

Diatomaceous ooze in a sedimentary core from Mariana Trench: implications for paleoceanography

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ABSTRACT:

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Diatomaceous ooze sampled from near the Mariana Trench sediment surface by gravity corer (Core JL7KGC05) revealed a high sedimentary abundance of *Ethmodiscus rex* (Rattray, 1890) Wiseman and Hendey, 1953 fragments and tropical open ocean planktonic diatom taxa including *Azpeitia nodulifera* (Schmidt, 1878) Fryxell and Watkins in Fryxell, Sims and Watkins, 1986 and *Alveus marinus* (Grunow, 1880) Kaczmarek and Fryxell, 1996. Subsurface sediments from the ooze are assigned a Marine Isotope Stage 2 age, approximately at the Last Glacial Maximum. The occurrence of *Ethmodiscus* ooze suggests massive late Pleistocene blooms in the Northwestern Pacific Ocean and provides a plausible link to paleoceanographic and paleoclimatic changes related to Antarctic Intermediate Water mass, which carried a high dissolved silica content as silicon leakage that reduced dissolution rate of diatom frustules. Northward flow of Antarctic Intermediate Water was probably related to surface current migration and southward shift of the Northwest Pacific Gyre to form oligotrophic conditions that triggered *Ethmodiscus rex* blooms under unusual nutrient recycling conditions within the ocean system. This bloom hypothesis may help explain differential silica dissolution during the last glacial stage.

Key words: Diatomaceous ooze; Diatom; *Ethmodiscus rex*; Mariana Trench; Challenger Deep.

INTRODUCTION

Diatomaceous ooze is a widely distributed type of marine sediment composed of siliceous diatom frustules that is deposited on deep sea floor, espe-

cially below the Calcium Carbonate Compensation Depth (CCD). The white, yellowish-gray, yellowish-brown or reddish-brown diatomaceous ooze is also known as diatom dump (Mikkelsen 1977; Burckle and Cirilli 1987; Kemp and Baldauf 1993; Rea *et al.*

Author(s) and year	Leg/Cruise	Hole	Location	Water depth (m)	Area	Core length (m)
Wiseman and Hendeby (1953)	H.M.S. Challenger 1872–1876	225	11°24.0'N, 143°16.0'E	8186	Mariana Trench	no data
Martini (1982)	DSDP 60	453	17°54.42'N, 143°40.95'E	4693	Mariana Trench	605
	DSDP 60	459	17°51.75'N, 147°18.09'E	4121		3.5
	DSDP 60	460	17°40.14'N, 147°35.92'E	6452		85
	DSDP 60	460A	17°40.02'N, 147°35.16'E	6445		99.5
Janecek and Rea (1985)	DSDP 68	503B	4°03.02'N, 95°38.32'W	3682	Eastern Pacific	112.8
Rea <i>et al.</i> (1993)	ODP 145	882	50°21.8'N, 167°36.0'E	3244	Northern Pacific	398
	ODP 145	883	51°11.9'N, 167°46.1'E	2385		830
Kemp <i>et al.</i> (1995)	ODP 138	850A	1°17.84'N, 110°31.28'W	3672	Eastern Pacific	74.2
De Deckker and Gingele (2002)		BAR 9442	6°04.56'S, 10°25.08'E	2542	Eastern Indian	9.8
Zhai <i>et al.</i> (2012)	Kexue Yihao-2004	WPD03	17°19.82'N, 138°27.28'E	5250	Eastern Philippine Sea	4.05
		WPD12	20°35.95'N, 139°14.53'E	4954		1.0
Luo <i>et al.</i> (2018)	Haiyang Six-2012	GC 05	10°59.73'N, 141°59.74'E	7118	Mariana Trench	2.7
		BC 11	11°0.38'N, 141°57.14'E	7016		0.74
this study	Haiyang Six-2012	JL7KGC05	10°59.75'N, 141°59.70'E	7120	Mariana Trench	2.15

Table 1. Location data for cores cited herein

1993; Romero and Schmieder 2006; Smetacek 2009). The ooze sediments of the Equatorial Ocean zone are usually composed of giant *Ethmodiscus rex* (Rattray, 1890) Wiseman and Hendeby, 1953, reduced to frustule fragments (Villareal 1993). Detailed study of deep sea cores recovered by the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP) and other expeditions (see Table 1) show *Ethmodiscus* ooze to be associated with specific environmental conditions and a potential indicator of past climatic and oceanographic regime changes (Smetacek 2009; Rackebrandt *et al.* 2011; Kemp and Villareal 2013).

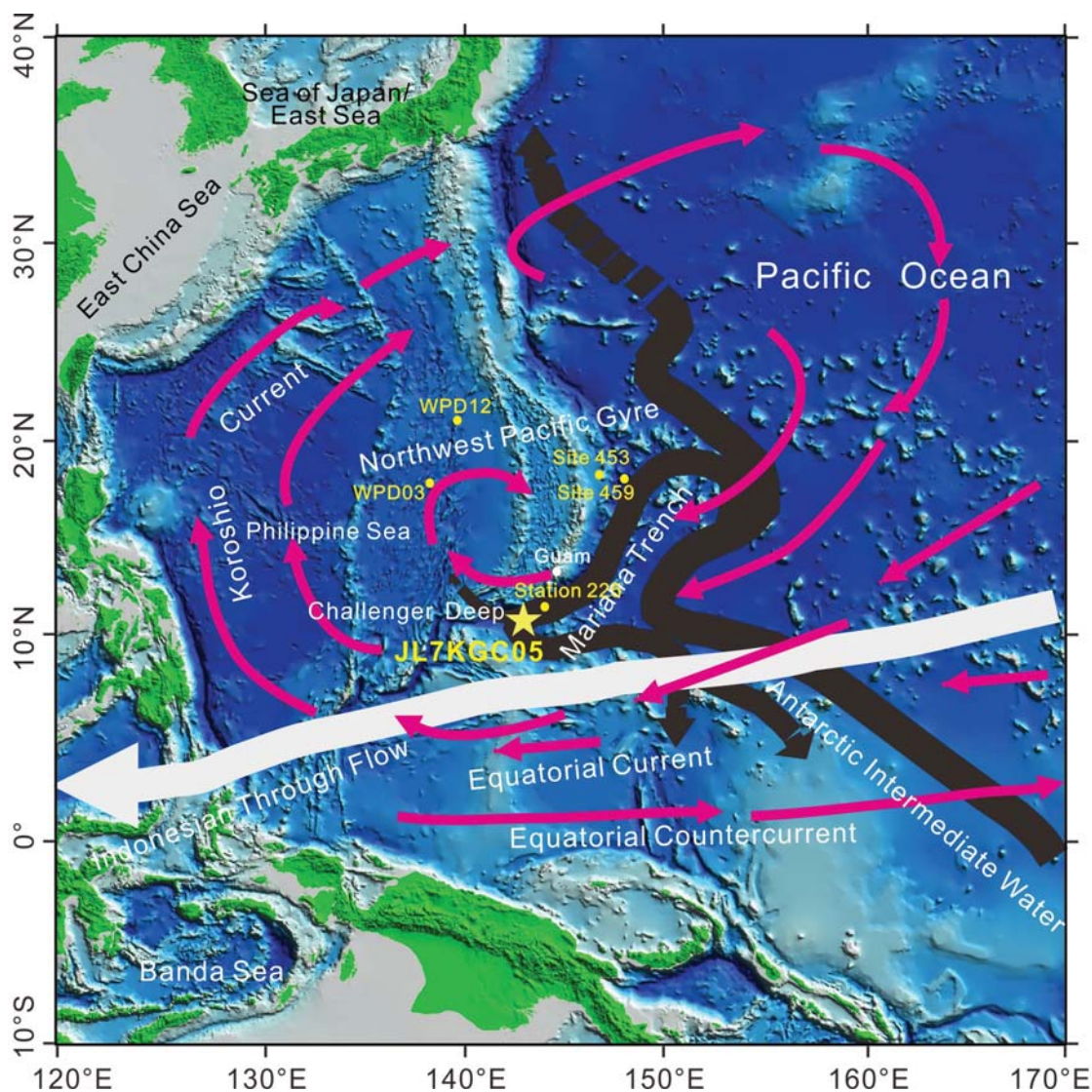
In 1875, scientists on board R/V H.M.S. Challenger discovered the deepest sea floor at Station 225, 8186 m water depth below mean sea level, named this the Challenger Deep area and applied a term “diatomaceous ooze” to sediments retrieved from this site (Wiseman and Hendeby 1953). Hanzawa (1933) described submarine ooze sediments from the tropical Northwestern Pacific Ocean recovered by Japanese research expeditions of 1926 through 1933 that studied separate areas from 2780 to 5714 m bathymetrical range between 19°08.5'N – 8°40.0'N and 136°22.6'E – 153°06.5'E. These studies included observation of abundant *Ethmodiscus*, a taxon originally identified from Bay of Bengal by Wallich (1868; Grunow and Kitton 1879). Sediment cores retrieved from DSDP Hole 453 at 4693 m below sea floor (bsf) and Holes 459, 460, 460A at 4121, 6452 and 5445 m bsf, respectively (Table 1), in the northern Mariana Trench slope showed occurrence of siliceous ooze with abundant microfossils such as diatoms and radiolarians on

