

## 15. DATA REPORT: BACKSCATTERED ELECTRON IMAGERY ANALYSIS OF EARLY PLIOCENE LAMINATED *ETHMODISCUS* OOZE, SITE 1010<sup>1</sup>

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### ABSTRACT

Giant diatoms from the genus *Ethmodiscus* Castracane are a ubiquitous but relatively rare component of the warm-surface ocean plankton. *Ethmodiscus* oozes have been documented as occurring during the geological past; however, the debate over the mechanism of formation of these oozes is still unresolved. This report documents the nature and occurrence of early Pliocene *Ethmodiscus* ooze from Ocean Drilling Program Site 1010. The sediment fabric of the ooze interval has been analyzed using scanning electron microscopy, specifically backscattered electron imagery. This has shown that the sediment consists of an irregular alternation between laminae rich in *Ethmodiscus* fragments; mixed-sediment laminae comprising silt grains, clays, and nannofossils; and horizontal to subhorizontal burrows filled with nannofossil clay that is similar to sediment deposited above and below the diatom-rich interval. The short stratigraphic occurrence of *Ethmodiscus* ooze at Site 1010 precludes any substantial contribution to the debate over the mechanism of formation of these deep-sea oozes; it is suggested, however, that further studies should consider the concentration (and subsequent deposition) of these giant diatoms along convergent oceanic frontal zones.

### INTRODUCTION

*Ethmodiscus* Castracane is a widely distributed, warm-water diatom genus recorded mainly from oligotrophic waters (Villareal, 1993, and references therein). *Ethmodiscus* cells are the largest known diatoms, reaching 2–3 mm in diameter (Round et al., 1990). In the central and western Pacific, abundance of *Ethmodiscus* cells in the euphotic zone is on average 0.01–0.1 cells m<sup>-3</sup>; however, off the coast of Chile, the maximum reported abundance of *Ethmodiscus* in equatorial waters is 21.7 cells m<sup>-3</sup>. In the California Current, *Ethmodiscus rex* (Rattray) Wiseman & Hendey was recorded in 74% of quantitative vertical net tows, with a range in abundance of 0.001–0.25 cells m<sup>-3</sup> (Villareal, 1993, and references therein).

Given the low abundance of *Ethmodiscus* in oceanic surface waters, it is surprising that *Ethmodiscus* oozes have been reported from the Pacific, Atlantic, and Indian Oceans (Mikkelsen, 1977). The *Ethmodiscus* oozes are principally found in the large depressions (Ricard, 1970, cited in Rivera et al., 1989) or in belts of sediment beneath tropical oceans (Round, 1980). Two mechanisms have been suggested for accumulation of *Ethmodiscus* into oozes. The first is differential dissolution of carbonate vs. silica, coupled with resuspension and deposition. The second is that glacial blooms, triggered by high nutrient content from upwelling, are responsible for the oozes (Mikkelsen, 1977; Stabell, 1986). These mechanisms were proposed on the basis of inferences from the sediment record and sediment dissolution experiments (Villareal, 1993); however, more recent work on the growth rate and chemical composition of *Ethmodiscus* has shown that cells from this genus are positively buoyant (Villareal, 1993; Villareal and Carpenter, 1994). *Ethmodiscus* cells behave in a similar way to chains and mats of the diatom genus *Rhizosolenia* Brightwell (Villareal and Carpenter, 1989). *Rhizosolenia* chains and mats and *Ethmodiscus* cells are positively buoyant and have decoupled their light and nutrient utilization, taking up nitrate from a depth just below the nutricline and rising to the surface to photosynthesize

(Villareal et al., 1993; Villareal and Carpenter, 1994). Indeed, positively buoyant *Ethmodiscus* cells have been caught by downward-facing sediment traps at 5400-m water depth in the Pacific Ocean (Villareal, 1993), suggesting the possible presence of a hitherto unrecorded population of *Ethmodiscus* at depth. Positively buoyant populations of *Rhizosolenia* and *Ethmodiscus* have been documented as accumulating at the surface under low wind-speed conditions (Collingwood, 1868, cited in Villareal, 1993; Villareal and Carpenter, 1989); therefore, meteorological conditions may be responsible for accumulations of *Ethmodiscus* in the sediment rather than in situ growth.

