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31. HIGH-RESOLUTION SEDIMENTOLOGY AND MICROPALEONTOLOGY OF LAMINATED DIATOMACEOUS SEDIMENTS FROM THE EASTERN EQUATORIAL PACIFIC OCEAN[1]

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ABSTRACT

Scanning electron microscope (SEM)-based analyses of the laminated diatom oozes encountered during Leg 138 reveal three major laminae types. The first lamina type is composed of multiple layers of ~20-µm-thick diatom mats, which form laminae dominated by assemblages of the pennate diatom, *Thalassiothrix longissima*. More than one variety/subspecies of *T. longissima* occurs within these laminae (referred to as the *T. longissima* Group). The second lamina type is composed of a mixed-assemblage of several species of diatoms (centric and pennate varieties), calcareous nannofossils, and subordinate quantities of radiolarians, silicoflagellates and foraminifers. The third lamina type is dominated by an assemblage of nannofossils and minor amounts of those fossil components mentioned above. This last form of lamination is compositionally similar to the background sediment type, foraminifer-nannofossil ooze (F-NO). Two lamina associations occur within the laminated intervals; the first comprises alternations of *T. longissima* Group and mixed-assemblage laminae (average thickness is ~6 mm) and the second is composed of *T. longissima* and nannofossil-rich laminae (average thickness is ~3.5 mm). The arrangement of laminae probably originates from the deposition of multiple layers of 20-µm-thick mats from one mat-flux episode. The much thinner nannofossil-rich laminae are interpreted to represent periods of more "normal" deposition between mat-flux episodes. The occurrence of several varieties/subspecies of *T. longissima* within individual mat layers is consistent with observations of *Rhizosolenia* diatom mats in the modern world ocean.

INTRODUCTION

Laminated diatomaceous marine sediments can provide unique information about the record of interannual and seasonal variability in marine systems, for example in the California Borderland Basins (Gorsline, 1984), within the Gulf of California (Baumgartner et al., 1985) and off Peru (Kemp, 1990). However, the distribution of such laminated sediments hitherto has been thought to be restricted to relatively isolated anoxic basins or continental margins, where an intense oxygen minimum zone intersects the continental shelf/slope. The discovery of widespread deposits of deep-sea laminated diatom ooze in the oxygenated deep waters of the eastern equatorial Pacific Ocean (Kemp and Baldauf, 1993) provides the first opportunity to identify ancient individual flux events in the deep sea and relate these to short-time-scale oceanographic processes.

Recent research has shown that only backscattered electron imagery (BSEI) of resin-impregnated sediment has sufficient resolution to identify the individual components of laminated fine-grained sediments (Kemp, 1990; Grimm, 1992; Kemp and Baldauf, 1993; Brodie and Kemp, in press). The purpose of this paper is to report detailed sedimentological investigations of laminated diatomaceous sediments recovered during Ocean Drilling Program (ODP) Leg 138 drilling and to relate these using electron microscope techniques to micropaleontological observations.

METHODOLOGY

Electron Microscopy

The sediments were prepared for SEM examination using the method described by Kemp (1990). In brief, samples were taken using standard ODP paleomagnetic sample cubes or U-channels, which minimize deformation of the sediment. The sediments were refrigerated prior to preparation to avoid drying them out. The material was prepared for sectioning by carefully cutting subsamples from each sample using scalpel and forceps. The subsamples were placed in plastic boxes, and while still damp, removed to a Logitech vacuum impregnator. The impregnator was evacuated to an internal pressure of about 10^{-6} mb prior to the introduction of pre-evacuated low-viscosity epoxy resin. Because each sample effectively dried out during the evacuation process, the pump-down time ranged up to 36 hr. Impregnated samples were mounted on frosted glass slides and polished using a Logitech lapping machine. The preparation process was finished with a cloth impregnated with aluminum powder that maximized the polish. Polished slides were carbon-coated and analyzed with a JEOL JSM 6400 SEM, fitted with a Tracor Series 2 energy dispersive system and a solid-state backscattered electron detector. Goldstein et al. (1981) discussed the use of BSEI in SEM work, while geological applications were outlined in Krinsley et al. (1983) and references therein.

Diatoms

Samples were processed (using HCl and H_2O_2), and slides were prepared for examination following a procedure similar to that discussed by Boden (1991). Each glass slide was examined using ×750 and ×1250 magnifications with a Zeiss transmitted light microscope. For the data presented in Figure 5, relative abundance of specific species were based on the number of specimens observed per field of view at ×750 magnification. The abundance of the *Thalassiothrix longissima* Group (lengths greater than 70 µm), and *Denticulopsis* are defined as follows: barren (B) = no specimens observed; rare (R) = less than one specimen observed per horizontal traverse; few (F) = one to five specimens observed per horizontal traverse; common (C) = one to five specimens per field of view; and abundant (A) = greater than five specimens per field of view. In each sample, the abundance of diatom species (shown in Fig. 5 as "Other Diatoms"), other than specimens of the *T. longissima* Group, but including *Denticulopsis* specimens, is presented as the average number (in percent) of specimens observed per field of view.

Diatom preservation was assessed qualitatively by (1) comparing the relative abundance of finely silicified forms (e.g., specific species of *Thalassiosira* and *Nitzschia*) to robust forms (e.g., specific species of *Coscinodiscus*, *Craspedodiscus* and *Denticulopsis*), (2) examining the degree of dissolution (pitting, etching, etc.) of individual frus-

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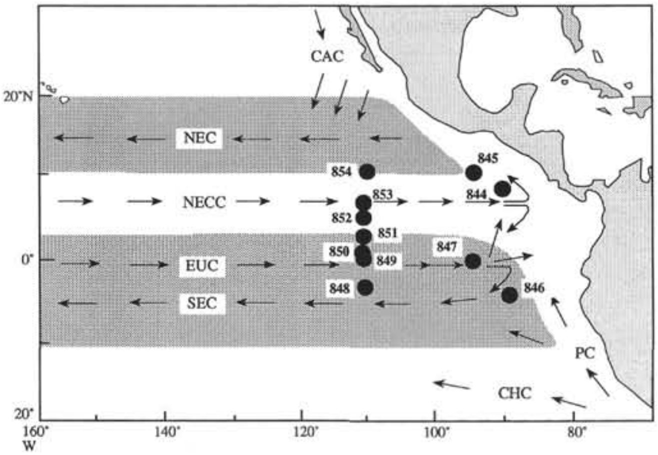

Figure 1. Location map of Leg 138 drilling sites containing LDOs. CAC = California Current; NEC = North Equatorial Current; NECC = North Equatorial Countercurrent; EUC = Equatorial Undercurrent; SEC = South Equatorial Current; CHC = Chile Current; and PC = Peru Current.

tules, and (3) analyzing the degree of fragmentation of individual frustules (specimens of specific species, other than those from the *T. longissima* Group).

Poorly preserved samples typically contain rare specimens of several species (generally *Cosinodiscus*, *Rossiella* and *Craspedodiscus*) that exhibit pitting and etching. *Craspedodiscus coscinodiscus* specimens, if present, are fragmented, with only the central portion of each valve face preserved. In addition, *Denticulopsis* specimens, when present, typically contain only the girdle portion of the valves. Specimens of *Nitzschia* or *Thalassiosira*, as well as silicoflagellates, are extremely rare if present at all.

Moderately preserved samples contain few specimens exhibiting pitting or etching. Specimens of *C. coscinodiscus* generally exhibit the valve face and a portion of the mantle. The number of *Denticulopsis* girdle bands was seen to be reduced and generally low, when compared with the abundance of complete valves of the species. Silicoflagellates, and specimens of *Nitzschia* and *Thalassiosira* are rare, but generally present.

Samples containing a well-preserved diatom assemblage consist of diatom frustules without pitting or etching. Specimens are generally complete, with the exception of those from the *T. longissima* Group.

Foraminifers and Radiolarians

The absolute abundances of planktonic foraminifers, benthic foraminifers, and radiolarians were estimated for several intervals from the ×20 magnification BSEI photomosaics. For each interval, the total number of foraminifers and radiolarians was counted, and the number per square centimeter of sediment was calculated. The abundances of planktonic foraminifers, benthic foraminifers, and radiolarians were defined as follows: barren (B) = no specimens observed; rare (R) = less than one specimen per square centimeter; common (C) = one to five specimens per square centimeter; abundant (A) = more than five specimens per square centimeter.

OCCURRENCE OF THE LAMINATED DIATOM OOZE INTERVALS

Laminated diatom ooze (LDO) of middle Miocene through early Pliocene age was recovered from Sites 844 and 847 (located north and west of the Galapagos Islands respectively), and 849 through 851 (Fig. 1) which form part of the 110°W north-south equatorial transect. LDO also occurs at DSDP Sites 572 through 574 (133°W) (Kemp and Baldauf, 1993) and DSDP Site 158 (85°W) (11.1 Ma). Thus, deposition of these sediments has occurred across as much as 3000 km of the eastern equatorial Pacific Ocean, in an east-west direction. The north-south extent of the LDOs is more restricted. Plate tectonic backtracking of the Leg 138 site positions shows that LDOs were probably deposited in two latitudinally separate regions: (1) within a narrow band immediately south of the equator between 0° and 2°S; and (2) north of the equator, centered around the early to mid Miocene positions of Sites 844 and 845 (4°–6°N) (see Kemp et al., this volume). The tight latitudinal control on LDO between 0° and 2°S, is well illustrated at Sites 850 and 851 by the Gamma Ray Attenuation Porosity Evaluator (GRAPE) record across the youngest mat interval (4.4 Ma) (see Fig. 6 in Kemp et al., this volume). The LDOs are concentrated within the time intervals: 12.8–12.5, 11.8–11.5, 11.1, 10–9.5, 6.3–6.1, 5.8–5.1, and 4.4 Ma, with less widespread intervals at 14.6, 8.2, 7.35–7, 6.75, and 5.1–4.5 Ma. The episodes of mat deposition at each site have been plotted vs. depth (mbsf) and age (Ma) (Figs. 2A and 2B, respectively). Individual LDO deposits can be correlated between sites using biostratigraphy, and continuous GRAPE data (see Kemp et al. and Bloomer et al., this volume).