the trench wall (Martini 1982). Until now, there has been little additional sampling and exploration of the Mariana Trench and thus only a few diatom reports are available (Table 1).

In 2012, the Chinese R/V Haiyang Six supported piloted submersible R/V Jiaolong to retrieve near-surface sediments from the Challenger Deep area at 7120 m water depth (Zhang *et al.* 2015). The present paper reports on the diatom assemblages of diatomaceous ooze, along with age interpretation and paleoceanographic significance of these sediments.

GEOLOGICAL AND OCEANOGRAPHIC SETTING

The Mariana Trench is situated in a vast Pacific Plate subduction zone that thrusts beneath the Eurasian Plate (Hussong and Fryer 1982; Gardner *et al.* 2014). The research site (Text-fig. 1) is located in the Challenger Deep area, influenced by the North Equatorial Current driven by trade winds that provide warm temperature (~29.5°C), high salinity (~34.5 psu) and low surface water nutrient concentrations to the tropical Western Pacific Warm Pool (Delcroix *et al.* 1996; Picaut 1996; Lin *et al.* 2013). The region is associated with high average annual rainfall of ~3500 mm (Delcroix *et al.* 1996; Picaut 1996). The Mariana Trench is positioned in a low primary productivity region controlled by the Northwest Pacific Gyre (Broecker 1991; NASA Ocean Biology 2014). In addition, the research area is located on



Text-fig. 1. Location of sampling site (made with ArcGIS V10.0; currents model modified from Broecker 1991 and Kawabe *et al.* 2009)

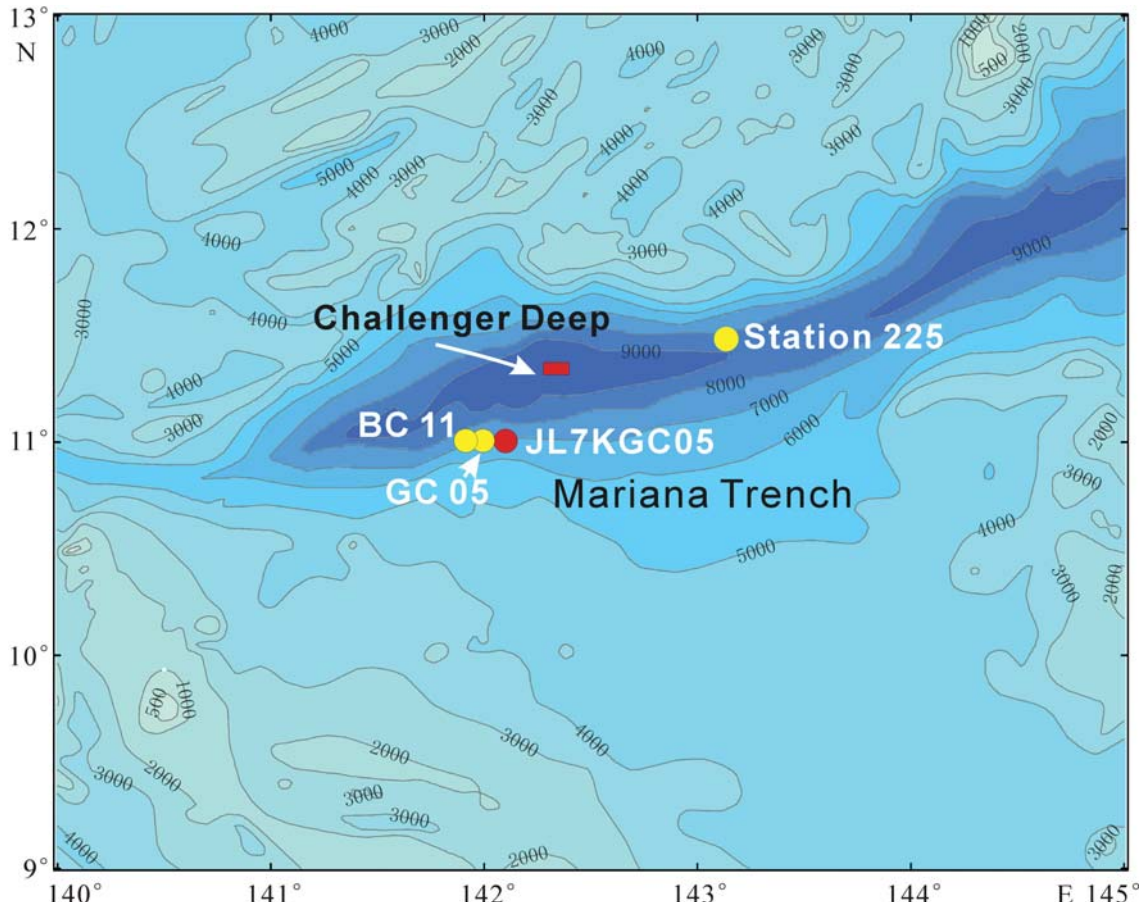
main pathway where Antarctic Intermediate Water (AAIW) invades the Northwest Pacific Ocean in global oceanic conveyor belt (Broecker 1991; Kawabe *et al.* 2009). The Indonesian Through Flow (ITF) current also influences subsurface oceanographic conditions in the Pacific-Indian Ocean connecting zone (Rahmstorf 2002, 2003).

MATERIAL AND METHODS

Deep water gravity core JL7KGC05, 215 cm in length (Text-fig. 3), was retrieved from the south-

east slope of the Mariana Trench slope ($10^{\circ}59.75'N$, $141^{\circ}59.70'E$) at 7120 m water depth (Text-figs 1 and 2, Table 1), which is ~ 2600 m below CCD in this part of the Pacific (Broecker 1991). Core top sediments are gray to slightly brown diatomaceous ooze that appears homogenized. The uppermost 10 cm of core is unconsolidated diatomaceous ooze with a brownish-gray color. From 10 to 13 cm bsf is a mixed yellowish-brown mud and pelagic red clay. Below 13 cm bsf, core sediment grades to a stiffer eupelagic red clay with low iron and manganese oxides content observed between 15 and 19 cm bsf.