The current uncertainty over the depositional mechanism makes it important to document each newly recovered occurrence of *Ethmodiscus* ooze, particularly because these oozes could have paleoclimatic implications (Stabell, 1986). The purpose of this data report is to document the nature and occurrence of an early Pliocene *Ethmodiscus* ooze, recovered at Ocean Drilling Program (ODP) Site 1010 located ~100 km north of Guadalupe Island, seaward of Baja California (29°57.9'N, 118°6.0'W; Lyle, Koizumi, Richter, et al., 1997).

### MATERIALS AND METHOD

#### Materials

Intervals of early Pliocene (3.86 Ma; Shipboard Scientific Party, 1997) laminated diatom ooze from Holes 1010C (interval 167-1010C-5H-4, 77–90 cm) and 1010E (interval 167-1010E-5H-2, 22.5–41.5 cm) were identified on board ship. These two intervals were sampled subsequently at the ODP Gulf Coast Repository, using the ODP sediment slab cutters and following the procedure described in Pike and Kemp (1996). Slabs were subsampled and highly polished thin sections prepared for scanning electron microscope (SEM) backscattered electron imagery (BSEI) analysis (Pike and Kemp, 1996).

#### BSEI Sediment Fabric Analysis

BSEI is a powerful technique for investigating laminated diatom-rich sediment fabrics (Grimm, 1992; Kemp, 1990; Kemp et al., 1998; Pearce et al., 1998; Pike and Kemp, 1997). When analyzing a pol-

<sup>1</sup>Lyle, M., Koizumi, I., Richter, C., and Moore, T.C., Jr. (Eds.), 2000. *Proc. ODP, Sci. Results*, 167: College Station TX (Ocean Drilling Program).

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ished thin section, the number of backscattered electrons, or backscatter coefficient (recorded as image brightness) of a grain, is principally related to the mean atomic number of that grain; the greater the average atomic number, the brighter the image (Goldstein et al., 1981). Thus, images may be regarded as porosity maps. In the early Pliocene *Ethmodiscus* ooze from Site 1010, high-porosity sediment rich in *Ethmodiscus* valve fragments records a dark image (e.g., Figs. 1–3). Low-porosity sediment that is rich in high average atomic number mineral grains (such as quartz) and biogenic debris (such as coccoliths and discoasters) records a bright image (e.g., Figs. 1, 2, 4).

Macroscopic core photographs are compared to low-magnification BSEI photomosaics for gross sediment fabric analysis (see Figs. 1, 2), and higher magnification BSEI photography is used to highlight the characteristic features of the laminated *Ethmodiscus* ooze intervals (see Figs. 3, 4).

## RESULTS

The two intervals of the laminated *Ethmodiscus* oozes that were embedded and analyzed (intervals 167-1010C-5H-4, 79–88 cm, and

167-1010E-5H-2, 24–43 cm) are of similar stratigraphic thickness and have similar macroscopic and microscopic sediment fabric (Figs. 1, 2). It is likely that they represent the same sediment interval recovered in each core. When sample intervals from the two different cores are converted to the same depth scale, using the shipboard-defined meters composite depth (mcd), the laminated oozes occur at 44.15–44.24 mcd in Hole 1010C and 43.92–44.11 mcd in Hole 1010E (Shipboard Scientific Party, 1997).