Preservation of the Laminated Diatom Ooze Intervals

Carbonate Dissolution

Extensive SEM investigations of the laminated diatom ooze intervals reveals no substantive evidence that carbonate dissolution occurred preferentially in the *T. longissima* mat deposits. Planktonic and benthic foraminifer tests from *T. longissima*-rich laminae show no signs of dissolution (Pls. 4 and 5) and both intact and deeply pitted/etched coccoliths occur within individual laminae. Further details on silica/carbonate variation in the sediments of the eastern equatorial Pacific Ocean can be found in chapters by Kemp et al. and Kemp (this volume).

Bioturbation

Bioturbation of the laminated intervals occurs preferentially at the upper boundary with the overlying F-NO (e.g., 4.4 Ma interval, Fig. 3). The lower boundary of the laminated intervals is characterized by well-laminated and rarely bioturbated sediment (Pl. 2). The preservation of the diatomaceous laminated intervals, is thought to relate to the physical subjugation of the benthos by the *Thalassiothrix longissima* meshwork (Kemp and Baldauf, 1993; King et al., this volume), rather than a decrease in dissolved oxygen concentration. Burrows within the laminated intervals are most frequently horizontal and show little or no sign of disrupting the overlying laminae (Pl. 4, Fig. 1 and Pl. 5, Fig. 1). In some instances, the diatom mats have been parted by the action of the organism. The composition of the burrows resemble that of the laminae in which they occur, but the frustules within them are very fragmented (see later section on "Synthesis of the Sedimentology and Micropaleontology").

Sedimentation Rates

The LDO intervals of greatest mat production/flux have abnormally high bulk sedimentation rates. For example, at Site 850, accumulation rates across the time intervals 6.3–6.1, and 5.1–4.66 Ma are 122 and 97.73 m/m.y., respectively (Mayer, Pisias, Janecek, et al., 1992). At other sites, there is a similar record; sedimentation rates of 84.1 m/m.y. are recorded from Site 847 (Hole 847B) at 4.4 Ma, and at Site 849 (Hole 849D) 92.2–108 m/m.y. are recorded between 4.98–4.5 Ma (Mayer, Pisias, Janecek, et al., *op cit.*). New calculations based on the orbitally tuned time scale of Shackleton et al. (this volume) give rates through the 6.3–6.1 Ma interval at Site 850 as high as 160 m/m.y.

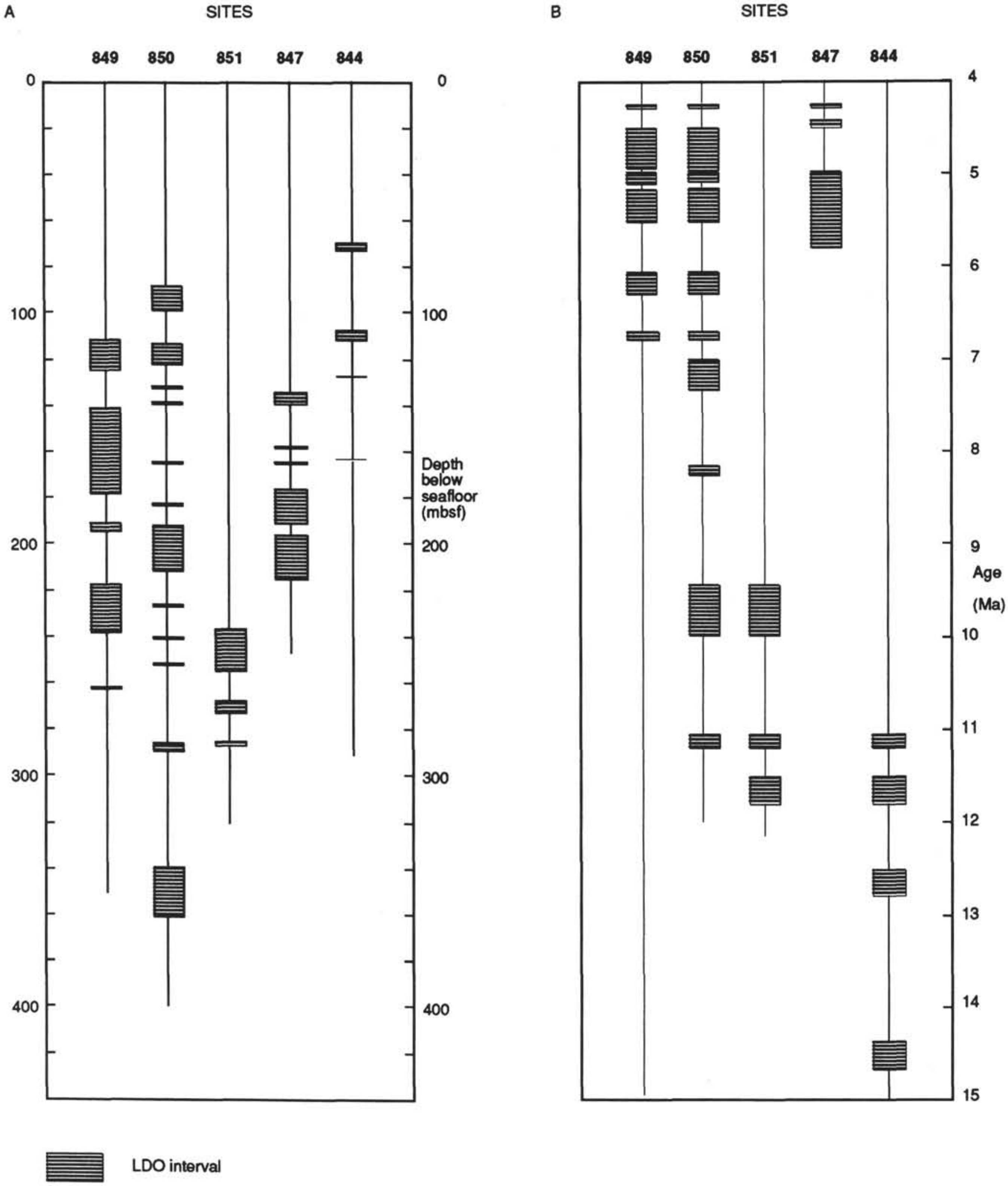

Figure 2. **A.** Downhole position of the laminated intervals at the Leg 138 sites. **B.** Episodes of LDO deposition using Berggren et al.'s (1985) time scale. The resolution of the age dating varies downcore, such that the number of LDO intervals between Figures 2A and 2B are not equal.

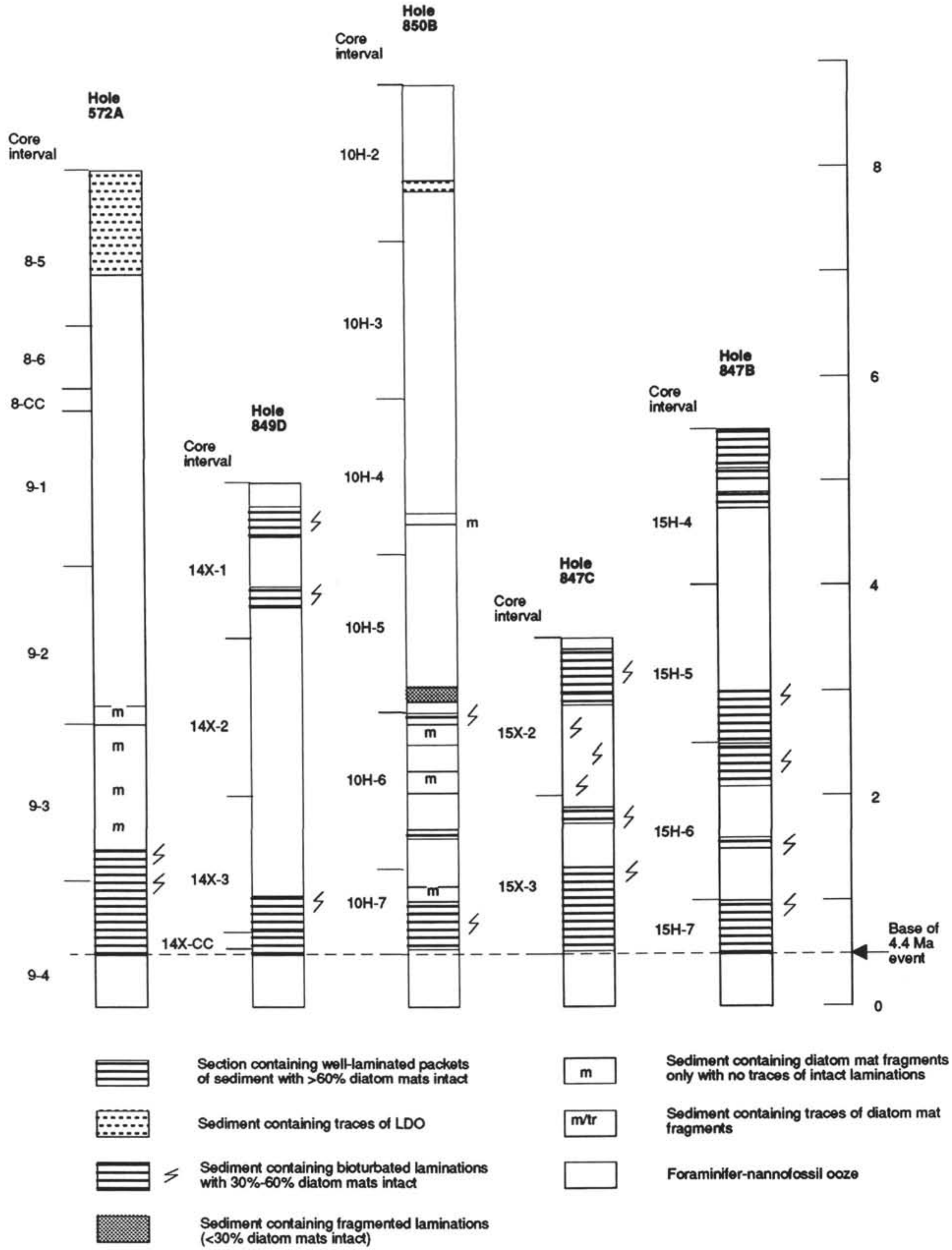

Figure 3. The sedimentary record across the 4.4-Ma interval at Sites 847, 850, 849, and 572. The distribution and preservation of LDO packets is variable.