The 0–13 cm core section was divided into 5 mm

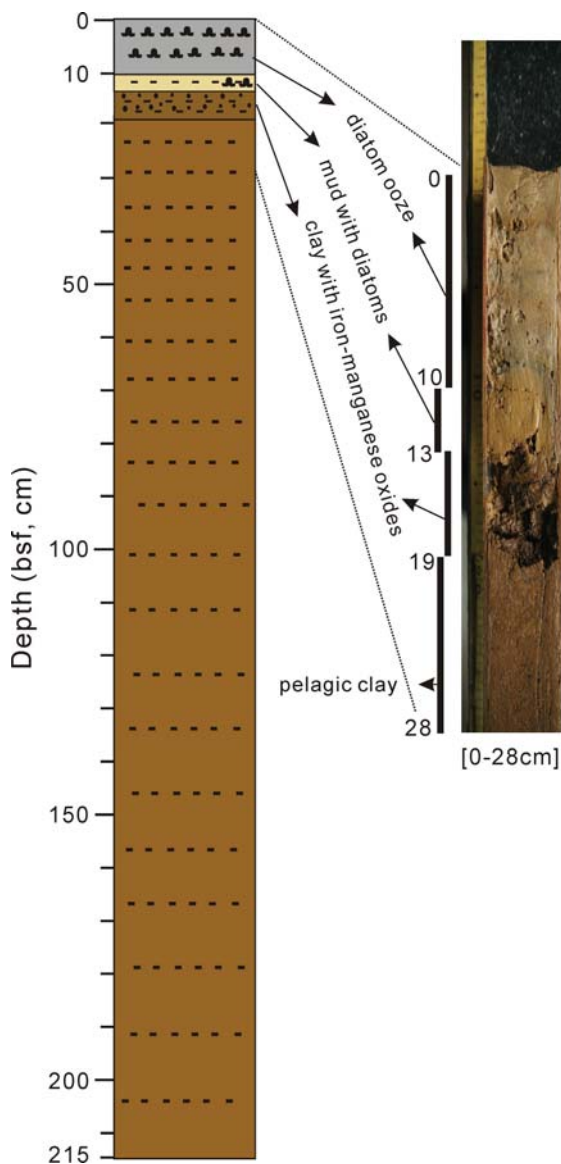


Text-fig. 2. Sampling sites in the Mariana Trench. Core JL7KGC05 is from this study; cores GC 05 and BC 11 are from Luo *et al.* (2018); Station 225 is from Wiseman and Hendey (1953). Red rectangle shows the deepest site in the Challenger Deep area (from Gardner *et al.* 2014)

thickness sub-sampling followed by one sample in the 13–14 cm interval. Dried sediment samples (0.1 g) were soaked in water. The uppermost turbid liquid was decanted every 6 h over 24 h, followed by removal of the upper turbid liquid layer at 4-hour intervals (in 48 h). The material was then transferred to a scale centrifugal tube as a reserve.

Twenty subsamples of red clay (1 cm in thickness) were collected at 10 cm intervals from 15 cm to the core bottom. About ~1 g of dry sediment was soaked in distilled water and transferred as suspension to 50 ml centrifuge tubes. After settling and removal of upper clean water, zinc iodide, a heavy liquid with a density of 2.4 g/cm³ was added. After flotation, about 15 ml distilled water with suspended material was placed as a reserve. Finally, the upper clean liquid from all samples was removed, the remaining volume made constant by addition of distilled water to 5 ml, from which 50 µl used to prepare a microscope

slide with 22×22 mm cover-slip and Naphrax® as mounting medium. The identification of diatoms was carried out over the entire slide with ×400 and ×1000 magnifications (using ×100 oil immersion lens) by Olympus BX63 light microscope. Counting of valves included whole and fragmented specimens of more than half a diatom valve. The volume of material used in slide preparation and dried weight of each sample was used to calculate the diatom sedimentary abundance in terms of absolutely abundance (valves/g) (e.g., Abrantes 2001; Abrantes *et al.* 2016). *Ethmodiscus rex* fragments > 50 µm, while less than half a valve, were counted using the methodology of Abrantes (2001) in 10 random view fields at ×400 magnifications, and then the diatom sedimentary abundances were calculated (valves/g). For the accompanying diatom counts, the observed number of valves for each species in the whole slide was used to calculate sedimentary abundance (valves/g).



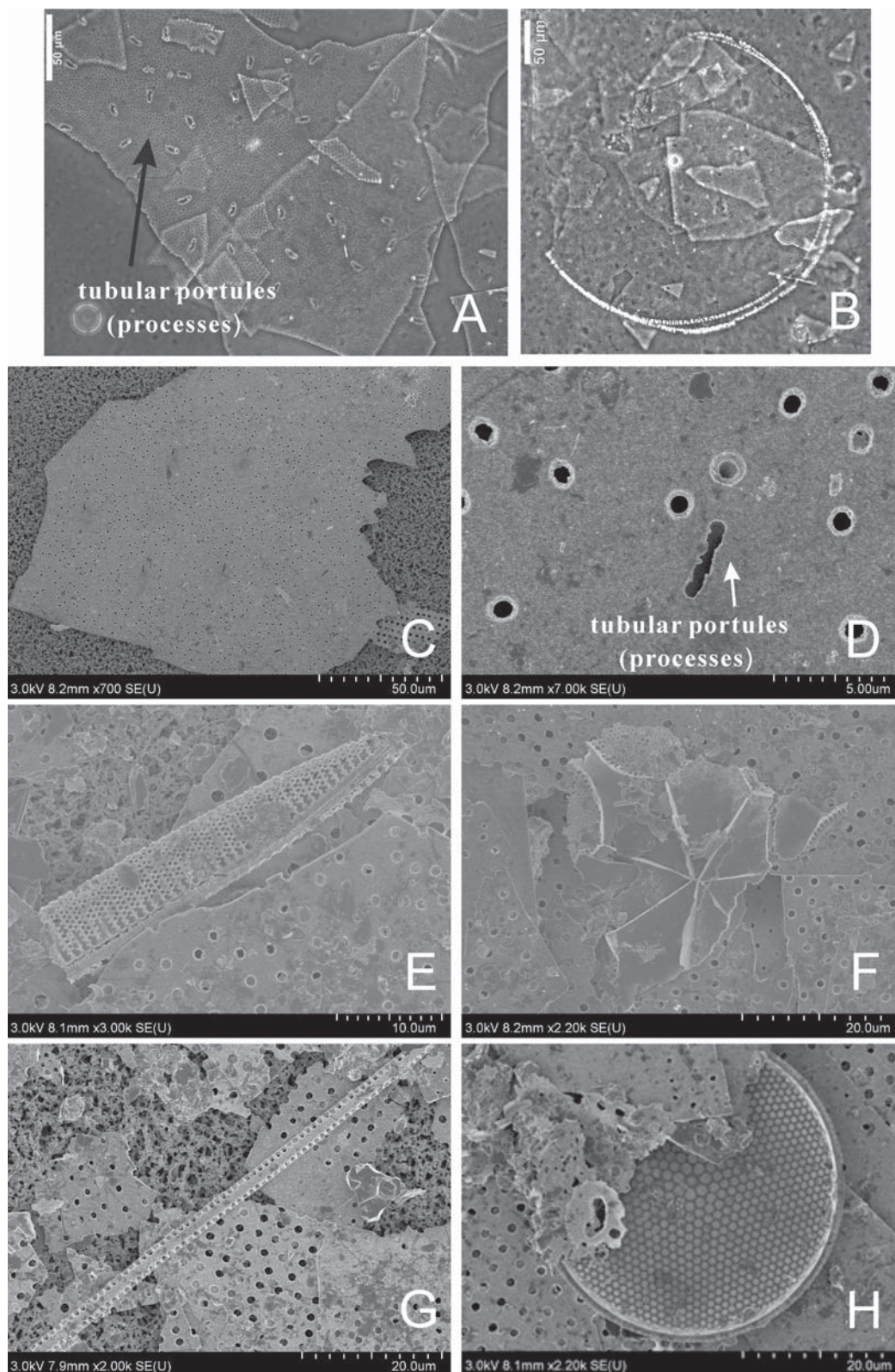
Text-fig. 3. Lithological log of core JL7KGC05