Low-magnification BSEI photomosaics reveal an irregular alternation between (1) bright, very low porosity, horizontal to subhorizontal burrows (marked “x” on Figs. 1, 2) filled with silt, clays, coccoliths, and discoasters (Fig. 4B); (2) dark, porous laminae rich in *Ethmodiscus* fragments (Fig. 3A–3E); and (3) bright, low-porosity mixed-sediment laminae comprising silt grains and clays, coccoliths, and discoasters (Fig. 4A). Core photographs and BSEI photomosaics show that the top 4 and 9 cm of the *Ethmodiscus* ooze interval in Holes 1010C and 1010E, respectively, are dominated by macroscopic burrows (Figs. 1, 2). High-magnification BSEI analysis further shows that the burrows push between the darker, more porous layers of *Ethmodiscus* fragments, displacing the fragments (Fig. 4C). Burrows are filled with sediment that is similar in nature to nannofos-

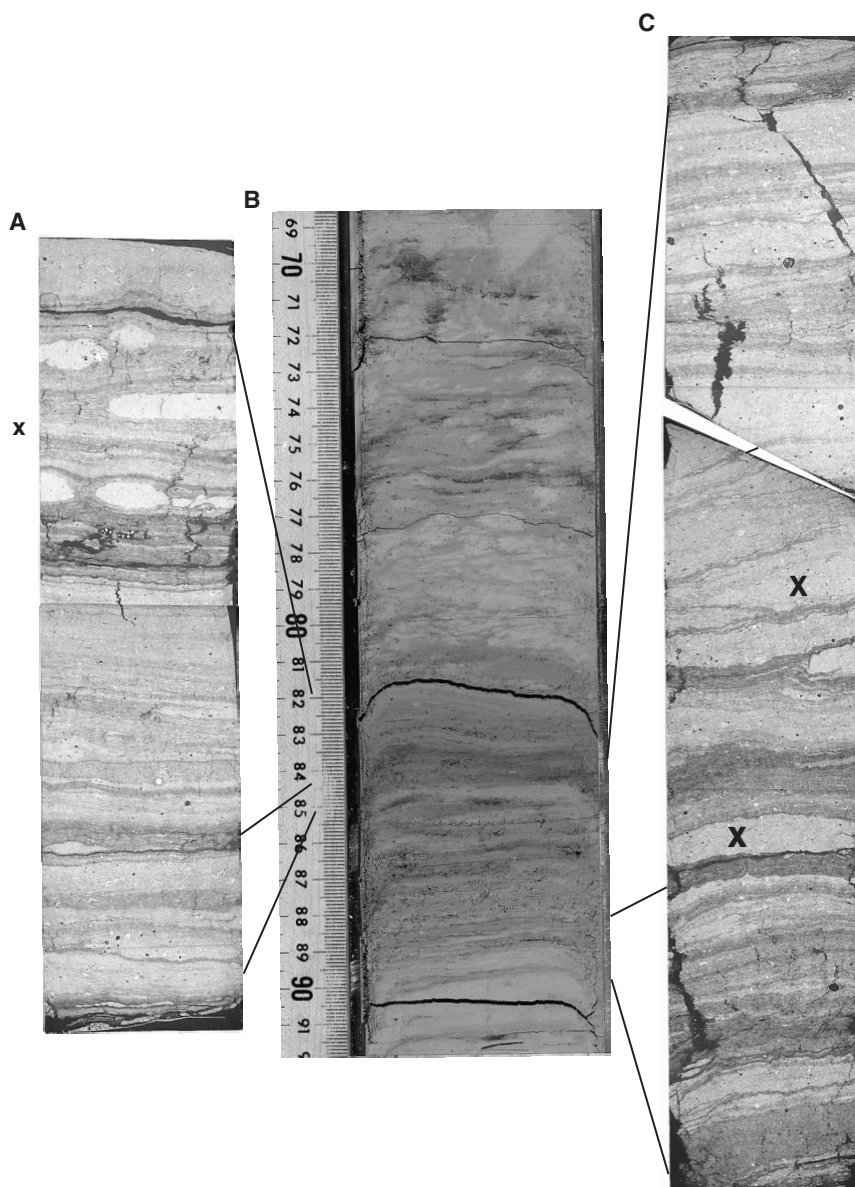


Figure 1. Interval 167-1010C-5H-4, 69–92 cm. **A, C.** BSEI photomosaics of laminated *Ethmodiscus* ooze. Brighter layers are mixed-sediment laminae, and darker, more porous layers are *Ethmodiscus*-fragment laminae. An “x” marks the position of bright, low-porosity burrows, with sharp boundaries, running horizontally along *Ethmodiscus* laminae, pushing the laminations apart. **B.** Core photograph of laminated *Ethmodiscus* ooze with scale in centimeters running down left side. Straight black lines tie the magnified BSEI mosaics to the core photograph.

