also present along most of the interval, whereas other taxa such as *D. speculum speculum* and *D. perlaevis perlaevis* gradually decrease and eventually disappear at the top of the zone. Several subspecies of *Dictyocha perlaevis* were observed in this interval (*D. perlaevis flexatella, D. perlaevis ornata,* and *D. perlaevis delicata),* some of them allowing the identification (from bottom to top)

P1. Silicoflagellates, p. 17.



P2. Silicoflagellates, p. 18.



of the *D. perlaevis ornata* Subzone (Bukry, 1981b) and the *D. perlaevis delicata* Subzone (Bukry, 1976).

In general, the fossil assemblage characterizing this zone has a lower specific diversity with respect to the underlying zone. Most of the species belonging to the genus *Distephanus* have their last occurrence at the top of the zone.

The presence of *D. crux* s.l. and *C. triachanta* in this zone are problematic and could be related to reworking. In particular, the presence of *C. triachanta* is also recorded in the *D. stapedia stapedia* at DSDP Site 503A at ~51 mbsf (Bukry, 1982), suggesting reworking of older sediments.

The presence of *D. lingii,* a taxon usually reported from younger sediments, could be explained by an extended range of this species, as also suggested by Bukry (1983), who reported this taxon in the *D. stapedia stapedia* Zone from the bottom of the *D. perlaevis ornata* Subzone.

***Dictyocha perlaevis ornata* Subzone (Bukry, 1981a).**

Boundaries

Base = FO of *D. stapedia stapedia* in Sample 185-1149A-8H-4, 135–140 cm (67.05 mbsf).

Top = FO of *D. perlaevis delicata,* in Sample 185-1149A-6H-3, 133–139 cm (46.53 mbsf).

Fossil Assemblage

D. speculum speculum, M. circulus, D. fibula, D. crux s.l., *D. perlaevis perlaevis, Distephanus speculum minutus, D. speculum pentagonus, D. stapedia aspinosa, C. triachanta, D. calida calida, D. stapedia stapedia, D. perlaevis flexatella, D. perlaevis ornata,* and *D. calida ampliata.*

Comments

The marker species *D. perlaevis ornata* is rare in the assemblage. Noteworthy are the presence of *D. perlaevis flexatella,* which is usually rare, and limited to the lower *D. perlaevis ornata* Subzone, and the scattered occurrence of *D. speculum speculum* above Sample 185-1149A-8H-3, 127–133 cm (65.47 mbsf).

***Dictyocha perlaevis delicata* Subzone (Bukry, 1976)**

Boundaries

Base = FO of *D. perlaevis delicata* in Sample 185-1149A-6H-3, 133–139 cm (46.53 mbsf).

Top = acme beginning of *M. quadrangula* in Sample 185-1149A-5H-3, 131–137 cm (37.01 mbsf).

Fossil Assemblage

D. speculum speculum, D. fibula, D. crux s.l., *D. perlaevis perlaevis, D. speculum pentagonus, D. stapedia aspinosa, D. calida calida, D. stapedia stapedia, D. perlaevis ornata, D. calida ampliata, D. lingii, M. quadrangula,* and *D. perlaevis delicata.*

Comments

The marker species *D. perlaevis delicata*, together with *M. quadrangula,* are present in low abundances in this subzone.

Mesocena quadrangula Zone (Bukry and Foster, 1973; emended this work)

Boundaries

Base = beginning of the acme of *M. quadrangula*, in Sample 185-1149A-5H-3, 131–137 cm (37.01 mbsf).

Top = LO of *D. lingii*, in Sample 185-1149A-4H-1, 134–141 cm (24.54 mbsf).

Fossil Assemblage

D. fibula, D. speculum pentagonus, D. calida calida, D. stapedia stapedia, D. calida ampliata, D. lingii, M. quadrangula, Dictyocha aculeata subaculeata, Distephanus octangulatus, and *D. aculeata aculeata.*

Comments

In the original definition, this zone is described as the acme interval of the marker *M. quadrangula* (Bukry and Foster, 1973). This sharp signal has not been recorded in the studied material, where *M. quadrangula* shows a relatively high abundance only in Sample 185-1149A-5H-3, 131–137 cm. Other samples studied from Core 185-1149A-5H are barren of silicoflagellates, and this could obliterate the acme signal in the studied section.

Since the acme end of *M. quadrangula* is not clearly recognizable at Site 1149, in this work the top of the zone is here recognized with the LO of *D. lingii,* which correlates to the acme end of *M. quadrangula* (Perch-Nielsen, 1985). In addition, *D. lingii* is the most common taxon in this zone.

Within this zone, the specific diversity and total abundance of silicoflagellates drop dramatically. The extreme rareness of the genus *Distephanus* also characterizes this zone.

D. aculeata aculeata occurs in high abundance in the upper part of this subzone; this datum is in agreement with other findings in the same time interval (Perch-Nielsen, 1985) and suggests an extended range of this taxon.

Dictyocha aculeata aculeata Zone (Bukry, 1979)

Boundaries

Base = LO of *D. lingii* in Sample 185-1149A-3H-5, 125–131 cm (20.95 mbsf).

Top = recent.

Fossil assemblage

D. fibula, D. calida calida, D. aculeata subaculeata, and *D. aculeata aculeata.*

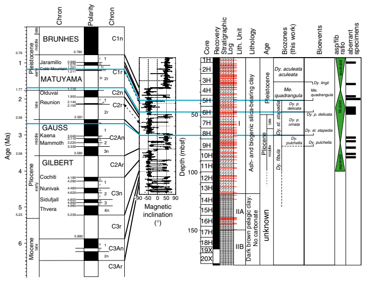
Comments

D. aculeata aculeata dominates the assemblage; in general, other *Dictyocha* spp., with a non-aculeatid morphology, dramatically decline in this interval. Specimen size is smaller than in the underlying sediments.