RESULTS

The diatom analysis shows ooze sediments of core section from 0 to 14 cm bsf to be rich in diatoms, while no diatom remains were observed in the eupelagic red clay below 25 cm depth. Ooze is dominated by large quantities of fragmented frustules (~10–300 μm) of the giant diatom *Ethmodiscus rex*, which unfragmented could reach 2–3 mm in diameter (Round *et al.* 2007). No complete valves of this species were observed, thus identification of *Ethmodiscus*

rex is based on the presence of numerous long tubular processes (length ~11 μm) and sparse areola emblazonment on the almost flat valve surface (see Text-figs 4, 5). The *Ethmodiscus rex* fragments (Text-fig. 4A–D) are accompanied by more than twenty eupelagic, warm water planktonic diatom taxa that include: *Actinocyclus ehrenbergii* Ralf in Pritchard, 1861 (Text-fig. 5U); *Alveus marinus* (Grunow, 1880) Kaczmarek and Fryxell, 1996 (Text-figs 4E, 5A); *Asterolampra marylandica* Ehrenberg, 1844 (Text-fig. 5F); *Asterolampra vanheurckii* Brun, 1891 (Text-fig. 4F, 5E); *Asteromphalus arachne* (Brébisson, 1857) Ralfs in Pritchard, 1861 (Text-fig. 5I); *Asteromphalus imbricatus* Wallich, 1860 (Text-fig. 5G); *Asteromphalus roperianus* (Greville, 1860) Ralfs in Pritchard, 1861 (Text-fig. 5J); *Asteromphalus* sp. (Text-fig. 5H); *Azpeitia africana* (Janisch in Schmidt, 1878) Fryxell and Watkins in Fryxell, Sims and Watkins, 1986 (Text-fig. 5C); *Azpeitia neocrenulata* (Grunow, 1884) Fryxell and Watkins in Fryxell, Sims and Watkins, 1986 (Text-fig. 5D); *Azpeitia nodulifera* (Schmidt, 1878) Fryxell and Watkins in Fryxell, Sims and Watkins, 1986 (Text-fig. 5B); *Fragilariopsis doliolus* (Wallich, 1860) Medlin and Sims, 1993 (Text-fig. 5V); *Hemidiscus cuneiformis* Wallich, 1860 (Text-fig. 5K); *Rhizosolenia bergonii* Peragallo, 1892 (Text-fig. 5N); *Rhizosolenia styliformis* Brightwell, 1858 (Text-fig. 5O); *Roperia tesselata* (Roper, 1858) Grunow in Pelletan, 1889 (Text-fig. 5L, M); *Thalassiosira leptopus* (Grunow in Van Heurck, 1883) Hasle and Fryxell, 1977 (Text-fig. 5P); *Thalassiosira oestrupii* (Ostenfeld, 1900) Hasle, 1960 (Text-fig. 5R); *Thalassiosira pacifica* Gran and Angst, 1931 (Text-figs 4H, 5Q); *Thalassiosira* sp. (Text-fig. 5S, T) and *Thalassiothrix longissima* Cleve and Grunow, 1880 (Text-figs 4G, 5W). From 15 to 25 cm bsf, sparse fragments of *Ethmodiscus rex*, a few fragments of *Azpeitia africana* and *Thalassiosira* sp. were observed.

The diatom sedimentary abundance of *Ethmodiscus rex* fragments in the 0–14 cm interval averages several million fragments per gram of dried sediment (hereafter abbreviated as /g), with a maximum value ~ 60×10^6 fragments/g in the 6–10 cm interval (Text-fig. 6). This value is consistent with data from the Eastern Equatorial Atlantic Ocean (Stabell 1986). The sedimentary abundances of accompanying diatoms exceed several million/g (Text-fig. 6). *Azpeitia nodulifera* and *Alveus marinus* sedimentary abundances are higher than other accompanying taxa, reaching 30×10^3 valves/g and 13×10^3 valves/g, respectively. Diatom sedimentary abundances are highest in the 6–10 cm bsf interval, followed by 0–6 cm and 10–14 cm bsf intervals.



Text-fig. 4. Diatoms from core collected in the Mariana Trench (water depth 7120 m, 0–14 cm bsf). **A–D** – *Ethmodiscus rex* (Rattray, 1890) Wiseman and Hende, 1953; **E** – *Alveus marinus* (Grunow, 1880) Kaczmarzka and Fryxell, 1996; **F** – *Asterolampra vanheurckii* Brun, 1891; **G** – *Thalassiothrix longissima* Cleve and Grunow, 1880; **H** – *Thalassiosira pacifica* Gran and Angst, 1931

DISCUSSION

Regional comparison of diatom component in ooze

The diatomaceous ooze in the 0–14 cm core interval is predominantly composed of *Ethmodiscus rex* as *E. rex* ooze, and shows results similar to previous analyses from low latitude ocean beds in the *Ethmodiscus* ooze distribution area as outlined by Mikkelsen (1977). Wiseman and Hendey (1953) and Riedel (1954) studied *Ethmodiscus* oozes in terms of taxonomy but did not report other diatom species from Challenger Deep area materials. Seventeen diatom species were identified from DSDP Legs 59 and 60, northern Mariana Trench slope (Martini 1982; Table 2), although other diatom species associated with the mass occurrence of *Ethmodiscus rex* were significantly less abundant and diverse, representing only a few specimens of genera *Thalassiosira* and *Thalassionema* in Hole 460, and *Hemidiscus*, *Coscinodiscus*, *Thalassionema*, and *Asteromphalus* in Hole 459 (Martini 1982).

Twenty diatom species were observed in our samples, a diversity lower than observed in the Eastern Philippine Basin (Zhai *et al.* 2012). The diatomaceous ooze in the Eastern Philippine Sea shallow submarine sediments (Cores WPD03 and WPD12; Text-fig. 1, Table 1) consists mainly of fragmented *Ethmodiscus rex* as well, but with much higher diversity, up to 101 diatom species (Zhai *et al.* 2012). Surface sediments from Western Philippine Basin have about 68 identified diatom species in the *Ethmodiscus rex* ooze (Shen *et al.* 2017). In the *Ethmodiscus rex* ooze distribution area of the Eastern Equatorial Pacific, dominance by other diatom species such as *Thalassiothrix longissima* may be observed (Kemp *et al.* 1995). Luo *et al.* (2018) discussed geochemical characters of two Mariana Trench cores, GC 05 and BC 11, from near Core JL7KGC05 location on the same cruise (Text-fig. 2, Table 1), but did not identify the diatom flora in detail, although these were from *Ethmodiscus rex* ooze. Luo *et al.* (2018) recorded diatomaceous ooze in the Core GC 05 to occur 0–5 cm bsf, and showed the ooze layer at c. 18 cm bsf in Core BC 11.

The diatom component comparison presented here improves the record of fossil diatoms from this trench, and supports a potential implication that more diatom species could be observed in future studies. Diatom component differences among these locations reflect regional variation across the low latitude Pacific Ocean, and the relatively special Mariana Trench geological environment.