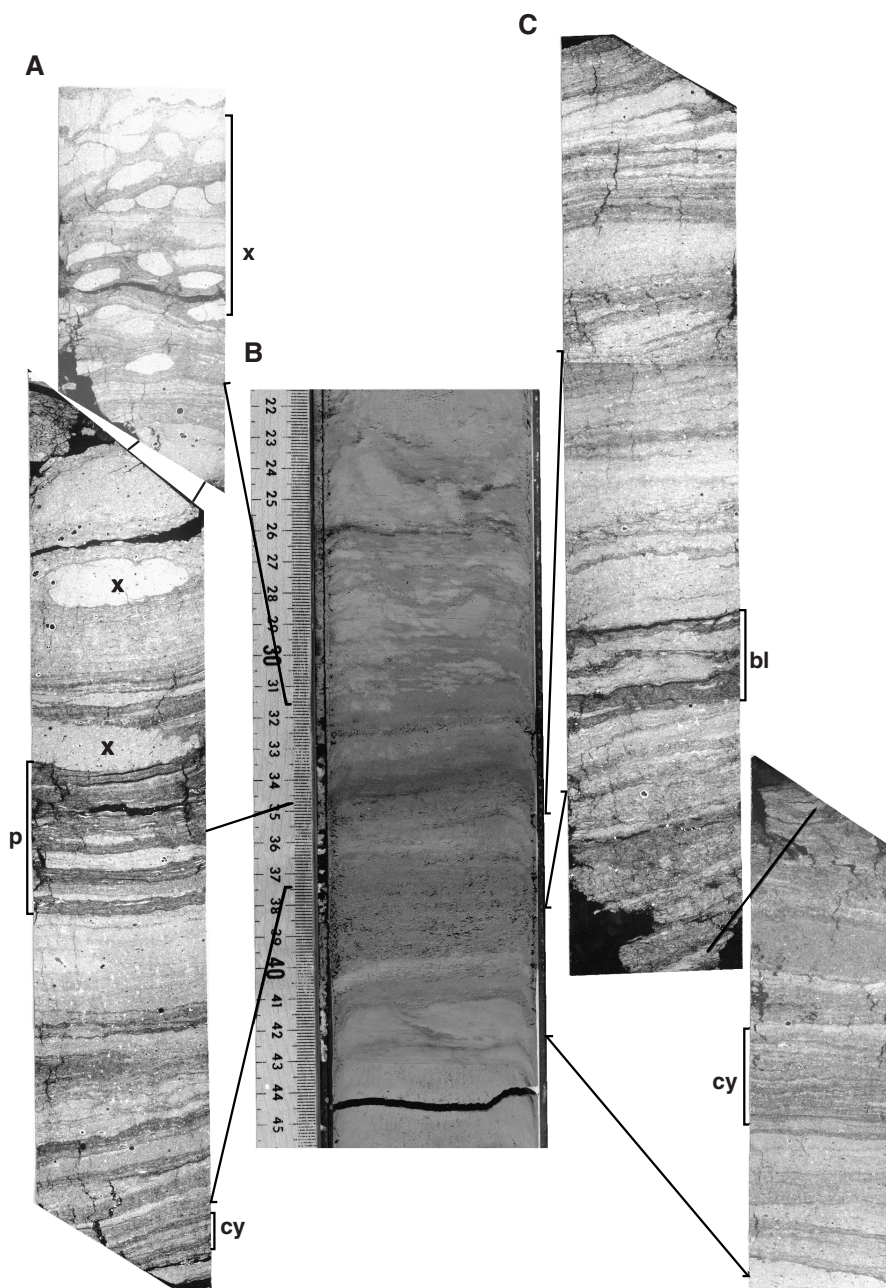


Figure 2. Interval 167-1010E-5H-2, 22–46 cm. **A, C.** BSEI photomosaics of laminated *Ethmodiscus* ooze. Brighter layers are mixed-sediment laminae, and darker, more porous layers are *Ethmodiscus*-fragment laminae. An “x” marks the position of bright, low-porosity burrows, with sharp boundaries, running horizontally along *Ethmodiscus* laminae, pushing laminations apart; “bl” indicates an interval where the horizontal burrows have likely doubled the thickness of an *Ethmodiscus*-fragment lamina; “p” marks the interval of *Ethmodiscus* laminations containing pyritized frustules that are seen as very bright, short, horizontal lines; and “cy” marks intervals of alternating *Ethmodiscus* and mixed-sediment laminae that are undisturbed by burrows. **B.** Core photograph of laminated *Ethmodiscus* ooze with scale in centimeters running down left side. Straight black lines tie the magnified BSEI mosaics to the core photograph.

sil clay that is found above and below the laminated interval (Shipboard Scientific Party, 1997) and to mixed-sediment laminae (compare Fig. 4A, 4B). The margins of the burrows are very sharp (Fig. 4C, 4D) with a clear demarcation between the burrow and the *Ethmodiscus* fragments. Beneath the top 4 and 9 cm, the burrows become much less common and appear to be mainly restricted to the most porous, *Ethmodiscus*-rich laminae (marked “bl” on Fig. 2C).