LAMINATION STYLE

Scales of Lamination

The LDO intervals most frequently occur as packets of sediment between 10 and 20 m thick in the time intervals discussed above. The 4.4-Ma interval (Fig. 3) is a typical example. Normally within these packets, three scales of alternation can be seen between LDO and the background sediment type, F-NO. These alternations are at the submillimeter, the millimeter to centimeter, and the decimeter scale (Fig. 4; Pl. 1). The submillimeter lamination is discussed later. The millimeter to centimeter scale alternation is between nannofossil-bearing diatom ooze (NDO) and purer diatom ooze (DO) (Pl. 1, Fig. 2). These laminae vary in color from white or pale cream to green. Under an optical microscope (up to ×20 magnification), the white laminae appear either slightly translucent, with a layered texture, or homogeneous and nontranslucent. The translucent layered laminae are composed of successive, high-porosity, diatom mats. The nontranslucent white laminae are composed of bioturbated diatom-rich laminae and nonbioturbated NDO laminae. Some nonbioturbated NDO laminae also are green, as are most bioturbated sediments (burrowed laminae and pellets). Pyrite-bearing sediment is normally dark green. F-NO appears cream to beige in color.

On a decimeter scale, beds of unlaminated F-NO alternate with thinner beds of LDO and/or bioturbated DO. Occasionally, laminated beds more than 0.5 m thick can occur; for example, the sedimentary record across the 11.8 to 11.5 Ma interval at Site 844 is continuously laminated for more than 1.5 m.

The basal contact of LDO beds generally is sharp, and is characterized by an abrupt transition from F-NO to DO; for example, at the base of the 4.4 Ma interval (Fig. 3; Pl. 2). These abrupt changes from nannofossil ooze to LDO record the rapid onset of sustained mat-flux episodes (Kemp and Baldauf, 1993).

Description and Classification of Laminae

The laminae have been classified according to observations made using SEM BSEI of polished thin sections and broken sediment surfaces. All fossil assemblage percentage values have been calculated by area from the backscattered images.

The laminae can be subdivided into three types, in order of decreasing porosity: (1) assemblages dominated by *T. longissima* Group diatoms (95%+) (dark tone in BSEI); (2) mixed-assemblages of centric and pennate diatoms, (including specimens of the *T. longissima* Group), radiolarians, nannofossils, foraminifers and silicoflagellates (intermediate in BSEI); and (3) laminae containing more than 80% nannofossils with rare foraminifers and minor quantities of radiolarians and diatoms (bright in BSEI) (Tables 1 and 2).

T. longissima*-rich Laminae*

Individual diatom mats, closely resembling modern examples of *Rhizosolenia* mats (Villareal and Carpenter, 1989), have an average thickness of 20 µm (thickness range is 15 to 25 µm), and form the building blocks of the *T. longissima*-rich laminae (Pl. 3, Figs. 1 and 2). Any one *T. longissima*-rich lamina typically will be composed of 25 of these microlaminae. Several varieties/subspecies of *T. longissima*, referred to as the *T. longissima* Group, make up between 95% and 100% of the fossil assemblage. The *T. longissima* frustules are between 1.5 and 5 µm wide, up to 3.8 mm long, and form an interlocking meshwork (Pl. 3, Figs. 1–3). Between, and in some cases within, the individual mats are found rare calcareous nannofossils, planktonic and benthic foraminifers (e.g., *Cibicides* spp., *Gyroidina* spp., see King et al., this volume), non-*T. longissima* Group diatoms, silico-flagellates and radiolarians (see Pl. 3, Figs. 1–3). Bed-parallel partings within laminated sections have been interpreted as the contacts between successively deposited mats, as these are likely to be the zones of greatest weakness.

Table 1. Classification of the laminae.

Lamina type	Composition	Thickness: Range	Thickness: Mean (µm)	Thickness: Standard deviation (µm)	Spacing	Regularity	Boundaries
T. longissima-rich	Assemblages of *T. longissima* Group diatoms.	50 µm–4 mm	470	270	Submm	The spacing of the laminae may vary from regular to irregular within a laminated diatom ooze interval.	Abrupt to transitional between *T. longissima*-rich and mixed-assemblage laminae (Pls. 4 and 5). Abrupt between *T. longissima*-rich and nannofossil-rich laminae (Pl. 4).
Mixed-assemblage	Centric and pennate diatoms (including *T. longissima* Group species), nannofossils, foraminifers, and radiolarians.	25–900 µm	170	75	Submm to mm	Irregular to regular.	
Nannofossil-rich	Nannofossils with subordinate quantities of diatoms, foraminifers and radiolarians.	50µm–1.35 mm	420	410	Submm	Spacing of the laminae is predominantly regular within a laminated interval.	

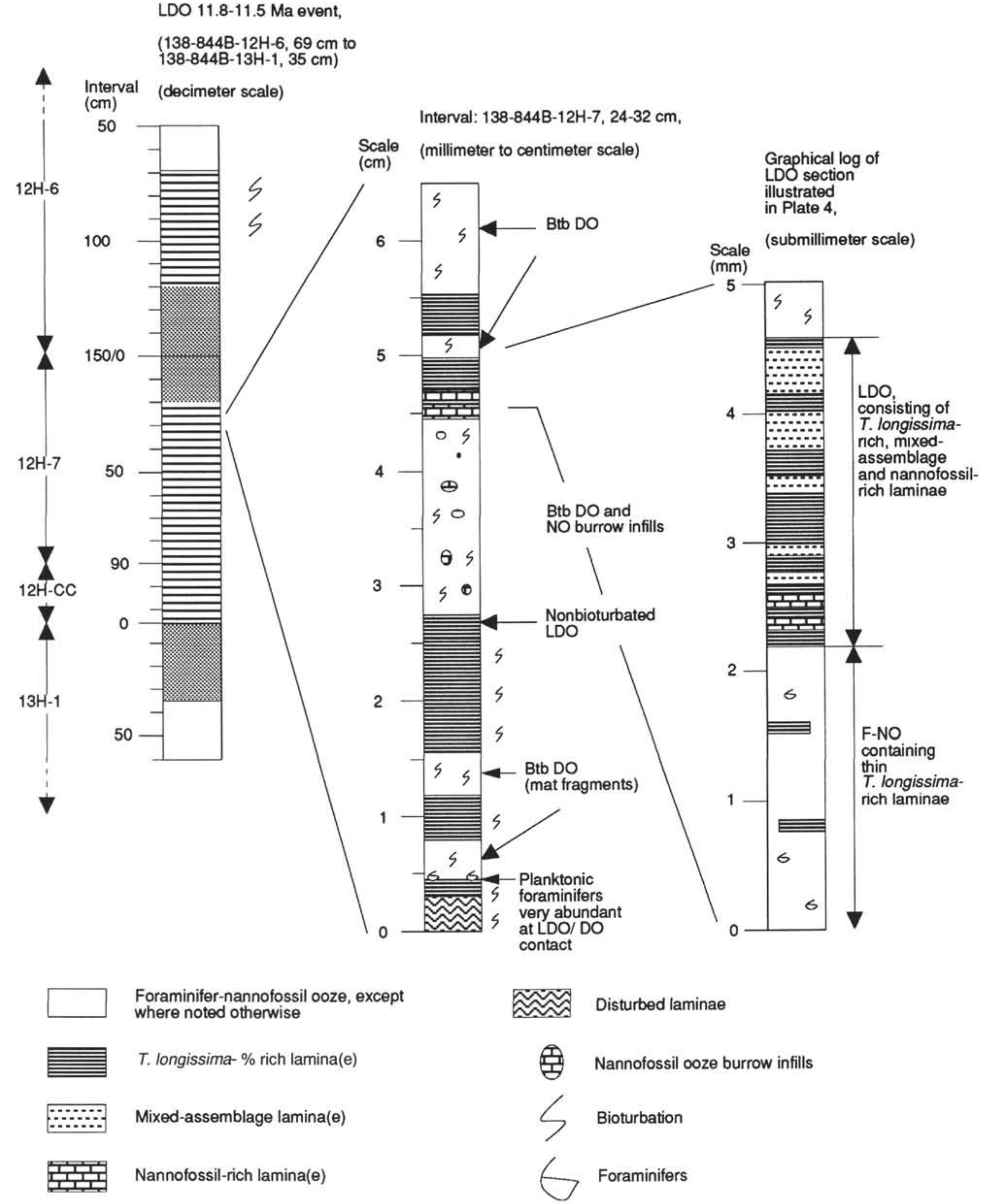

Figure 4. Three scales of alternation are seen between LDO and the background sediment type (F-NO). At Site 844, the 11.8- to 11.5-Ma interval consists of several extensive LDO sections, one of which is illustrated to show the submillimeter and the millimeter to centimeter scale alternation. The sedimentary interval corresponding to the submillimeter scale alternation is shown in Plate 4.