Main Biostratigraphic and Paleoclimatic Events Recorded at Site 1149

The paleomagnetic stratigraphy obtained from continuous core recovery in Hole 1149A (103% average recovery rate in Unit I) (Plank, Ludden, Escutia, et al., 2000) allowed silicoflagellate events to be directly calibrated to the geomagnetic timescale (Berggren et al., 1995) for the first time. The boundary between the *D. fibula* and the *D. stapedia stapedia* Zones falls in Subchron C2An.1n, in the upper middle Pliocene, in agreement with data presented by Rio et al. (1989). The boundary between the *D. perlaevis ornata* and the *D. perlaevis delicata* Subzones falls in Subchron C1r.2r.2r and results as a good proxy for the Pliocene/Pleistocene boundary (Fig. F2). The base of the *M. quadrangula* Zone is correlated to Subchron C1r.2r.1r (lower Pleistocene).

F2. Stratigraphy of upper Cenozoic Unit I, p. 15.



Several authors in the past have stressed that silicoflagellates are very sensitive to temperature variations (Gemeinhardt, 1934; Mandra, 1969; Ciesielsky and Weaver, 1974; Van Valkenburg, 1980; Bukry and Monechi, 1985). At present, assemblages dominated by the genus *Distephanus* correlate with low surface temperature, whereas the genus *Dictyocha* dominates in warm to temperate waters (Mandra, 1969; Mandra and Mandra, 1971, 1972; Ciesielsky and Weaver, 1974; Ciesielsky, 1975; McCartney, 1993). The *Dictyocha/Distephanus* ratio is then used as temperature proxy in extant and fossil material. Moreover, in older sediments, the ratio between two *Dictyocha* morphotypes (asperoid/fibuloid) could be used as paleotemperature proxy, with dominant fibuloid morphologies correlating to warmer conditions. We record this reversal in lower Pliocene sediments, confirming the observation of Bukry (1981b, 1995) that this bioevent can no longer be used as a proxy for the Miocene/Pliocene boundary (Martini, 1971); in fact it is diachronous and it only has climatic significance, indicating a major climatic change toward warmer climates.

At Site 1149 the asperoid/fibuloid reversal occurs in Sample 185-1149A-9H-3, 141–147 cm (75.11 mbsf), and it is closely followed by the change in the *Distephanus/Dictyocha* ratio above (*Distephanus* decreases abruptly at 70.11 mbsf). The LO of *D. boliviensis,* a well-known cool-water marker, is recorded in Sample 185-1149A-8H-5, 126–132 cm (68.46 mbsf). All these events, pointing to a warming of the surface waters between 75 and 68 mbsf (Subchron C2An.1n; lower–middle Pliocene), occur in the upper part of the *D. fibula* Zone (*D. pulchella* Subzone). The close succession of these events, pointing to increasingly unstable water conditions (asperoid/fibuloid reversal and *Distephanus* crisis) followed by a sharp warming (disappearance of *D. boliviensis*) occur in a relatively short time interval (middle Pliocene; 3.3–2.8 Ma). This same time interval has recently been indicated as the final stage of the closure of the Central American Seaway (Tsuchi, 1997), culminating in the final emergence of the Isthmus of Panama. This paleotectonic event marked a dramatic change in the hydrodynamic conditions of both the Pacific and Atlantic Oceans, decreasing the east-west flow and improving the circulation of gyrelike currents. According to Tsuchi (1997), this resulted in an increased strength of the warm Kuroshio Current and led to the present-day hydrodynamic regime. The Kuroshio Current moved its flow closer to the eastern edge of the Asian continent, thus warming both the open ocean waters and the nearshore areas, as it is also recorded by the so-called Sagara molluscan fauna from the sediments of the Pacific coast of Japan (Tsuchi, 1997).

Other biostratigraphic and paleoclimatic signals recorded in our material are the beginning of the acme of *M. quadrangula* occurring in Sample 185-1149A-5H-3, 131–137 cm (37.01 mbsf), which correlates to a well-known warm-water event (Martini, 1971; Bukry and Foster, 1973; Burkle, 1977; Bukry, 1979).

The beginning of the acme of *D. aculeata* is present in Sample 185-1149A-4H-3, 134–141 cm (27.54 mbsf), and correlates to the sharp decline of other (fibuloid) dictyochid morphotypes; small-sized aculeatid silicoflagellate skeletons that record adverse environmental conditions (Perch-Nielsen, 1985; McCartney, 1993) are present upsection from this level.

We have also recorded the abundance of aberrant morphologies in the silicoflagellate assemblages; this datum has been regarded as an interesting palaeoecological proxy in recent studies on extant laboratory cultured assemblages (Van Valkenburg and Norris, 1970; McCartney and Loper, 1989; McCartney, 1993). However, our preliminary data do not show a sharp correlation with silicoflagellate blooms or with low volcanic glass in the sediments (Fig. F2, Table T1), even if, in general, high abundances of volcanic glass correlate with low silicoflagellate abundances and absence of aberrant morphologies.

SUMMARY

Silicoflagellate analyses of clayey sediments recovered in Unit I from Hole 1149A allowed us to

1. Identify four zones and three subzones;
2. Calibrate the boundary between the *D. perlaevis ornata* and the *D. perlaevis delicata* Subzones to Subchron C1r.2r.2r (close to the Pliocene/Pleistocene boundary);
3. Calibrate the boundary between the *D. fibula* and the *D. stapedia stapedia* Zones to Subchron C2An.1n (upper middle Pliocene);
4. Calibrate the base of the *M. quadrangula* Zone to Subchron C1r.2r.1r (lower Pleistocene);
5. Track the increasing warming of surface waters due to the diverted Kuroshio Current in relation to the middle Pliocene closure of the Central American Seaway using three closely spaced events: the asperoid/fibuloid reversal at 75.11 mbsf, the change in the *Distephanus/Dictyocha* ratio at 70.05 mbsf, and the LO of *D. boliviensis* at 68.46 mbsf; and
6. Identify the *M. quadrangula* acme beginning at 37.01 mbsf (lower Pleistocene) and correlate it to a warm-water event.