*Ethmodiscus* laminae are porous and are defined by dark laminae/patches on the BSEI photomosaics (Figs. 1, 2). The laminae range in thickness from 0.05 to 4.73 mm, with an average thickness of 0.67 mm ( $N = 152$ ); however, the thickness is influenced by the presence or absence of burrows within laminae (see individual burrows marked “x” on Fig. 2A). The brightness of the *Ethmodiscus* laminae on the photomosaics also ranges from being slightly less bright than the mixed-sediment laminae (Fig. 3A) to very dark (Fig. 3C); the darker the image, the greater the abundance of *Ethmodiscus* fragments relative to other sediment components. The darker laminae in

the lower, well-laminated portion of the *Ethmodiscus* ooze interval tend to have concentrations of burrows within them (marked “bl” on Fig. 2C). One particular short interval of *Ethmodiscus* laminations contains rare pyritized frustules (Fig. 3E; marked “p” on Fig. 2A); otherwise, pyrite is relatively commonly dispersed within the laminae.

The mixed-sediment laminae are of similar composition to the nanfossil clay in which the *Ethmodiscus* ooze interval is found (Shipboard Scientific Party, 1997). Mixed-sediment laminations have a porosity intermediate between the low-porosity burrows and the higher porosity *Ethmodiscus* laminae. Laminae contain coccoliths, discoasters, carbonate grains, foraminifers, clays, and quartz and feldspar silt grains (Fig. 4A). There appears to be a gradation from laminae that are pure mixed-sediment laminae (Fig. 4A), to laminations that are mixed sediment with a few *Ethmodiscus* fragments (Fig. 3A), to *Ethmodiscus* laminae with mixed sediment (Fig. 3B), and to laminae that are pure *Ethmodiscus* fragments (Fig. 3C,