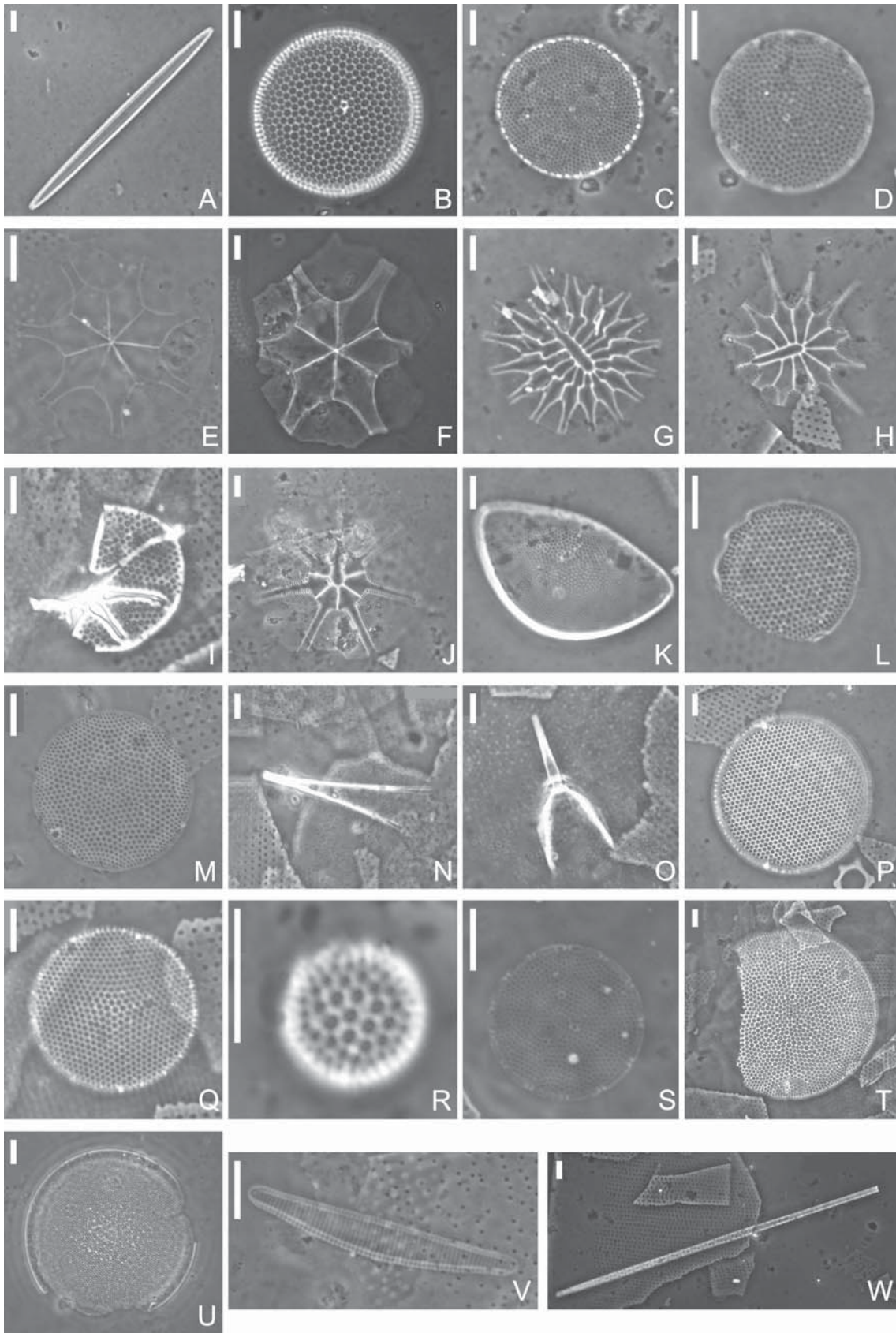
Diatom species	Reference
<i>Actinocyclus subtilis</i> Gregory, 1857	Martini (1982)
<i>Actinoptychus</i> cf. <i>splendens</i> (Shadbolt, 1854) Ralfs in Pritchard, 1861	Martini (1982)
<i>Alveus marinus</i> (Grunow, 1880) Kaczmarek and Fryxell, 1996	Martini (1982)
<i>Asterolampra marylandica</i> Ehrenberg, 1844	Martini (1982)
<i>Asteromphalus</i> cf. <i>brookei</i> Bailey, 1856	Martini (1982)
<i>Asteromphalus hookeri</i> Ehrenberg, 1844	Martini (1982)
<i>Cocconeis</i> sp.	Martini (1982)
<i>Coscinodiscus</i> sp.	Martini (1982)
<i>Diploneis</i> sp.	Martini (1982)
<i>Ethmodiscus rex</i> (Rattray, 1890) Wiseman and Hendey, 1953	Wiseman and Hendey (1953); Martini (1982); Luo <i>et al.</i> (2018)
<i>Hemidiscus cuneiformis</i> Wallich, 1860	Martini (1982)
<i>Nitzschia bicapitata</i> Cleve, 1901	Martini (1982)
<i>Nitzschia</i> sp.	Martini (1982)
<i>Pseudotriceratium wallichii</i> (Ralfs in Pritchard, 1861) Simonsen, 1979	Martini (1982)
<i>Rhizosolenia bergonii</i> Peragallo, 1892	Martini (1982)
<i>Rhizosolenia</i> sp.	Martini (1982)
<i>Thalassionema</i> sp.	Martini (1982)

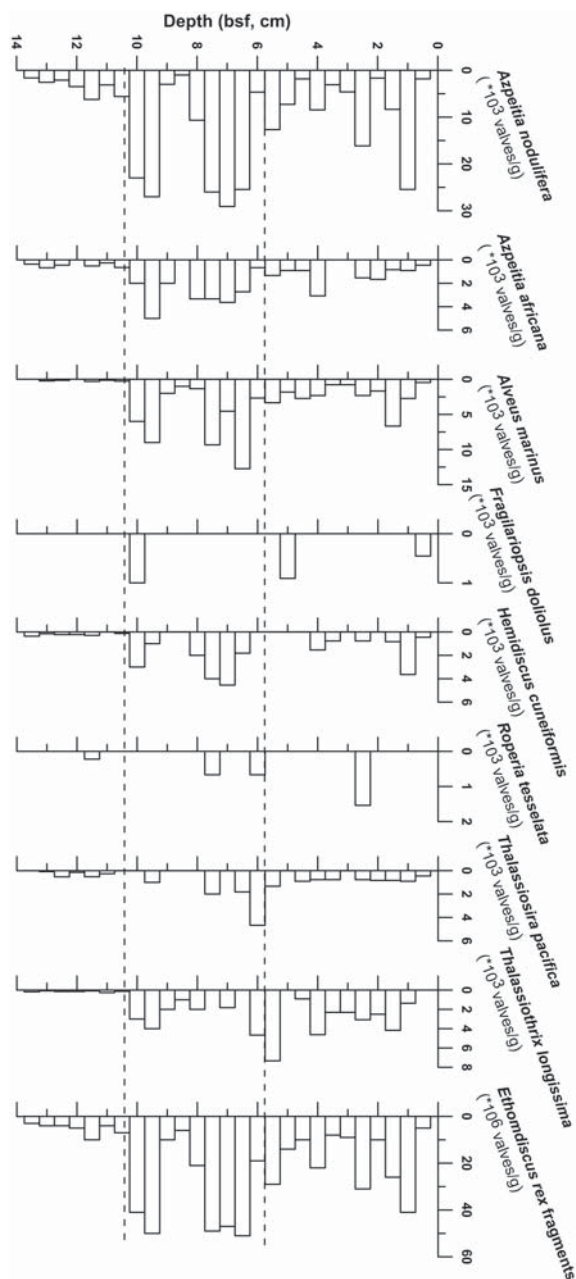
Table 2. Fossil diatom species found in the Mariana Trench during previous studies