Table 2. Details of laminated intervals observed during this study.

Interval sampled (cm)	Thickness of laminated interval(s)	Lamina-type: *T. longissima*-rich				Mixed-assmblage				Nannofossil-rich				Lamina associations
		Number	Mean thickness	Standard deviation	Thickness range	Number	Mean thickness	Standard deviation	Thickness range	Number	Mean thickness	Standard deviation	Thickness range	
844B-12H-7, 24–32	1.85	6	0.165	0.070	0.100–0.300					5	0.110	0.050	0.050–0.200	B
	2.00	6	0.225	0.140	0.100–0.500	4	0.050	0.000	0.050	2	0.200	0.100	0.100–0.300	A, B
	2.76	10	0.130	0.090	0.050–0.350	6	0.170	0.070	0.075–0.250	4	0.245	0.165	0.080–0.500	A, B
	3.80	8	0.330	0.130	0.150–0.750	7	0.165	0.050	0.100–0.200					A
844B-12H-7, 75–79	4.70	6	0.425	0.140	0.200–1.250	6	0.325	0.140	0.150–0.400					A
	1.60	5	0.180	0.070	0.100–0.300	5	0.120	0.050	0.050–0.200					A
	3.50	6	0.460	0.125	0.250–0.600	5	0.120	0.070	0.125–0.300					A
	4.35	8	0.430	0.155	0.200–0.700	8	0.080	0.030	0.025–0.100					A
844B-14H-6, 143–149	7.75	9	0.640	0.740	0.150–2.40	8	0.250	0.200	0.050–0.650					A
844B-20H-5, 46–51	4.45	5	0.870	0.875	0.150–2.50	4	0.115	0.040	0.050–0.150					A
	1.55	4	0.240	0.055	0.150–0.300	4	0.080	0.020	0.050–0.100					A
844C-8H-2, 125–130	2.75	6	0.210	0.105	0.100–0.400	5	0.280	0.135	0.150–0.550					A
844C-8H-3, 13–17	7.75	5	0.640	0.385	0.100–1.25	4	0.075	0.020	0.050–0.100					A
	3.75	5	1.330	0.435	1.00–2.15	6	0.125	0.040	0.050–0.150					A
844C-8H-3, 142–150	3.75	5	0.490	0.220	0.150–0.750	4	0.300	0.060	0.200–0.350					A
844C-8H-5, 20–25	5.50	9	0.245	0.140	0.100–0.550	9	0.145	0.105	0.050–0.350					A
847B-15H-7, 39–49	3.46	11	0.365	0.265	0.100–1.00	10	0.195	0.140	0.100–0.550					A
847C-15X-3, 110–115	6.30	6	0.900	0.780	0.050–2.00	5	0.180	0.350	0.100–0.450					A
847C-15X-3, 134–144	2.40	7	0.260	0.155	0.150–0.550	6	0.315	0.130	0.175–0.550					A
849B-19X-6, 53–66	3.54	6	0.415	0.170	0.250–0.750	5	0.210	0.085	0.100–0.350					
	5.00	9	0.430	0.315	0.050–0.950	9	0.125	0.115	0.050–0.400					A
	5.62	9	0.500	0.215	0.100–0.800	8	0.140	0.010	0.050–0.350					A
	9.36	13	0.575	0.365	0.100–1.45	12	0.155	0.010	0.050–0.350					A
	7.74	10	0.665	0.350	0.200–1.40	9	0.115	0.080	0.050–0.250					A
849D-23X-6, 31–39	7.25	7	0.300	0.300	0.100–1.00					7	1.130	0.870	0.200–1.35	B
	7.78	8	0.155	0.100	0.050–0.400	7	0.265	0.105	0.100–0.400					A
850B-20X-7, 25–27	18.00	15	0.775	0.530	0.150–2.00	15	0.125	0.060	0.050–0.200					A
851E-28X-2, 104–112	25.55	33	0.710	0.845	0.050–4.00	29	0.115	0.120	0.025–0.700					A

Mixed-assemblage Laminae

Mixed-assemblage laminae are composed of fossil assemblages intermediate in composition between the *T. longissima*-rich and nannofossil-rich laminae types (Pl. 3, Fig. 4, and Pl. 5, Fig. 2). In detail, mixed-assemblage laminae are composed of variable quantities of diatoms (fragmented specimens of the *T. longissima* Group make up between 10% and 60% of the assemblage, and other diatom species between 10% and 50%), calcareous nannofossils (0%–80%), and foraminifers, radiolarians and silicoflagellates (0%–10%). *Denticulopsis* and *Rossiella* are typical non-*T. longissima* Group diatom species from the 12.8–12.5, 11.8–11.5, and 11.1 Ma mat intervals.

Nannofossil-rich Laminae

Compositionally, nannofossil-rich laminae are F-NO and diatom-nannofossil oozes (DNO) (Pl. 4, Fig. 3). Thus, they are similar to the regionally prevalent background sedimentation. In addition to the dominance of nannofossils in these laminae (~80%+), they are also characterized by an absence of diatom mats, although *T. longissima* Group diatoms may be present as a minor sediment component (0%–10%). Subordinate quantities of non-*T. longissima* Group diatoms (<30%), foraminifers (<10%), and radiolarians (<10%) also occur. Foraminifers are significantly more abundant in these laminae than in either the mixed-assemblage or diatom-rich laminae.

Association of Lamina Types

Two types of lamina associations were observed, a mixed-assemblage/*T. longissima* lamination (Pl. 4, Fig. 1, and Pl. 5, Fig. 1), and a F-NO/*T. longissima* lamination (Pl. 4) (Table 3). The mixed-assemblage/*T. longissima* lamina association is dominant within packets of LDO, and the transition between F-NO and LDO is most frequently marked by a F-NO/*T. longissima* lamina association. Site-by-site occurrences of the lamination types are summarized in Table 4.

Detailed sedimentological investigations of the 11.8–11.5, 11.1, and 4.4 Ma intervals indicate some slight variations in the lamina associations from those described above. The 11.8–11.5 Ma interval is characterized by more than 2 m of almost continuous LDO. Within this interval, there are intermittent, but persistent occurrences of F-NO/*T. longissima* lamina associations. At the base of the 11.1-Ma interval, there are several occurrences of subcentimeter-sized LDO packets. These laminated sediments rarely contain a F-NO/*T. longissima* lamina association across the F-NO/LDO boundary, rather, there is normally an abrupt transition from F-NO to a mixed-assemblage/*T. longissima* lamina association. On a macroscopic scale, the 4.4 Ma interval is characterized by an abrupt transition from F-NO to LDO (see previous section). Microscopic evidence from Sites 847 and 850 indicates that this change is marked by a transition from F-NO to a mixed-assemblage/*T. longissima* lamina association, that is, no nannofossil-rich laminae occur at this boundary.

As discussed in Kemp et al. (this volume), the millimeter to centimeter scale alternations in the LDO intervals, record periods of more or less intense mat flux, these cycles may be analogous to periods of stronger/weaker El Niño/La Niña cycles. On the submillimeter scale, a similar signal is recorded by the mixed-assemblage/*T. longissima* lamina associations, where the laminae probably represent individual events. The F-NO/*T. longissima* lamina associations represent periods of high mat flux alternating with periods of either low or negligible mat flux, and thus may indicate more extreme fluctuations in the paleoceanographic conditions.

A CASE STUDY: MICROPALEONTOLOGY OF THREE LAMINATED DIATOM OOZE INTERVALS

Detailed SEM-led micropaleontological investigations were undertaken on three laminated intervals from the middle Miocene *Actinocyclus moronensis*, *Craspedodiscus coscinodiscus*, and *Cestodiscus peplum* zones, (138-844C-8H-3, 135–140 cm; -844B-12H-7, 75–79 cm; and -844B-20H-5, 46–51 cm, respectively) (Baldauf and Iwai, this volume) (Figs. 5 and 6).

The diatom assemblages are dominated by specimens of the *T. longissima* Group. Most of these specimens are fragmented and have a length of less than about 40 µm. The occurrence of specimens of *T. longissima* longer than 70 µm that contain at least one apice varies from rare to abundant.

Diatom species other than *T. longissima* occur in each interval sampled. In Section 138-844C-8H-3, 135–140 cm, species consistently observed include *Denticulopsis simonseii* s.l. and *Rossiella paeleacea*. After specimens of *T. longissima*, specimens of *Denticulopsis* are the next most abundant. *Denticulopsis* occurs in greatest numbers in Sample 3, where most of the specimens consist of girdle bands, rather than complete valves. In addition, rare specimens from the *Thalassiosira yabei* Group, *Hemidiscus cueniformis*, and *Asterolampra* sp. also were observed.

The abundance of "Other Diatoms," including *Denticulopsis,* is lower in Section 138-844B-12H-7, 75–79 cm, than in the other two intervals (Fig. 5B). Only scattered specimens of the *T. yabei* Group, *Thalassionema nitzschoides*, *T. nitzschioides* var. *parva,* and *Triceratium* sp. were observed.

In Section 138-844B-20H-5, 46–51 cm, *Denticulopsis* specimens here are actually *Denticulopsis kanayae,* rather than *D. simonsenii. Rossiella* is extremely rare in this section.

The absolute abundance of diatoms throughout the sequences is in part controlled by preservation. Diatom preservation varies between poor and moderate, with one exception, Sample 138-844B-12H-7, 75–79 cm. This sample contains a well-preserved flora composed of the specimens mentioned previously, as well as specimens of *Azpeitia praenodulifer, Actinocyclus moronensis, Nitzschia praereinboldii,* and *C. coscinodiscus*. Poorly preserved diatom assemblages (e.g., Sample 3 in Section 138-844B-8H-3, 135–140 cm) are dominated by numerous girdle bands of *Denticulopsis*, and fragments (<70 µm long) of the *T. longissima* Group.