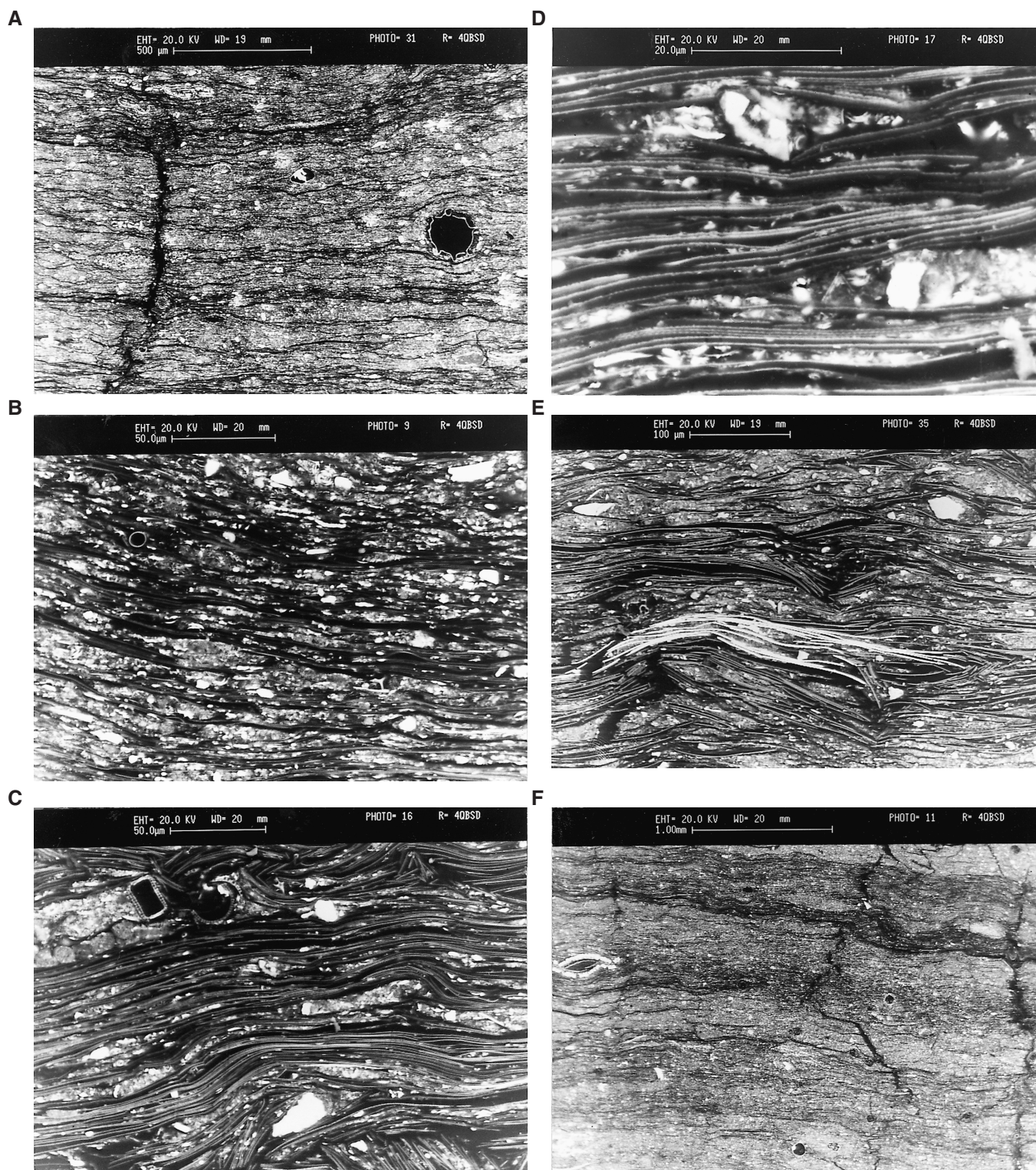


Figure 3. High-magnification, detailed BSEI photographs. **A.** Bright, mixed-sediment lamina with a few dark, horizontal lines containing *Ethmodiscus* fragments. **B.** Dark *Ethmodiscus* lamina containing a large proportion of mixed sediment. **C.** Dark *Ethmodiscus* lamina containing little mixed sediment and many frustule fragments stacked together. **D.** Close-up of *Ethmodiscus* lamina showing the submicron- to micron-scale thickness of the *Ethmodiscus* fragments. **E.** Dark *Ethmodiscus* lamina containing very bright, pyritized frustule fragments. **F.** Cyclical alternation of dark *Ethmodiscus* laminae and brighter mixed-sediment laminae in the absence of horizontal burrows. All scale bars are given in the data zone at the top of the photographs.