ACKNOWLEDGMENTS

We are indebted to ODP for providing samples for this study. We would also like to specially thank David Bukry for his precious help and Raffaella Ruffini for useful discussion on the volcanic input. The reviews of the referees Isabella Raffi and Francine McCarthy are warmly acknowledged. This research used samples provided by the Ocean Drilling Program (ODP). The ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI), Inc. Funding for this research was provided by CNR (Consiglio Nazionale delle Ricerche, Italy) and MIUR (Ministero dell'Istruzione, Università e Ricerca, Italy).

REFERENCES

Baccelle, L., and Bosellini, A., 1965. Diagrammi per la stima visiva della composizione percentuale nelle rocce sedimentarie. *Ann. Univ. Ferrara, N. Ser., Sez. IX, Sci. Geol. Paleontol.,* 1:59–62.

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. *In* Berggren, W.A., Kent, D.V., Aubry, M.-P., and Hardenbol, J. (Eds.), *Geochronology, Time Scales and Global Stratigraphic Correlation.* Spec. Publ.—SEPM, 54:129–212.

Bukry, D., 1975. Silicoflagellate and coccolith stratigraphy, Deep Sea Drilling Project, Leg 29. *In* Kennett, J.P., Houtz, R.E., et al., *Init. Repts. DSDP,* 29: Washington (U.S. Govt. Printing Office), 845–872.

————, 1976. Silicoflagellate and coccolith stratigraphy, southeastern Pacific Ocean, Deep Sea Drilling Project Leg 34. *In* Yeats, R.S., Hart, S.R., et al., *Init. Repts. DSDP,* 34: Washington (U.S. Govt. Printing Office), 715–735.

————, 1977. Coccolith and silicoflagellate stratigraphy, central north Atlantic Ocean, Deep Sea Drilling Project Leg 37. *In* Aumento, F., Melson, W.G., et al., *Init. Repts. DSDP,* 37: Washington (U.S. Govt. Printing Office), 917–927.

————, 1978. Cenozoic coccolith and silicoflagellate stratigraphy, offshore northwest Africa, Deep Sea Drilling Project Leg 41. *In* Lancelot, Y., Seibold, E., et al., *Init. Repts. DSDP,* 41: Washington (U.S. Govt. Printing Office), 689–707.

————, 1979. Comments on opal phytoliths and stratigraphy of Neogene silicoflagellates and coccoliths at Deep Sea Drilling Project Site 397 off northwest Africa. *In* Luyendyk, B.P., Cann, J.R., et al., *Init. Repts. DSDP,* 49: Washington (U.S. Govt. Printing Office), 977–1009.

————, 1980. Silicoflagellate biostratigraphy and paleoecology in the eastern equatorial Pacific, Deep Sea Drilling Project Leg 54. *In* Rosendahl, B.R., Hekinian, R., et al., *Init. Repts. DSDP,* 54: Washington (U.S. Govt. Printing Office), 545–573.

————, 1981a. Silicoflagellate stratigraphy of offshore California and Baja California, Deep Sea Drilling Project Leg 63. *In* Yeats, R.S., Haq, B.U., et al., *Init. Repts DSDP,* 63: Washington (U.S. Govt. Printing Office), 539–557.

————, 1981b. Synthesis of silicoflagellate stratigraphy for Maestrichtian to Quaternary marine sediments. *In* Warme, T.E., Douglas, R.C., and Winterer, E.L. (Eds.), *The Deep Sea Drilling Project: A Decade of Progress.* Spec. Publ.—SEPM, 32:433–444.

————, 1982. Cenozoic silicoflagellates from offshore Guatemala, Deep Sea Drilling Project Site 495. *In* Aubouin, J., von Huene, R., et al., *Init. Repts. DSDP,* 67: Washington (U.S. Govt. Printing Office), 425–445.

————, 1983. Upper Cenozoic silicoflagellates from offshore Ecuador, Deep Sea Drilling Project Site 504. *In* Cann, J.R., Langseth, M.G., Honnorez, J., Von Herzen, R.P., White, S.M., et al., *Init. Repts. DSDP,* 69: Washington (U.S. Govt. Printing Office), 321–342.

————, 1984. Pacific climatostratigraphy by oceanic silicoflagellates. *U.S. Geol. Surv. Prof. Pap.,* 1375:1–179.

————, 1985. Tropical Pacific silicoflagellate zonation and paleotemperature trends of the late Cenozoic. *In* Mayer, L., Theyer, F., Thomas, E., et al., *Init. Repts. DSDP,* 85: Washington (U.S. Govt. Printing Office), 477–497.

————, 1995. Silicoflagellates and their geological application. *Open-File Rep.—U.S. Geol. Surv.,* 95–260:1–27.

Bukry, D., and Foster, J.H., 1973. Silicoflagellate and diatom stratigraphy, Leg 16, Deep Sea Drilling Project. *In* van Andel, T.H., Heath, G.R., et al., *Init. Repts. DSDP,* 16: Washington (U.S. Govt. Printing Office), 815–871.

————, 1974. Silicoflagellate zonation of Upper Cretaceous to lower Miocene deep sea sediments. *J. Res. U.S. Geol. Surv.,* 2:303–310.

Bukry, D., and Monechi, S., 1985. Late Cenozoic silicoflagellates from the Northwest Pacific, Deep Sea Drilling Project Leg 86: paleotemperature trends and texture classification. *In* Heath, G.R., Burckle, L.H., et al., *Init. Repts. DSDP,* 86: Washington (U.S. Govt. Printing Office), 367–397.