Smear-slide analysis shows that radiolarians and silicoflagellates occur rarely, but consistently, throughout the samples. The silicoflagellate assemblage in the three sections consists of specimens of both *Dictyocha* and *Distephanus*. Specimens of *Dictyocha* generally outnumber those of *Distephanus* in Section 138-844B-8H-3, 135–140 cm, but in Section 138-844B-12H-7, 75–79 cm, *Distephanus* specimens are slightly more numerous than *Dictyocha* specimens. The numbers of both species of silicoflagellate are equal in Section 138-844B-20H-5, 46–51 cm, with the exception of Sample 1, here *Dictyocha* is rarely observed.

Radiolarians are generally common, as determined by the BSEI method. The numbers of foraminifers (planktonic and benthic) are more variable, and planktonic forms generally outnumber benthic forms. Peaks in planktonic foraminifer abundance normally coincide with peaks in benthic foraminifer abundance.

Synthesis of the Sedimentology and Micropaleontology

In Sections 138-844B-12H-7, 75–79 cm and -844B-20H-5, 46–51 cm, there generally is (1) an increased abundance of *T. longissima* fragments greater than 70 mm long (moderate to good preservation) within the *T. longissima*-rich laminae, accompanied, in some instances, by a reduction in the numbers of benthic foraminifers, and (2) an increased abundance of *T. longissima* fragments less than 70 mm long (poor to moderate preservation) in mixed-assemblage laminae, accompanied by a slight increase in benthic foraminifers. The abundance of other diatoms does not show a positive correlation with mixed-assemblage laminae. Bioturbated horizons are dominated by fragmented (<70 mm in length), and poorly preserved *T. longissima* frustules. There is also some evidence to suggest that the abundance of other diatoms increases in bioturbated laminae. No relationship

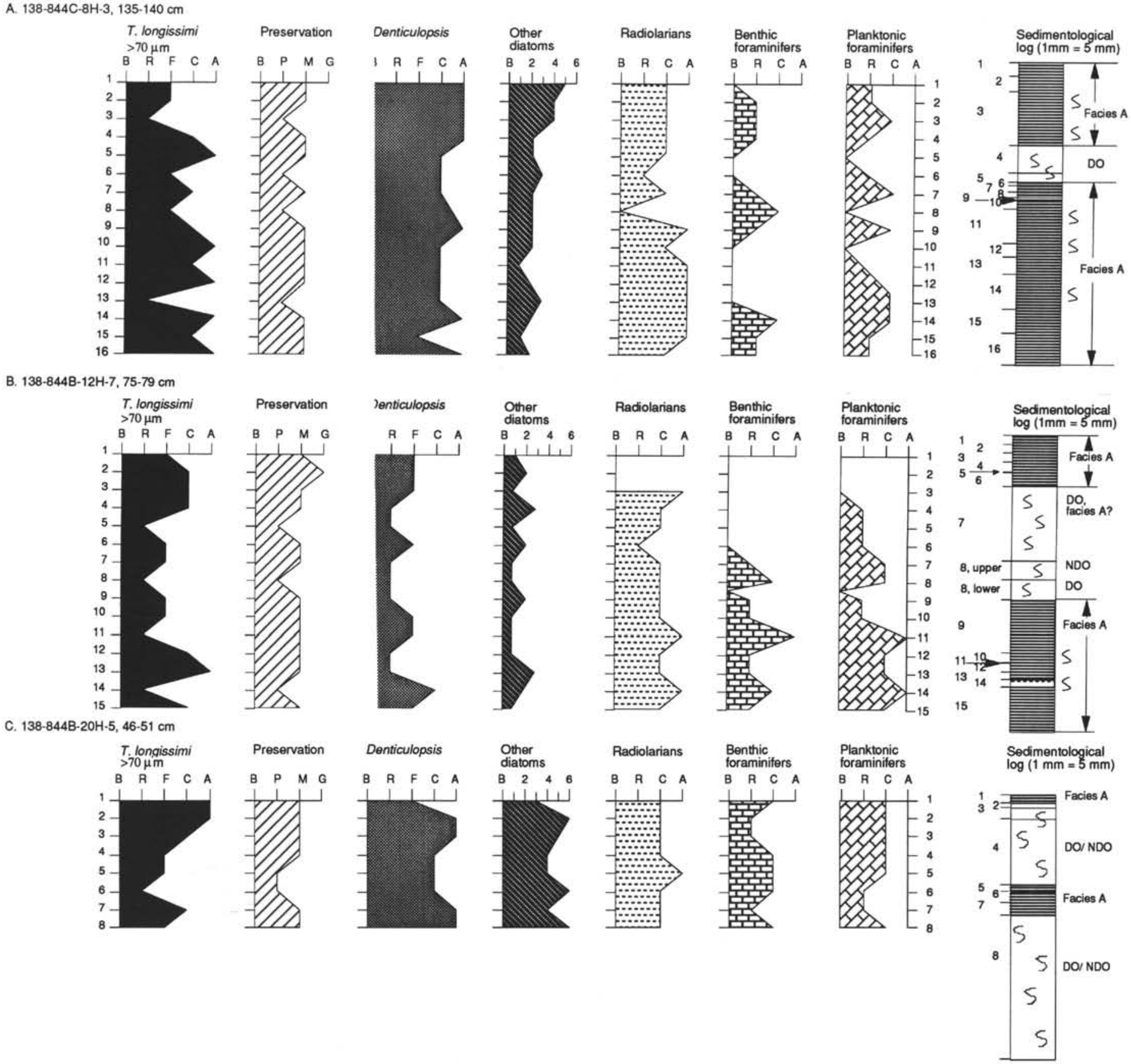

Figure 5. Graphs of microfossil abundances. **A.** Section 138-844C-8H-3, 135–140 cm. **B.** Section 138-844B-12H-7, 75–79 cm. **C.** Section 138-844B-20H-5, 46–51 cm.

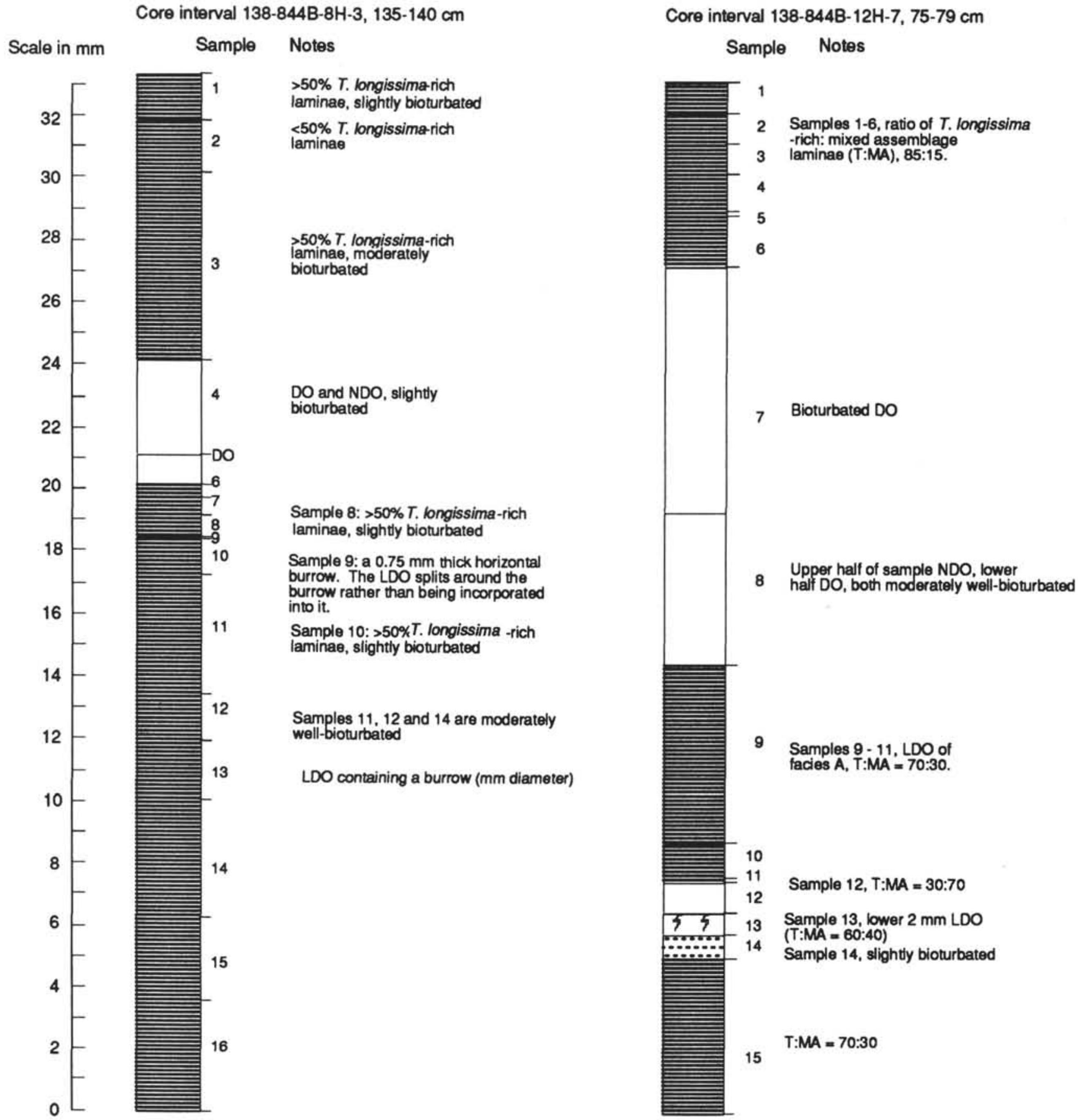

Figure 6. Sedimentological logs of the intervals examined in the case study. All the LDO intervals belong to Facies A. T:MA = ratio of *T. longissima*-rich laminae to mixed-assemblage laminae. Symbols are the same as those used in Figure 4.