Diatomaceous ooze formation age

Gardner and Burckle (1975) noted the Pleistocene *Ethmodiscus rex* ooze widely recorded in Western Pacific Ocean, although the Neogene *Ethmodiscus rex* ooze in Challenger Deep area was a special case recorded by Riedel (1954), and dated as late Oligocene to Miocene based on radiolarian biostratigraphy. According to the description of Riedel (1954), *Ethmodiscus rex* ooze in Station 225, located about 149 km from Core JL7KGC05 site, was below an iron-manganese oxide layer. However, the *Ethmodiscus rex* ooze in Core JL7KGC05 is above the iron-manganese oxides interval (Text-fig. 3), although no evidence could be used to correlate the chronology of iron-manganese oxides between Station 225 and Core JL7KGC05 in the Challenger Deep area. The diatomaceous ooze in Core JL7KGC05 may be younger than the ooze recorded in Station 225 if the ages of iron-manganese oxides layers are equivalent. Moreover, whether remains of this species have been transported from the Mariana Trench upper levels is uncertain.

Chronology determined by means of calcareous microfossils was not applicable due to deposition at a water depth below CCD in the Challenger Deep





Text-fig. 6. Distribution of diatom sedimentary abundances of major species in the ooze

area. In the studied core, the pelagic red clay at 25 to 215 cm interval lacks fossil diatoms and thus prevents diatom-based age control. *Fragilariopsis doliolus*, a Quaternary zonal marker in the low latitude Pacific Ocean (Burckle 1977; Bolli *et al.* 1985; Koizumi 1986), was found in several samples within the 0–14 cm interval of Core JL7KGC05. We consider the chronology of this diatomaceous ooze to fall within the *Fragilariopsis doliolus* Partial Range Zone of Quaternary age (Burckle 1977).

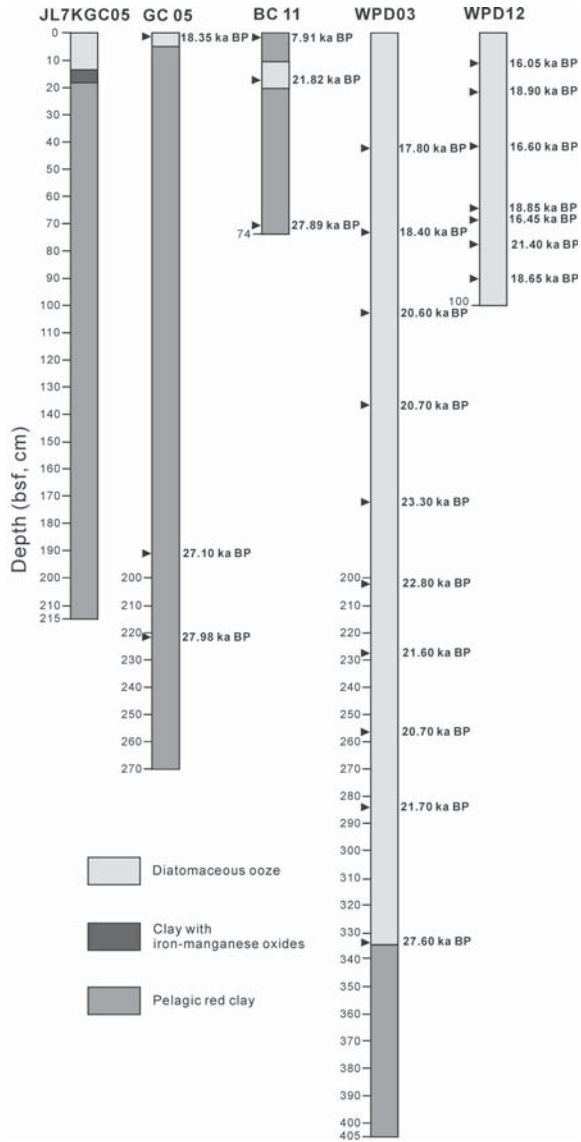
Recently, Luo *et al.* (2018) reported the AMS (Accelerator Mass Spectrometry) ^{14}C age of diatomaceous ooze materials from Cores GC 05 and BC 11 (Text-figs 2 and 7, Table 1) of the Challenger Deep area in close geographic proximity to Core JL7KGC05, at about 1.8 km and 4.9 km distance, respectively. The results show an *Ethmodiscus rex* ooze layer at 0–2 cm bsf, dated at 18.35 ka BP in Core GC 05, and at 16–18 cm bsf, dated at 21.82 ka BP in Core BC 11. These ages could be equivalent to the diatomaceous ooze with *Ethmodiscus rex* formed between 29 ka BP and 16 ka BP in Core WPD03 and Core WPD12 (Text-fig. 7) recorded in the Eastern Philippine Sea (Zhai *et al.* 2010). Thus, our assumption is that *Ethmodiscus rex* ooze in Core JL7KGC05 is dated to the Marine Isotope Stage (MIS) 2, near the Last Glacial Maximum (LGM). This result is consistent with the chronology of diatom biostratigraphy, i.e., the *Fragilariopsis doliolus* Partial Range Zone (Burckle 1977; Bolli *et al.* 1985).

Diatomaceous ooze formation mechanism and the paleoceanographic record

Diatomaceous ooze formation hypothesis

Ethmodiscus rex is often attributed to a group of taxa indicative of oceanic oligotrophic conditions of open ocean warm waters and distinguished from other taxa in the dystrophic habitat. The *Ethmodiscus rex* group may have a capability of vertical migration in the water column that offers a competitive advantage

← Text-fig. 5. Diatoms from the core collected in the Mariana Trench (water depth 7120 m, 0–14 cm bsf). **A** – *Alveus marinus* (Grunow, 1880) Kaczmarek and Fryxell, 1996; **B** – *Azpeitia nodulifera* (Schmidt, 1878) Fryxell and Watkins in Fryxell, Sims and Watkins, 1986; **C** – *Azpeitia africana* (Janisch in Schmidt, 1878) Fryxell and Watkins in Fryxell, Sims and Watkins, 1986; **D** – *Azpeitia neocrenulata* (Grunow, 1884) Fryxell and Watkins in Fryxell, Sims and Watkins, 1986; **E** – *Asterolampra vanheurckii* Brun, 1891; **F** – *Asterolampra marylandica* Ehrenberg, 1844; **G** – *Asteromphalus imbricatus* Wallich, 1860; **H** – *Asteromphalus* sp.; **I** – *Asteromphalus arachne* (Brébisson, 1857) Ralfs in Pritchard, 1861; **J** – *Asteromphalus roperianus* (Greville, 1860) Ralfs in Pritchard, 1861; **K** – *Hemidiscus cuneiformis* Wallich, 1860; **L**, **M** – *Roperia tessellata* (Roper, 1858) Grunow in Pelletan, 1889; **N** – *Rhizosolenia bergonii* Peragallo, 1892; **O** – *Rhizosolenia styliformis* Brightwell, 1858; **P** – *Thalassiosira leptopus* (Grunow in Van Heurck, 1883) Hasle and Fryxell, 1977; **Q** – *Thalassiosira pacifica* Gran and Angst, 1931; **R** – *Thalassiosira oestrupii* (Ostenfeld, 1900) Hasle, 1960; **S**, **T** – *Thalassiosira* sp.; **U** – *Actinocyclus ehrenbergii* Ralfs in Pritchard, 1861; **V** – *Fragilariopsis doliolus* (Wallich, 1860) Medlin and Sims, 1993; **W** – *Thalassiothrix longissima* Cleve and Grunow, 1880. Scale bars equal to 10 μm