Burckle, L.H., 1977. Pliocene and Pleistocene diatom datum levels from the equatorial Pacific. *Quat. Res.,* 7:330–340.

Ciesielski, P.F., 1975. Biostratigraphy and paleoecology of Neogene and Oligocene silicoflagellates from cores recovered during Antarctic Leg 28, Deep Sea Drilling Project. *In* Hayes, D.E., Frakes, L.A., et al., *Init. Repts. DSDP,* 28: Washington (U.S. Govt. Printing Office), 625–691.

Ciesielski, P.F., and Weaver, F.M., 1974. Early Pliocene temperature changes in the Antarctic Seas. *Geology,* 2:511–515.

Deflandre, G., 1950. Contribution a l'étude des silicoflagellidés actuels et fossiles. *Microscopie,* 2:72–108.

Dumitrica, P., 1973. Paleocene, late Oligocene and post-Oligocene silicoflagellates in southwestern Pacific sediments cored on DSDP Leg 21. *In* Burns, R.E., Andrews, J.E., et al., *Init. Repts. DSDP,* 21: Washington (U.S. Govt. Printing Office), 837–883.

Ehrenberg, C.G., 1839. Über die Bildung der Kreidefelsen und des Kreidemergels durch unsichtbare Organismen. *K. Akad. Wiss. Berlin,* Abh. 1838 (1840, separate 1839):59–148.

————, 1844. Untersuchungen über die kleinsten Lebensformen im Quellenlande des Euphrats und Araxes, so wie über eine an neuen Formen sehr reiche marine Tripelbildung von den Bermuda-Inseln. *K. Preuss. Akad. Wiss. Berlin, Ber.,* 253–275.

————, 1872. Mikrogeologische Studien als Zusammenfassung der Beobachtungen des kleinsten Lebens der Meeres-Tiefgrunde aller Zonen und dessen geologischen Einfluss. *K. Preuss. Akad. Wiss. Berlin, Monatsber.,* 1872:265–322.

Frenguelli, J., 1940. Consideraciones sobre los silicoflagelados fósiles. *Rev. Mus. La Plata, Secc. Geol.,* 2:37–112.

————, 1951. Silicoflagelados del Trípoli de Majillones (Chile). *Physis,* 20:272–284.

Gemeinhardt, K., 1934. Organismen Formen auf der Grenze Zwischen Radiolarien und Flagellaten. *Ber. Dtsch. Bot. Ges.,* 49:103–110.

Glezer, Z.I., 1966. Kremnevye zhgutikovye vodorosli (silicoflellaty). Silicoflagellatophyceae. In *Flora Sporovykh Rasteniy SSSR, Flora Plantarum Cryptogrammum USSR,* 7: Moskow (Akad. Nauk SSSR), 1–330.

Haeckel, E., 1887. Report on the Radiolaria collected by H.M.S. *Challenger* during the years 1873–1876. *Rep. Sci. Results Voy. H.M.S.* Challenger, *1873–1876, Zool.,* 18:1–1803.

Ichikawa, W., Shimizu, I., and Bachmann, A., 1967. Fossil silicoflagellates and their associated uncertain forms in Iida Diatomite, Noto Peninsula, Central Japan. *Sci. Rep. Kanazawa Univ.,* 12:143–172.

Lemmermann, E., 1901. Silicoflagellatae. *Ber. Dtsch. Bot. Ges.,* 19:247–271.

Locker, S., 1995. Silicoflagellates, ebridians, and actiniscidians from Pliocene and Quatemary sediments off southern Chile, Ocean Drilling Project Leg 141. *In* Lewis, S.D., Behrmann, J.H., Musgrave, R.J., and Cande, S.C. (Eds.), *Proc. ODP, Sci. Results,* 141: College Station, TX (Ocean Drilling Program), 223–233.

Mandra, Y.T., 1969. Silicoflagellates: a new tool for the study of Antarctic Tertiary climates. *U.S. Antarct. J.,* 4:172–174.

Mandra, Y.T., and Mandra, H., 1971. Upper Eocene silicoflagellates from New Zealand. *U.S. Antarct. J.,* 6:172–174.

————, 1972. Paleoecology and taxonomy of silicoflagellates from an upper Miocene diatomite near San Felipe, Baja California, Mexico. Occas. Pap., *Calif. Acad. Sci.,* 99:1–35.

Martini, E., 1971. Neogene silicoflagellates from the equatorial Pacific. *In* Winterer, E.L., Riedel, W.R., et al., *Init. Repts. DSDP,* 7 (Pt. 2): Washington (U.S. Govt. Printing Office), 1695–1708.

McCartney, K., 1993. Silicoflagellates. *In* Lipps J.H. (Ed.), *Fossil Prokaryotes and Protists*: Cambridge, MA (Blackwell Sci. Publ.), 143–154.

McCartney, K., and Loper, D.E., 1989. Optimized skeletal morphologies of silicoflagellate genera *Dictyocha* and *Distephanus*. *Paleobiology,* 15:283–298.

Perch-Nielsen, K., 1985. Silicoflagellates. *In* Bolli, H.M., Saunders, J.B., and Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy:* Cambridge (Cambridge Univ. Press), 811–846.

Plank, T., Ludden, J.N., Escutia, C., et al., 2000. *Proc. ODP, Init. Repts.,* 185 [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA.

Poelchau, H.S., 1976. Distribution of Holocene silicoflagellates in North Pacific sediments. *Micropaleontology,* 22:164–193.

Rio, D., Thunell, R., Sprovieri, R., Bukry, D., Destefano, E., Howell, M., Raffi, I., Sancetta, C., and Sanfilippo, A., 1989. Stratigraphy and depositional history of the Pliocene Bianco section, southern Italy. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 77:85–105.

Tsuchi, R., 1997. Marine climatic responses to Neogene tectonics of the Pacific Ocean seaways. *Tectonophysics,* 281:113–124.