Table 3. Classification of the LDO facies.

Lamina association	Number of intervals	Thickness Range (mm)	Thickness Average (mm)	Thickness Standard deviation	Occurrence
Mixed-assemblage/*T. longissima*	25	<2–>25	5.95	5.21	Dominant within laminated intervals.
F-NO/*T. longissima*	4	<1.9–7.5	3.45	2.21	Dominant at the transition between F-NO/LDO.

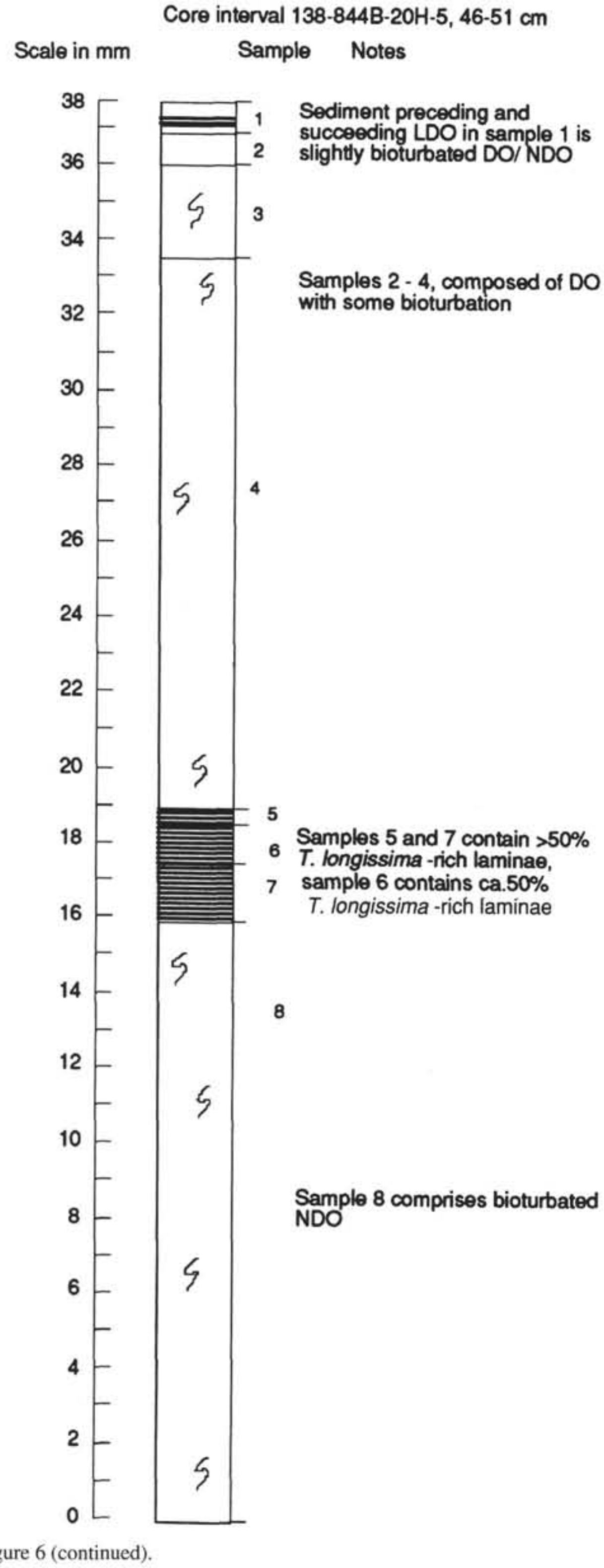

Figure 6 (continued).

between lamina type and fossil assemblage is seen in Section 138-844B-8H-3, 135–140 cm. The generally poor correlation between lamina type and fossil assemblage may result from the relatively coarse sampling strategy.

Contemporary studies of benthic foraminifers within well-preserved LDO show a reduction in numbers relative to nonlaminated sediment. This is attributed to the physical suppression of foraminifer benthic activity by the diatom meshwork (Kemp and Baldauf, 1993; King et al., this volume).

SUMMARY

It is clear that LDO occurs intermittently in time and space across the eastern equatorial Pacific Ocean, and in some instances, these events can be correlated more closely.

The basic building blocks of all the LDO sediments are 20-µm-thick mats of the diatom *Thalassiothrix longissima*. Several varieties/subspecies of *T. longissima* occur within individual mats. Similar observations have been made of present-day *Rhizosolenia* mats in the central North Pacific gyre, where six species were found in 10 different mat combinations (Villareal and Carpenter, 1989). Three types of lamination have been identified in the LDOs. These are (1) an assemblage dominated by *T. longissima* Group diatoms, consisting of diatom mats; (2) a mixed-assemblage of centric and pennate diatoms (including specimens of the *T. longissima* Group), radiolarians, silicoflagellates, nannofossils, and foraminifers, and (3) laminae containing more than 80% nannofossils with subordinate quantities of the fossil components mentioned above. These laminae occur in two lamina associations, a mixed-assemblage/*T. longissima* association and a F-NO/*T. longissima* association. The transition from F-NO to LDO is most frequently marked by a F-NO/*T. longissima* lamina association, and within packets of laminated diatom ooze, the mixed-assemblage/*T. longissima* lamina association dominates.

The average thickness of the *T. longissima*-rich laminae is 0.5 mm (25 layers of individual diatom mats, each about 20 µm thick), although, exceptionally, they range up to 4 mm. These laminae have been interpreted to result from individual episodes of multiple mat generation and flux, suggesting that, exceptionally, stacks of up to 200 mats may have been deposited from one mat-forming event (the likely origins of these mat-forming events is discussed in Kemp et al., this volume).

The microfossil assemblage within three laminated intervals at Site 844 was examined. Diatoms of the *T. longissima* Group occur within and between the mat intervals, whereas the various species of other diatoms, such as *Denticulopsis* (a common equatorial form) and *Rossiella*, are concentrated between the mats. Radiolarians and silicoflagellates, such as *Distephanus* and *Dictyocha*, occur in low numbers throughout the intervals sampled. Variations in the relative abundance of *Distephanus* and *Dictyocha* suggest systematic variation in temperature of the surface waters during episodes of mat flux. Both benthic and planktonic foraminifers are present in variable quantities. With increasing quantities of intact diatom mats, the abundance of benthic foraminifers decreases.

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Table 4. Distribution and occurrence of the sedimentary

LDO interval (cm)	Site	Lamina association(s)	Occurrence of lamina associations (location of samples)
14.6	844	Mixed-assemblage/*T. longissima*	In top 5 cm of a 15-cm packet of LDO.
12.8–12.5	844	Mixed-assemblage/*T. longissima*; F-NO/*T. longissima*	F-NO/*T. longissima* lamina associations occur immediately above the boundary between F-NO and a 40-cm-thick LDO packet. Mixed-assemblage/*T. longissima* lamina associations overly the nannofossil-rich/*T. longissima*-rich lamination.
11.8–11.5	844	Mixed-assemblage/*T. longissima*; F-NO/*T. longissima*	Samples were taken from within a thick LDO sediment packet (>0.5 m thick). Mixed-assemblage/*T. longissima* lamina associations dominate, and there are intermittent, but persistent, occurrences of F-NO/T. *longissima* associations.
11.1	844	Mixed-assemblage/*T. longissima*; F-NO/*T. longissima*	At the base of this LDO interval mixed-assemblage/*T. longissima* lamina associations occur as discrete LDO packets (sub cm scale) within F-NO sediments. Nannofossil-rich/*T. longissima*-rich lamination only rarely marks the transition between F-NO and LDO. Mixed-assemblage/*T. longissima* lamina associations only occur within.
10–9.5	851	Mixed-assemblage/*T. longissima*	Less than 5 cm above the base of a 60-cm-thick LDO packet, overlying 25 cm of intermittently laminated diatomaceous ooze.
6.3–6.1	850	Mixed-assemblage/*T. longissima*	Located within a 10-cm LDO packet.
	849	Mixed-assemblage/*T. longissima*	At the F-NO/LDO transition of a 10-cm-thick LDO packet, a F-NO/*T. longissima* lamina association occurs, and is succeeded by a mixed-assemblage/*T. longissima* lamina association.
5.8–5.1	847	Mixed-assemblage/*T. longissima*	An alternating mixed-assemblage and *T. longissima*-rich lamination occurs within a 20-cm-thick LDO packet, the boundary between the laminated interval and the background sediment is not seen due to core disturbance.
5.1–4.98	849	Mixed-assemblage/*T. longissima*	A LDO packet approximately 10 cm thick contains at least 9 cm of alternating mixed-assemblage and *T. longissima*-rich laminae. Transition to F-NO not seen.
4.4	847, 850	Mixed-assemblage/*T. longissima*	The 4.4 Ma interval consists of at least 50 cm of LDO at its base. The boundary between the F-NO and the LDO is abrupt, a mixed-assemblage/*T. longissima* lamina association occurs in direct contact with the F-NO. Laminae are poorly defined within the interval, but compositional data indicate that the *T. longissima*-rich and mixed-assemblage lamina types were probably dominant here.