Text-fig. 7. Correlation of sedimentary cores in the Challenger Deep area and Eastern Philippine Sea. Age data for Core BC 03 and BC 11 are from Luo *et al.* (2018), and for Core WPD03 and WPD12 from Zhai *et al.* (2010)

among dystrophic organisms in poor nutrition ecosystems (Villareal 1993; Villareal *et al.* 1999b). In the modern ocean, *Ethmodiscus rex* is a minor constituent of planktonic assemblages but is frequently found in monospecific deep sea oozes. This phenomenon is identified as the “*Ethmodiscus rex* problem” (Gardner and Burckle 1975). Mikkelsen (1977) proposed five hypotheses related to *Ethmodiscus rex* ooze formation: 1) plankton bloom hypothesis infers from a rare *Ethmodiscus rex* occurrence in modern plankton

that blooms would be required to accumulate thicker oozes; 2) dystrophic habitat hypothesis suggests that *Ethmodiscus rex* lived as heterotrophic organisms in large quantities at great water depth with oligotrophic conditions; 3) re-deposition hypothesis considers *Ethmodiscus rex* with large valves were separated from smaller frustules during current transport and concentrated in ocean floor depressions; 4) taxon decline hypothesis suggests *Ethmodiscus rex* to be a decaying form as minor constituents in the present plankton; and 5) differential dissolution hypothesis based on *Ethmodiscus rex* dissolution resistance compared to other diatom species, suggests that more easily dissolvable diatoms were removed from lower levels of the water column and sediment-water interface.

Abrantes (1994, 2001) expressed an additional (sixth) hypothesis that equatorial nutrient-rich conditions provided by upwelling and freshwater-discharged nutrients in the Eastern Atlantic Ocean could also support *Ethmodiscus rex* blooms. Kemp (1994, 1995) proposed that the *Ethmodiscus rex* ooze represents response to frontal zone convergence rather than upwelling. De Deckker and Gingele (2002) believed that there was no ocean front and relied on upwelling conditions to explain the presence of fossil *Ethmodiscus rex* accumulations in offshore southeast Sumatra, Eastern Indian Ocean (Hole BAR9442 record; Table 1). The Mariana Trench, being ~3400 km distant from the East Asia continent, does not have the advantages of either upwelling or massive riverine nutrient discharge. Meanwhile, there is no evidence to support oceanic front occurrence at Mariana Trench. Such oligotrophic conditions surrounding the Mariana Trench could be key factors in favor of *Ethmodiscus rex* blooms.

Strongly silicified diatom species such as *Azpeitia nodulifera* and *Alveus marinus* show higher abundance in Core JL7KGC05 compared with other associated species, i.e., *Asterolampra marylandica*, *Rhizosolenia bergonii* or *Roperia tessellata* (Text-fig. 6). As Zhai *et al.* (2012) noted, *Thalassionema frauenfeldii* (Grunow, 1880) Tempère and Peragallo, 1910 with weakly silicified frustules occurred with higher percentages in the laminated diatomaceous ooze core, while not reported at other sites (e.g., Core JL7KGC05, Hole 460) within the Mariana Trench. Besides, associated diatom species such as *Rhizosolenia* spp. in Core JL7KGC05 are relatively less abundant compared with laminated diatomaceous ooze cores WPD03 and WPD12 in the Eastern Philippine Sea (Zhai *et al.* 2012). Weakly silicified species were strongly dissolved at water depths exceeding 7000 m. Consequently, the *Ethmodiscus rex*

ooze in this study area may result from combined action of variable factors that include blooming, nutrient-poor ecological conditions and/or differential dissolution hypothesis, but without hypotheses of upwelling or freshwater discharged nutrients.

Paleoceanographic implication for *Ethmodiscus rex* ooze formation

Primary productivity expansion due to climate cooling

Formation of diatomaceous ooze, which results from high fluxes of primary production, may counteract the siliceous dissolution effect. The diatom primary production extent could have implications for global chemical budgets and influence rates of biogeochemical cycling, especially cycling of silica and other nutrients (Tréguer *et al.* 1995; Lyle and Baldauf 2015). The Eastern Equatorial Pacific Ocean ODP Sites 848 and 854 recovered laminated diatomaceous ooze accumulations at 15, 13–12, 10.5–9.5, 6.3–6.1, 5.8–5.1 and 4.4 Ma, while no laminated ooze originated after 4.4 Ma (Kemp *et al.* 1995). Kemp and Baldauf (1993) noted also that the depositional periods of Eastern Equatorial Pacific Ocean laminated ooze coincided with episodes of major cooling and ocean reorganization during 15–4.4 Ma. Nevertheless, in the North Pacific, diatomaceous ooze records from ODP Sites 882 and 883 (Table 1) begin at 7.1 Ma and opal deposition continued to increase after 5.0 Ma up to a remarkable drop at 2.7 Ma (Rea *et al.* 1993), usually interpreted as a Pliocene warm stage (Haywood *et al.* 2009).

Regardless of the above, Northern Hemisphere glaciation began during late Pliocene to early Quaternary (Ravelo *et al.* 2004). During this time, Northern Pacific sedimentation changed from abundant clay deposition to a clay–diatomaceous ooze (Dickens and Owen 1996). The diatomaceous ooze formation shift in the Western Pacific Ocean as recorded in Hole 460 shows massive deposition of *Ethmodiscus rex* in the Pliocene and Quaternary (Martini 1982). Gardner and Burckle (1975) considered the wide distribution of *Ethmodiscus rex* ooze in the Western Pacific Ocean to mainly occur in the Pleistocene cold stage. The *Ethmodiscus rex* ooze in Core JL7KGC05 was an extreme case with higher production flux and could be formed during MIS 2 of the last glacial stage according to AMS ¹⁴C dating results from the geographically nearby core ooze described by Luo *et al.* (2018).

These enlarged diatomaceous ooze deposits shifted within the Northern Pacific Ocean, were re-

lated to enhanced diatom paleoproductivity and coincided in time with global glacial conditions. This pattern is also observed beyond the Pacific Ocean, as *Ethmodiscus rex* ooze deposits are recorded in subtropical Southern Atlantic cores within glacial stages MIS 14 (537 ka BP) and MIS 12 (432 ka BP) (Romero and Schmieder 2006), where primary production increased over a short timescale. Meanwhile, the *Ethmodiscus rex* ooze occurred during the glacial stage as MIS 4 and MIS 6 in the Eastern Atlantic Ocean (Abrantes 2001), and during MIS 4 to MIS 2 in the Eastern Indian Ocean (Broecker *et al.* 2000; De Deckker and Gingele 2002).

Nutrients sources to support diatom bloom

Despite large frustule size, *Ethmodiscus rex* occurs in oligotrophic open sea waters, and possibly has adapted to survival by a vertical migration to utilize nutrients, based on observations of Villareal (1993) and Villareal *et al.* (1999a). The migration behavior is similar to other positively buoyant phytoplankton species such as *Rhizosolenia* spp. In the North Pacific Gyre oligotrophic waters, *Rhizosolenia* is known to form massive mats in the euphotic zone (Villareal *et al.* 2011), while *Ethmodiscus rex* has an abundance level of less than 2 cells·m⁻³ (Villareal 1993). Whether vertically migrating in the stratified water column or blooming in unstratified water (Kemp *et al.* 2000), the diatom needs nutrients to maintain productivity. *Ethmodiscus rex* being a siliceous microorganism, significant concentration of silica and related biological elements would supplement the continuous nutrient absorption for its blooms to support the high export fluxes that create ooze sediments.