Van Valkenburg, S.D., 1980. Silicoflagellates. *In* Cox, E.R. (Ed.), *Phytoflagellates:* New York (Elsevier), 335–350.

Van Valkenburg, S.D., and Norris, R.E., 1970. The growth and morphology of the Silicoflagellate *Dictyocha fibula* Ehrenberg in culture. *J. Phycol.,* 6:48–54.

Wailes, G.H., 1939. Canadian Pacific fauna. In *Le Protozoa-Mastigophora:* Toronto, Canada (Univ. Toronto Press), 1–45.

TAXONOMIC APPENDIX

Corbisema triacantha (Ehrenberg, 1844) Bukry and Foster (1974)
Dictyocha aculeata aculeata (Lemmermann, 1901) Bukry (1980)
Dictyocha aculeata subaculeata Bukry (1980)
Dictyocha aspera (Lemmermann, 1901) Bukry and Foster (1973)
Dictyocha brevispina ausonia (Deflandre, 1950) Bukry (1978)
Dictyocha brevispina brevispina (Lemmermamm, 1901) Bukry (1976)
Dictyocha calida ampliata Bukry (1979)
Dictyocha calida calida Poelchau (1976)
Dictyocha fibula Ehrenberg (1839)
Dictyocha lingii Dumitrica (1973)
Dictyocha longa Bukry (1982)
Dictyocha perlaevis delicata (Bukry, 1976) Bukry (1982)
Dictyocha perlaevis flexatella Bukry (1979)
Dictyocha perlaevis ornata (Bukry, 1977) Bukry (1982)
Dictyocha perlaevis perlaevis Frenguelli (1951)
Dictyocha pulchella Bukry (1975)
Dictyocha stapedia aspinosa Bukry (1976)
Dictyocha stapedia stapedia Haeckel (1887)
Distephanus boliviensis (Frenguelli, 1940) Bukry (1979)
Distephanus crux s.l. *ampl.* (Ehrenberg, 1840) Haeckel (1887)
Distephanus octangulatus Wailes (1939)
Distephanus speculum minutus (Bachmann in Ichikawa et al., 1967) Bukry (1981a)
Distephanus speculum pentagonus Lemmermann (1901)
Distephanus speculum speculum (Ehrenberg, 1839) Glezer (1966)
Mesocena circulus (Ehrenberg, 1840) Bukry (1979)
Mesocena elliptica (Ehrenberg, 1844) Bukry (1979)
Mesocena quadrangula (Ehrenberg, 1872) Bukry (1979)

Figure F1. Location of Site 1149, drilled during Leg 185; the bathymetric map shows the relative position with respect to the Izu-Bonin arc system (from Plank, Ludden, Escutia, et al., 2000).