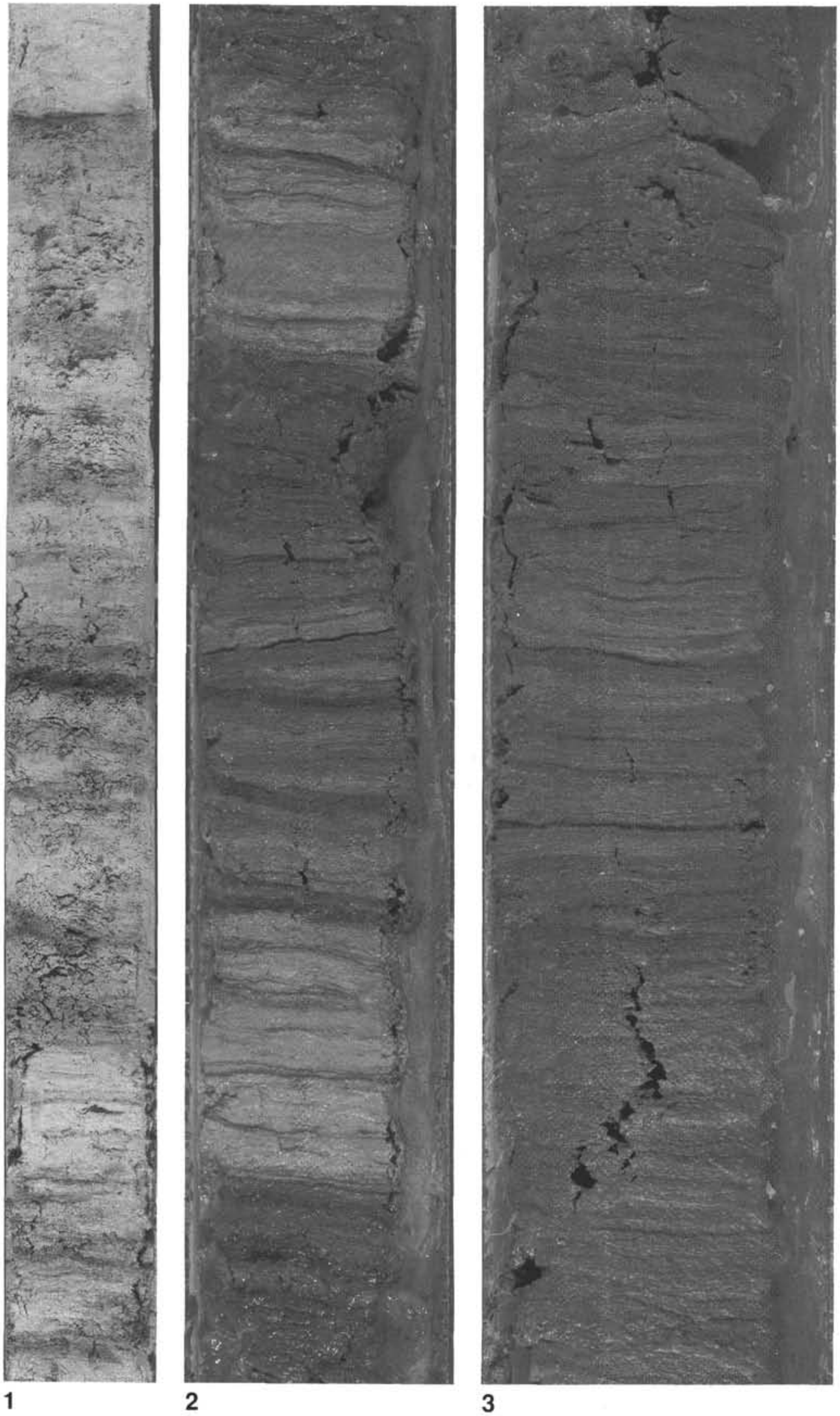

Plate 1. Section 138-850B-30X-5, 30–90 cm; effects of wire core-splitting, which caused considerable deformation of the LDO, making identification difficult, but creating a characteristic roughened surface. In Figures **1** and **2,** saw-cut surfaces are shown. They allow for close examination of the millimeter to centimeter scale alternation between the paler (off-white) pure diatom ooze and the darker (green) mixed diatom and calcareous nannofossil ooze. **2.** Section 138-851E-28X-2, 78–112 cm, shows the centimeter-scale alternation between darker DO and lighter NDO, but with lamination visible throughout. **3.** Section 138-851E-29X-5, 35–60 cm, shows the continuous laminated ooze characteristic of the 11.1-Ma interval at Sites 850 and 851. For scale refer to width of cores.

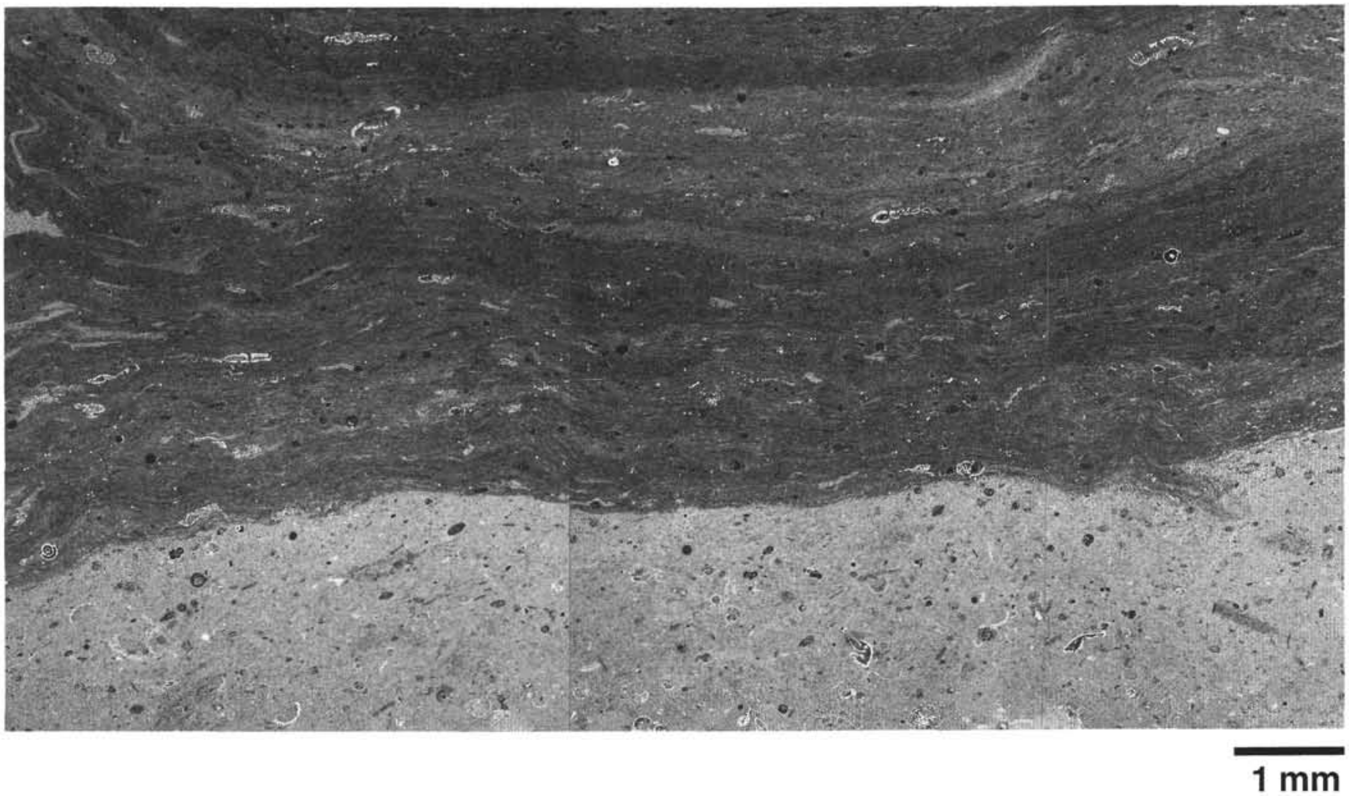

Plate 2. Rapid onset of the 4.4-Ma event, Site 850 (Sample 138-850B-10H-7, 74–81 cm). The darkest high-porosity sediment is the LDO containing an assemblage of *T. longissima* Group diatoms. This is underlain by the paler background sediment type F-NO, comprising primarily of calcareous nannofossils, but with minor quantities of diatoms, foraminifers, and radiolarians. Planktonic and benthic foraminifers are represented by the black objects having a white outline (0.1–0.3 mm).