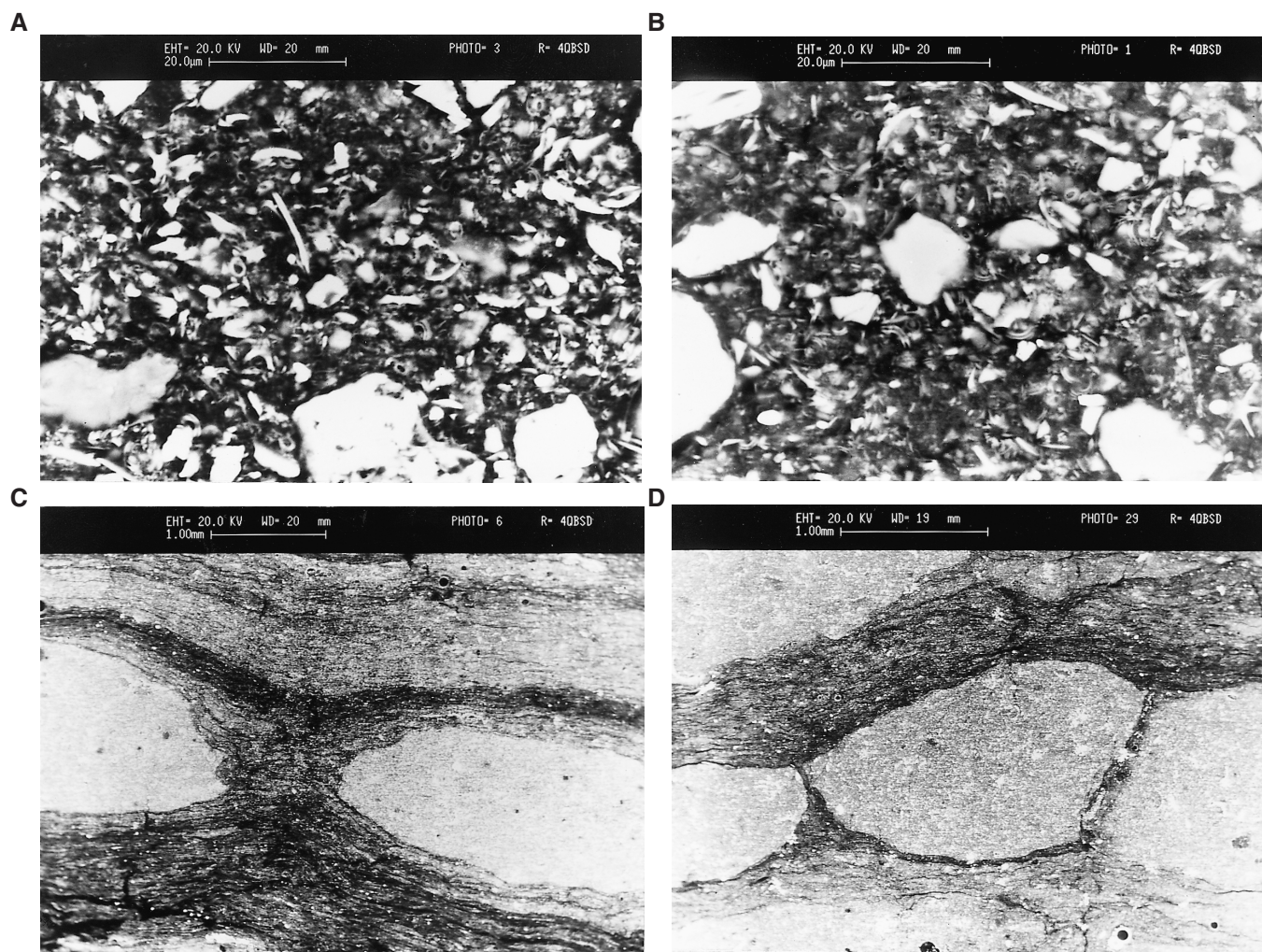


Figure 4. High-magnification, detailed BSEI photographs. **A.** Mixed-sediment lamina showing bright silt grains and bright circular coccoliths. **B.** A burrow fill showing bright silt grains, bright circular coccoliths, and a bright star-shaped discoaster in the bottom right corner. Note the similarity in composition between the burrow fill and the mixed-sediment lamina. **C.** Two bright, horizontal burrows distorting the dark, enclosing *Ethmodiscus* lamination and the bright, mixed-sediment lamina above. **D.** Bright horizontal burrows are distorting the enclosing dark, *Ethmodiscus* lamina. Between adjacent burrows, the *Ethmodiscus* fragments are vertical. All scale bars are given in the data zone at the top of the photographs.