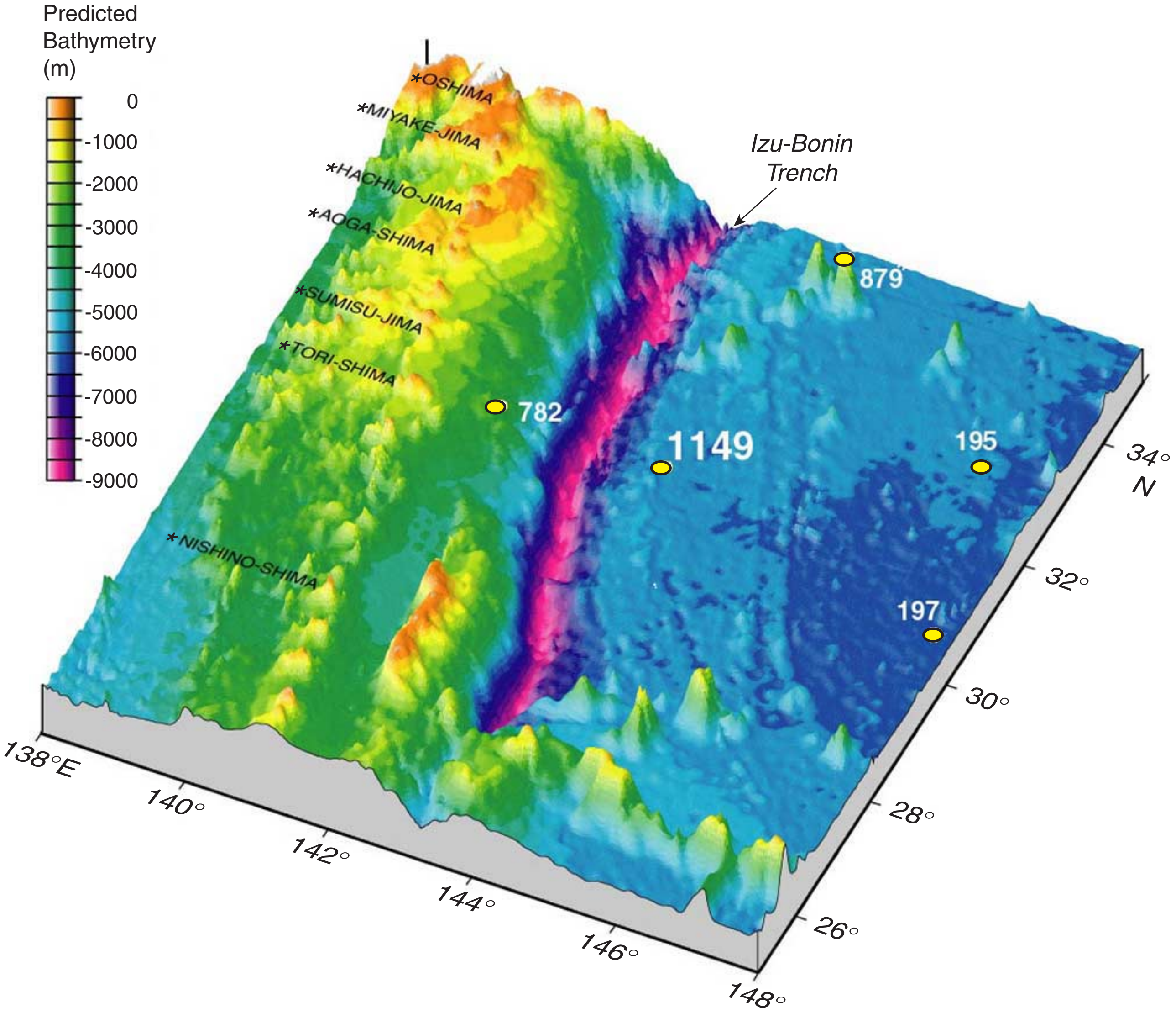


Figure F2. Stratigraphy of the upper Cenozoic Unit I recovered from Hole 1149A. Silicoflagellate bioevents are indicated and correlated to the magnetostratigraphic data (magnetic inclinations from Plank, Ludden, Escutia, et al., 2000) and the geochronologic timescale (according to Berggren et al., 1995). Change in the asperoid/fibuloid ratio and the relative abundance of aberrant specimens is also shown. Red lines in the lithostratigraphy column correspond to discreet ash layers. Blue lines correlate particularly significant bioevents to the geochronologic timescale (see **"Biostratigraphy,"** p. 3, for details).

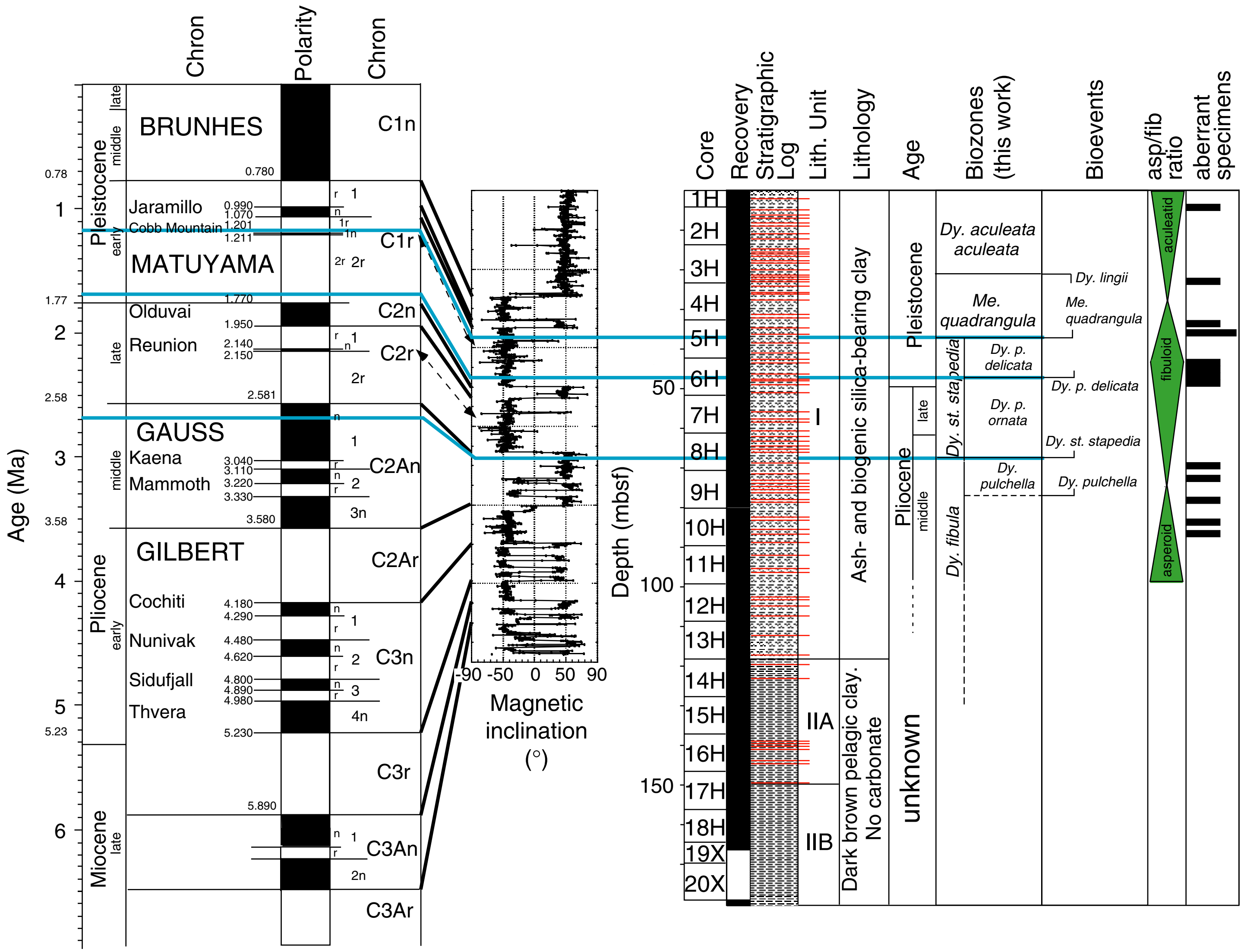


Table T1. Silicoflagellate distribution in selected samples, Hole 1149A.