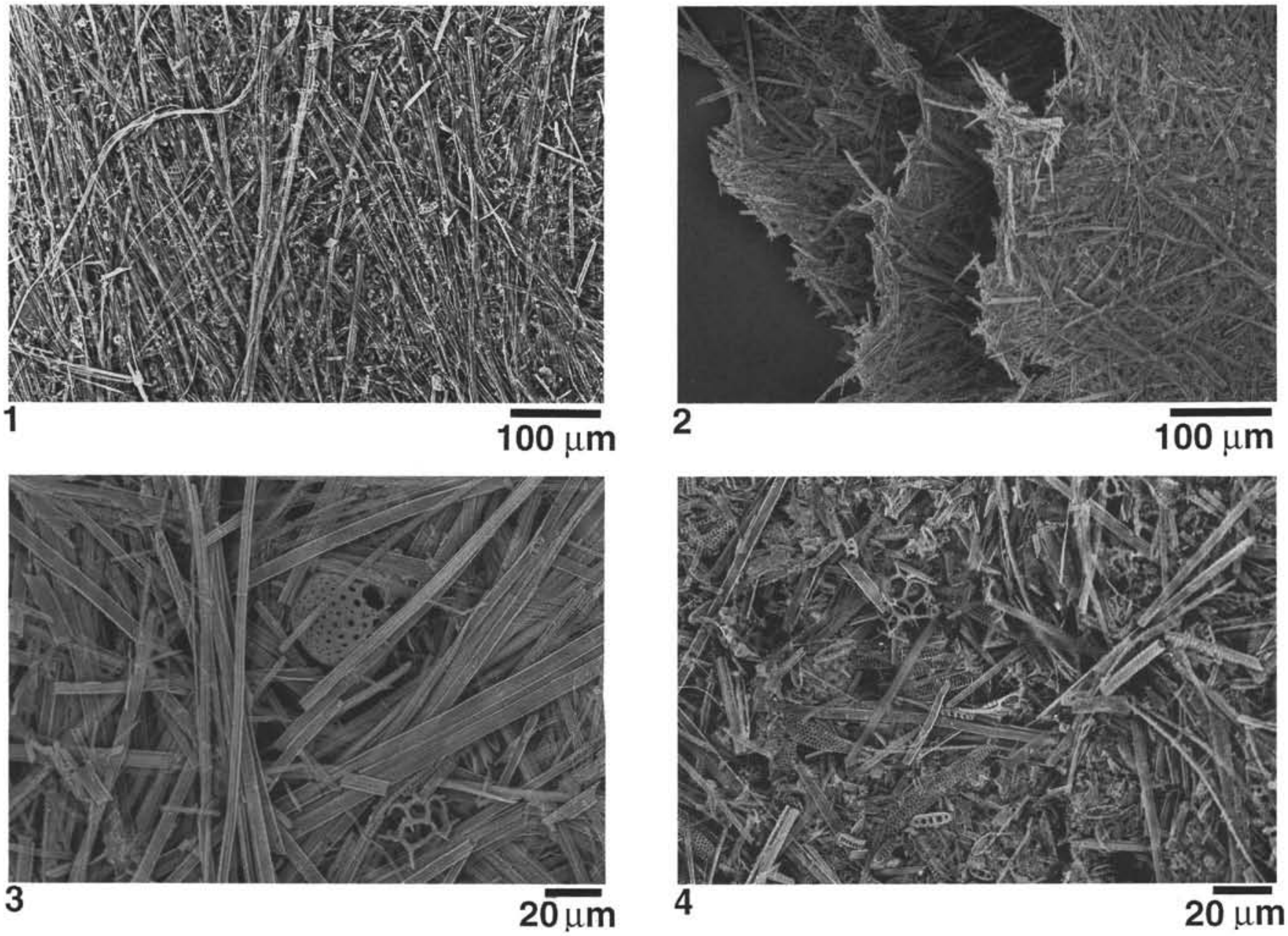

Plate 3. **1.** BSE topographic image of the surface of a peeled diatom mat. **2.** This BSEI topographic image shows successive diatom mats overlying one another. **3.** High-magnification topographic image of a mat surface (×500) with a radiolarian enclosed within the mat and a silicoflagellate on its surface. **4.** Topographic image of a mixed-assemblage lamina from the 11.1-Ma interval (Site 844) showing fragmented *T. longissima* Group diatoms, other diatom species (including *Denticulopsis* and *Rossiella*), and calcareous nannofossils.

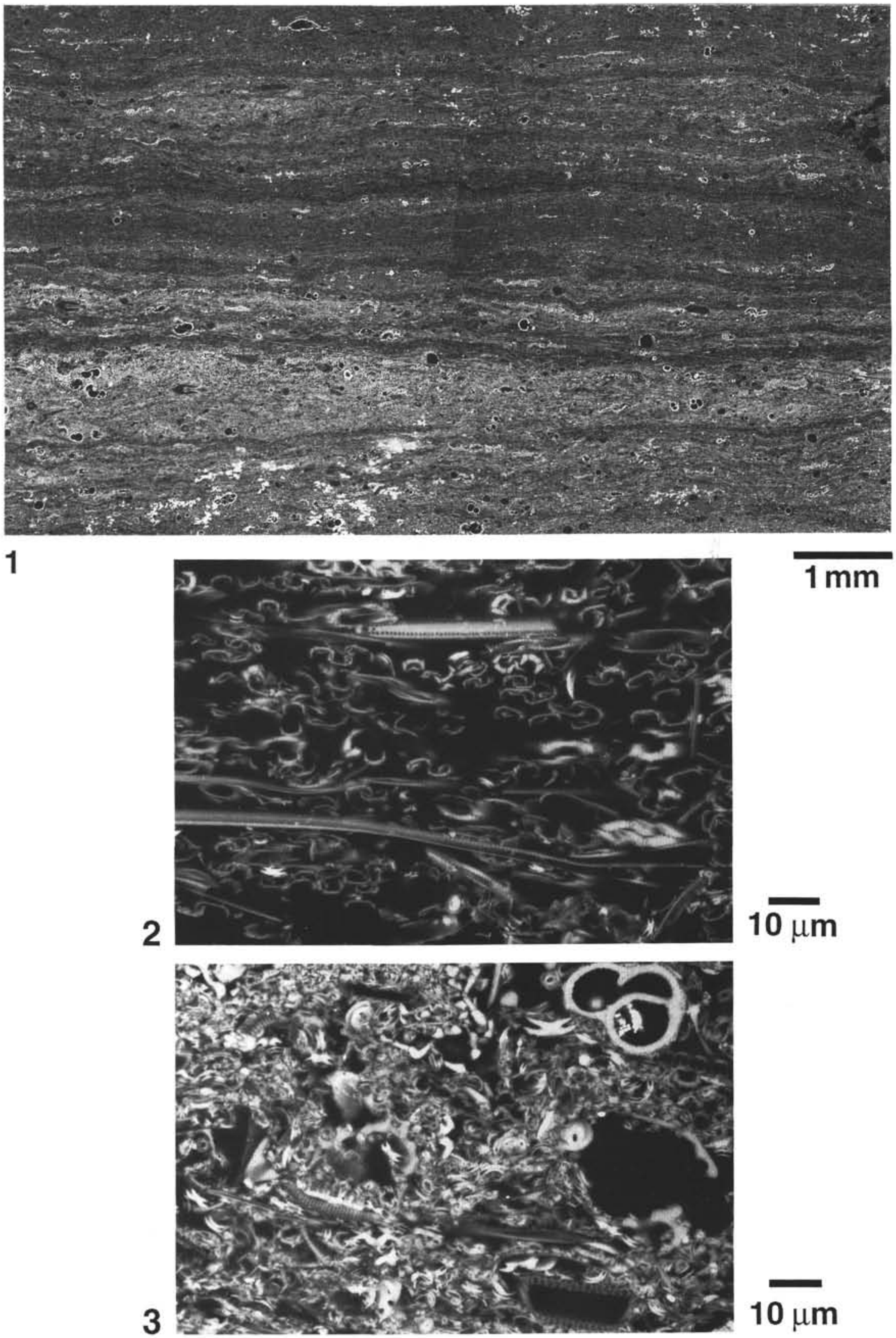

Plate 4. **1.** LDO from the 11.8- to 11.5-Ma interval (Site 844), showing the three types of laminae (see Fig. 4 for their identification). **2.** High-magnification image of a typical *T. longissima*-rich laminae. **3.** High-magnification image of a nannofossil-rich laminae containing scattered diatoms and foraminifers.

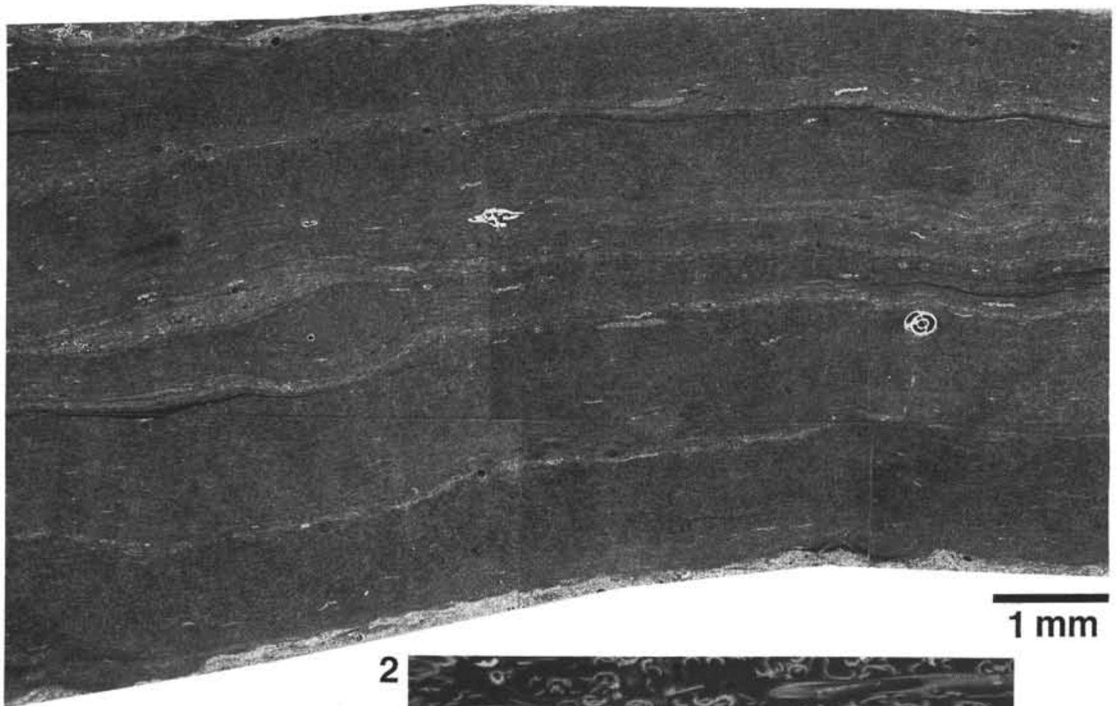

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Plate 5. **1.** This laminated interval (Sample 138-849B-19X-6, 53–69 cm) exhibits thick, well-defined *T. longissima*-rich laminae that contain well-preserved foraminifers, interbedded with thin mixed-assemblage laminae. **2.** This enlarged section of the lowermost mixed-assemblage lamina, 90 to 130 μm thick, shows a typical assemblage. It consists of calcareous nannofossils, centric and pennate diatoms, and a foraminifer. The pale gray areas above and below the foraminifer are composed of coccoliths and amorphous siliceous/calcareous matter.