3D). In the absence of burrows, the *Ethmodiscus* and mixed-sediment laminae appear to alternate cyclically (Fig. 3F; marked “cy” on Fig. 2A, 2C).

## DISCUSSION

The purpose of this data report is to document the nature and occurrence of this early Pliocene *Ethmodiscus* ooze. However, some features documented using the BSEI analysis are worthy of brief explanation and discussion. The *Ethmodiscus* laminae comprise layers, or stacks, of frustule fragments. The burrows are horizontal in attitude and appear to run along the *Ethmodiscus* laminae (Fig. 4C, 4D; marked “x” on Fig. 1A); the bioturbating organism presumably was feeding on the rich store of organic matter in the *Ethmodiscus* laminae. The flux of *Ethmodiscus* frustules may have temporarily overwhelmed the benthos, reducing the extent to which the infauna could mix the sediment. The mechanism for the concentration of *Ethmodiscus* frustules into laminations will continue to be a matter for further debate; the short stratigraphic occurrence of this one interval at Site 1010 precludes any meaningful interpretation. However, the alterna-

tion between *Ethmodiscus* laminae and mixed-sediment laminae is suggestive of a cyclical mode of deposition (Fig. 3F; marked “cy” on Fig. 2A, 2C).

*Ethmodiscus* cells behave in similar ways to *Rhizosolenia* chains and mats in that both are positively buoyant and concentrated in the surface waters by low wind speeds (Villareal, 1988, 1992, 1993; Villareal et al., 1993; Villareal and Carpenter, 1989). *Rhizosolenia* mats are also concentrated along convergent oceanic frontal zones in the Eastern Equatorial Pacific Ocean (Yoder et al., 1994), and *Ethmodiscus* oozes are often found in swaths beneath tropical seas (Round, 1980). *Ethmodiscus* is characteristic of oligotrophic waters, so there would appear to be no ecological support for an increase in nutrients facilitating blooms of *Ethmodiscus* that are sedimented to form oozes (as discussed in Villareal, 1993). Considering the similarity in behavior between the two genera, it is possible that in the geological past *Ethmodiscus* frustules may have been concentrated along oceanic convergences in a similar way to *Rhizosolenia* chains and mats today (Kemp, 1995). The *Ethmodiscus* cells may have been deposited en masse by a similar physical oceanographic process to that proposed for the Neogene *Thalassiothrix longissima* Cleve & Grunow dominated diatom mat deposits of the Eastern Equatorial Pacific and North

Atlantic (Bodén and Backman, 1996; Kemp et al., 1995). The alternation between the *Ethmodiscus* and mixed-sediment laminae could reflect the periodic movement of the frontal zone. Thorough investigation of other *Ethmodiscus* ooze deposits from the world's oceans would be required to test this hypothesis. However, it is interesting to note that the early Pliocene *Ethmodiscus* ooze interval recovered at Site 1010 occurs at the stratigraphic top of a diatom-bearing interval (Miocene to early Pliocene) and directly below a diatom-barren interval (Shipboard Scientific Party, 1997). This could suggest that the productive waters of the California Current are moving shoreward across Site 1010 during the late Miocene to early Pliocene and that the *Ethmodiscus* ooze was deposited at the outer edge of these productive waters, supporting a possible frontal mechanism of formation.

## ACKNOWLEDGMENTS

I would like to thank the UK ODP for funding my participation as a shipboard scientist on Leg 167 and John Barron for his comments and review of this manuscript. Shore-based research was funded by a UK ODP postdoctoral fellowship.

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**Date of initial receipt: 23 November 1998**

**Date of acceptance: 17 June 1999**

**Ms 167SR-233**