Core, section, interval (cm)	Depth (mbsf)	Organic fraction	Biogenic content	Volcanic glass	*Corbisema triachanta*	*Dictyocha aculeata aculeata*	*Dictyocha aculeata subaculeata*	*Dictyocha aspera aspera*	*Dictyocha brevispina ausonia*	*Dictyocha brevispina brevispina*	*Dictyocha calida ampliata*	*Dictyocha calida calida*	*Dictyocha fibula*	*Dictyocha lingii*	*Dictyocha longa*	*Dictyocha pentagona*	*Dictyocha perlaevis delicata*	*Dictyocha perlaevis flexatella*	*Dictyocha perlaevis ornata*	*Dictyocha perlaevis perlaevis*	*Dictyocha pulchella*	*Dictyocha stapedia aspinosa*	*Dictyocha stapedia stapedia*	*Distephanus boliviensis*	*Distephanus crux* s.l.	*Distephanus octangulatus*	*Distephanus speculum minutus*	*Distephanus speculum pentagonus*	*Distephanus speculum speculum*	*Mesocena circulus*	*Mesocena eliptica*	*Mesocena quadrangula*	Aberrant silicoflagellates
185-1149A-																																	
1H-1, 112–118	1.12	C	R + D + SP + S	N		C	F																										N
2H-1, 132–137	5.52	C	R + D + SP + S	S		F	R																										F
2H-3, 137–141	8.57	C	D + SP + S	S		C	R																										N
2H-5, 132–138	11.52	F	R + SP	S																													N
3H-1, 114–120	14.84	F	R + D + S	S		C	R					R	R																				N
3H-3, 133–139	18.03	C	R + D + SP + S	N		R																											N
3H-5, 125–131.	20.95	R	R + D	A																													N
4H-1, 134–141	24.54	C	R + D + S	N		R	F				R	R	R	C																			R
4H-3, 134–141	27.54	C	R + D + S	S		A	C				R	F	R	R												VR							N
4H-5, 131–138	30.51	R	R	S																													N
5H-1, 131–137	34.01	F	R + D + SP + S	N							VR			F									R					VR					R
5H-3, 131–137	37.01	F	R + D + S	N			R					C		C		VR							F									F	C
5H-5, 132–138	40.02	R	R	S																													N
6H-1, 133–139	43.53	C	R + D + S	N							A	R	F	R						F		F	F		VR				VR			R	F
6H-3, 133–139	46.53	C	R + D + S	N							A	C	R	R			R		R			R	F					VR	R			R	F
6H-5, 133–139	49.53	F	R + D + S	N								F										C	A					VR					F
7H-1, 133–139	53.03	F	R + D + S	N								R	R							R			VR					VR					N
7H-3, 133–139	56.03	C	R + D + S	N							C	F	C							R		F	C				VR	R	R				N
7H-5, 123–129	58.93	C	R + D + S	S							F	F	F						F	F		R	F					VR					N
8H-1, 144–150	62.64	C	R + D + S	N	VR								C									F	F					R	R				N
8H-2, 132–138	64.02	R	R + D + S	S									R					VR					R						VR				N
8H-3, 127–133	65.47	F	R + D + S	S								VR	C					F	R	VR		F	C		VR			VR	C	R			N
8H-4, 135–140	67.05	F	R + D + SP + S	N	VR							F	C					F		R			R						R				N
8H-5, 126–132	68.46	C	R + D + SP + S	N								F	F							VR	R			VR						VR			N
8H-6, 130–135	70.05	R	R + D + SP	A																													N
9H-1, 106–112	71.76	F	R + D + S	N									A							R	R			VR	VR			VR	C				C
9H-2, 85–91	73.05	F	R + D + S	S									C																R	R			N
9H-3, 141–147	75.11	C	R + D + S	N				VR	R				C							R		VR							C				F
9H-4, 136–142	76.56	F	R + D + S	N				F					C								R									R			N
9H-5, 142–148	78.12	F	R + D + S	N				F					R											VR					R	VR			N
9H-6, 142–148	79.62	F	R + D + S	N				F		R			C									R		VR	VR		R		R	VR			N
10H-1, 135–141	81.55	C	R + D + SP + S	N	R			A				VR	C		R					R		R							C	R			R
10H-2, 134–140	83.04	C	R + D + SP + S	N				C					C		R					c		R		VR	VR			R	C	R			R
10H-3, 125–131	84.45	C	R + D + SP + S	N	VR			F	VR				C		R					F		R			R			VR	C	R			N
10H-4, 135–141	86.05	C	R + D + SP + S	N				R							R	VR				R		F			R			VR		F			N
10H-5, 135–141	87.55	C	R + D + SP + S	N				C	R	VR			A							R									C	c			F
10H-6, 135–141	89.05	F	R + D + S	N				R					c							R				VR	VR			VR	C	R			N
11H-1, 136–142	91.06	C	R + D + SP + S	N				F					A							R							VR		C	F	C		R
11H-2, 100–106	92.2	R	R + SP + S	S																					R								N
11H-3, 131–137	94.01	R	R + D + S	S																R													N
11H-4, 142–148	95.62	F	R + D + SP + S	N									C																C				N
11H-5, 141–147	97.11	F	R + D + SP + S	S				R					C												VR				F	R			N
11H-6, 140–146	98.6	C	R + D + S	N				VR					C												VR				F	VR			N

Note: See text in "Material and Methods," p. 2, for definitions of abundance codes.

Plate P1. All pictures are 800×. **1, 2.** *Dictyocha aculeata aculeata* (Sample 185-1149A-4H-3, 131–141 cm); (1) high focus, (2) low focus. **3, 4.** *Dictyocha aculeata subaculeata* (Sample 185-1149A-5H-3, 131–137 cm); (3) low focus, (4) high focus. **5, 6.** *Dictyocha perlaevis delicata* (Sample 185-1149A-6H-3, 133–139 cm); (5) low focus, (6) high focus. **7.** *Dictyocha lingii* (Sample 185-1149A-6H-1, 133–139 cm). **8.** *Mesocena quadrangula* (Sample 185-1149A-6H-1, 133–139 cm). **9–11.** *Dictyocha perlaevis ornata* (Sample 185-1149A-7H-5, 123–129 cm); (9) high focus, (10) low focus, (11) specimen showing the accessory spine on the basal ring. **12, 13.** *Dictyocha perlaevis flexatella* (Sample 185-1149A-8H-3, 127–133 cm); (12) high focus, (13) low focus. **14, 15.** *Dictyocha stapedia stapedia* (Sample 185-1149A-8H-3, 127–133 cm); (14) low focus, (15) high focus. **16, 17.** *Dictyocha pulchella* (Sample 185-1149A-9H-1, 106–112 cm); (16) high focus, (17) low focus. **18, 19.** *Dictyocha stapedia aspinosa* (Sample 185-1149A-8H-3, 127–133 cm); (18) high focus, (19) low focus. **20.** *Dictyocha brevispina brevispina* (Sample 185-1149A-9H-6, 142–148 cm.) **21, 22.** *Dictyocha calida calida* (Sample 185-1149A-8H-3, 127–133 cm); (21) high focus, (22) low focus.

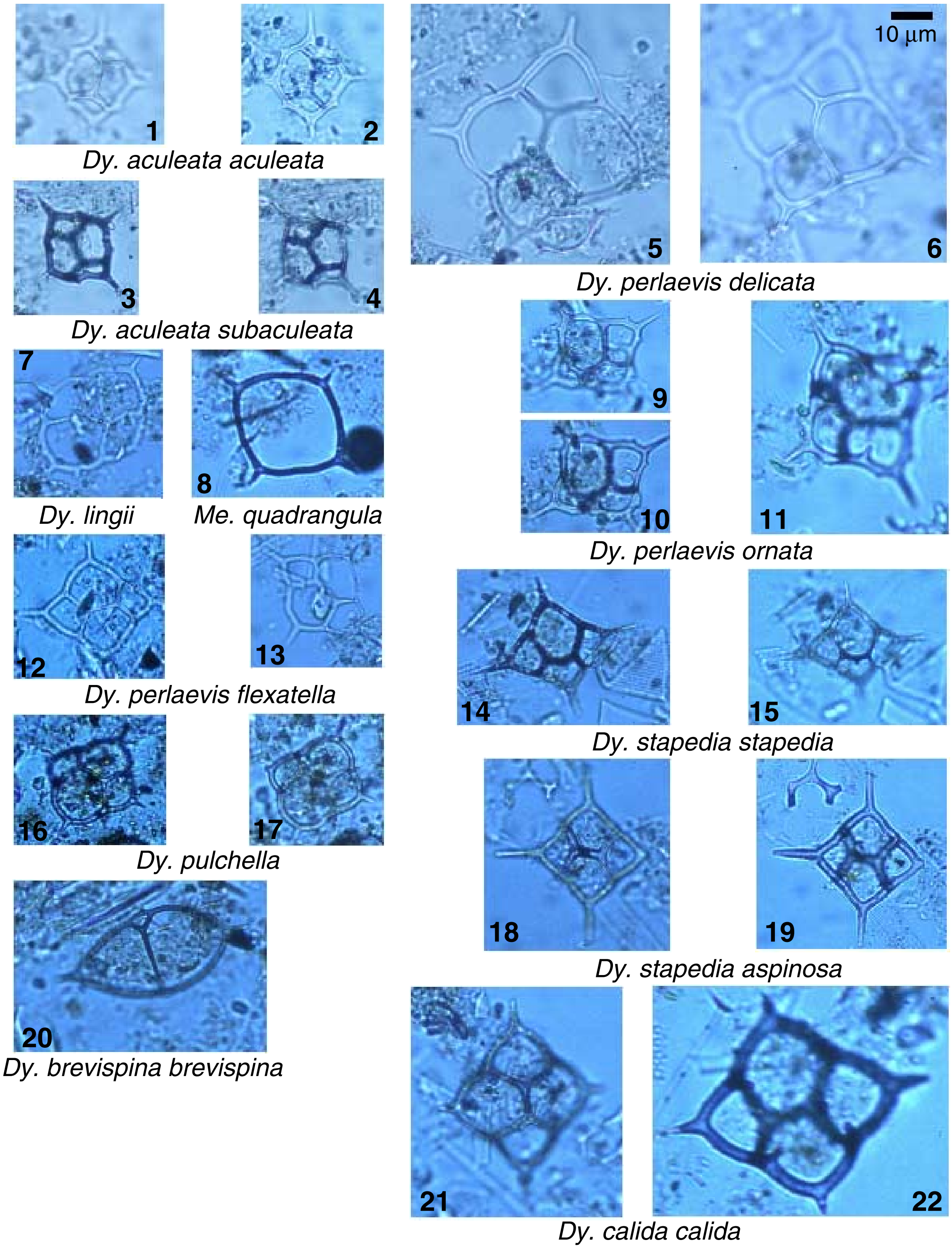


Plate P2. 1, 2. *Distephanus boliviensis* (Sample 185-1149A-10H-5, 135–141 cm); (1) low focus, (2) high focus. **3, 4.** *Distephanus speculum minutus* (Sample 185-1149A-9H-6, 142–148 cm); (3) low focus, (4) high focus. **5, 6.** *Dictyocha perlaevis perlaevis* (Sample 185-1149A-10H-2, 134–140 cm); (5) high focus, (6) low focus. **7, 8.** *Distephanus speculum speculum* (Sample 185-1149A-8H-3, 127–133 cm); (7) high focus, (8) low focus. **9.** *Dictyocha aspera* (Sample 185-1149A-10H-1, 135–141 cm). **10.** *Distephanus crux* (Sample 185-1149A-10H-2, 134–140 cm). **11.** *Mesocena circulus* (Sample 185-1149A-10H-2, 134–140 cm). **12.** *Dictyocha fibula* (Sample 185-1149A-10H-5, 131–141 cm). **13.** *Corbisema triachantha* (Sample 185-1149A-10H-3, 125–131 cm). **14, 15.** Aberrant morphotypes (Sample 185-1149A-5H-3, 131–137 cm).