Continental weathering and airborne/riverine nutrient transport could be potential sources for synchronous changes in ocean primary production. Asian winter monsoons could fertilize the Northern Pacific Ocean with higher rates of dust/clay transfer from Eastern Asian Interior arid and semiarid areas during the Pleistocene (Zhang K. *et al.* 2010; Zhang W.F. *et al.* 2016). As well, there is evidence of increased glacial wind velocities based on the grain size of accumulated dust. For example, Janecek and Rea (1985) estimated that glacial trade wind intensity at DSDP Hole 503B was 36% higher than during the interglacial, based on changes in aeolian sediment grain size distribution. Aeolian dust contributed iron and silica to nutrient contents driven by the Eastern Asian winter monsoon to support *Ethmodiscus rex* blooms during the LGM at ca. 20 ka BP (Xiong *et al.* 2012).

However, data along a 3000 km transect in the Northern Pacific Ocean roughly along 28°N provide no correlation between flux and Fe, N or P stress for *Ethmodiscus rex* (Villareal *et al.* 2007). Both Si and P residence times in the oceans are sufficiently short with 10 ka (Tréguer and De La Rocha 2013) and 10–20 ka (Filippelli and Delaney 1996), respectively. Such changes in weathering could rapidly influence ocean nutrient content. Nevertheless, we comment that the *Ethmodiscus rex* ooze is not correlated to these changes and thus the origin is not adequately explained by cooling stages through dust-supplied nutrients based on the known records.

Chemical weathering by strong precipitation, enhanced by summer Asian monsoons, could supply the nutrients consumed in the ocean. Even the weak presence of monsoonal rain in the cooling stage would have helped maintain high sea-surface salinities as well stratified, high oxygen, high silica and nutrient levels near the tropical Indian Ocean sea surface to support *Ethmodiscus rex* blooms (De Deckker and Gingele 2002). The *Ethmodiscus rex* ooze could form from stages MIS 4 to MIS 2, including stronger but unstable summer monsoons during MIS 3, and previous records suggest the *Ethmodiscus rex* ooze occurrence in the cooling stage is associated with weak precipitation conditions.

Nutrient recycling within the ocean inner system is another potentially important factor to support increased diatomaceous flora diversity/productivity. Dickens and Owen (1999) suggested a change in ocean circulation that upwelled more nutrients into the Indo-Pacific tropics. Broecker *et al.* (2000) commented that the entry of high silica-content Pacific thermocline water into the Indian Ocean during glacial times would have been a source of nutrients to support *Ethmodiscus rex* accumulations on offshore southeast Sumatra, Eastern Indian Ocean. However, Diester-Haass *et al.* (2004) linked high production in the biogenic bloom interval to lowered sea level along the South African margin, and thus to an Antarctic driver source. This scenario is supported by the link between deep bottom ventilation and diatom productivity and flux during the most recent termination of glaciation (Anderson *et al.* 2009).

Silicon leak and silica supplement

The ocean deep thermohaline circulation driven by Antarctic Ice Sheets disperses cold water northward to deep basins in the Pacific, Atlantic and Indian Oceans. This includes bottom meltwater, in particular during the global cooling stages (Broecker 1991;

Bullister *et al.* 2013). In the Southern Hemisphere, Antarctic deep water from the Southern Ocean provided low temperature, high salinity and density, silica and oxygen-rich waters related to Antarctic sea ice formation. This provided a strong Southern Ocean silicon leak that can influence the larger marine realm through northward directed conveyance in the deep sea over long distances. For instance, Sarmiento *et al.* (2004) showed that 75% of the silica primary production in southern latitude surface waters north of 30°S in abyssal subtropical basins is from the Southern Ocean.

The Southern Ocean silicon leak is considered an important mechanism to support diatom growth in the open ocean (Tréguer 2014). The ODP Leg 138 and 145 records were interpreted as AAIW effect on siliceous elements to support diatom blooms (Kemp and Baldauf 1993; Rea *et al.* 1993). Likewise, increased opal contribution to Pliocene and Quaternary sediments on Walvis Ridge in the Southeastern Atlantic Ocean was interpreted as silica-enriched intermediate water from Southern Ocean waters that supported diatom blooms (Lange *et al.* 1999).

The Core JL7KGC05 location is on a major pathway where AAIW enters the Northwest Pacific (Broecker 1991; Kawabe *et al.* 2009; Text-fig. 1). The AAIW originates from Southern Ocean currents that transport waters northward along the Southern Pacific, Atlantic and Indian Ocean sea beds and ascends gradually into intermediate water (Broecker 1991; Johnson and Toole 1993; Ferreira and Kerr 2017), ranging at water depth from 700 to 1200 m in the subtropical regions (Zenk *et al.* 2005). In the Western Equatorial Pacific Ocean, the AAIW has an approximate 800 m water depth (Zenk *et al.* 2005). After turning westward in the Northern Pacific Ocean, the AAIW changes to a southwest direction throughout the ITF (Rahmstorf 2002) which could enhance silica content in subsurface waters of Western Equatorial Pacific Ocean. De Deckker and Gingele (2002) confirmed *Ethmodiscus rex* ooze in the Eastern Indian Ocean generated at the end of the last glacial period, and suggested as cause high silica content and diatom blooms that resulted from ITF.

Xiong *et al.* (2013) commented that $\delta^{13}\text{C}_{\text{E}}$ *rex* testing result was consistent with an aeolian source of *Ethmodiscus rex* silica formed during the LGM in the Eastern Philippine Sea, as proposed by the ‘silica hypothesis’ and ‘silicon-induced alkalinity pump hypothesis’ but not by the ‘silicic acid leakage hypothesis’ in that paper. The ‘silica hypothesis’ is an alternative method selected by Xiong *et al.* (2013) to interpret the silica sources and challenged the deep

thermohaline circulations, but remains subject to uncertainty.

The silicic acid leakage is an effectual silica source for formation of siliceous skeletons in the global oceanic conveyor belt, especially during the MIS 2 near the LGM. We believe the silicon leak phenomenon caused by the Southern Ocean currents is an important source of silica supply for supporting diatom *Ethmodiscus rex* ooze formation in the study area. The AAIW and related silicon elements complementing effect in large scale in term of caused export in global level is an important driving mechanism to impact the Mariana Trench.

Oligotrophic conditions and meteorology

As mentioned above, *Ethmodiscus rex* is a warm water tropical oligotrophic diatom species shown by previous observations (e.g., Villareal 1992) to occur in a widely dispersed area. At present, nutrient poor conditions occur in the Northwest Pacific Gyre (Text-fig. 1), although occurrence of organism cells in the deep sea does not mandate formation of oozes. Following the ocean and wind transport, ocean current migration may have shifted the gyre to become a local factor in oceanographic environments of the past. During a glacial stage, the clockwise circulating Northwest Pacific Gyre spread southward, which could contribute to lower nutrient levels and thus stimulate the competitive advantage of *Ethmodiscus rex* to bloom under conditions of high dissolved silica content.

Based on flat valves of large size, the *Ethmodiscus rex* cells are easily transported via ocean currents that might redeposit *Ethmodiscus rex* into particular locations due to the effects of wind generated hydrodynamics on the drum-shape of this species cells (Gardner and Burckle 1975). In the Western Pacific Ocean region of this study, the Trade Wind drives westward motion of the North Equatorial Current, which could have transported *Ethmodiscus rex* frustules to the study area. In addition, Villareal (1993) showed local *Ethmodiscus rex* ooze accumulations in the Northern Pacific Ocean as the result of meteorological events that mediated redeposition, not *in situ* growth of *Ethmodiscus*. These arguments deserve more study, especially modern ocean observations.

In the context of *Ethmodiscus rex* ooze research results in the adjacent sea area of the Mariana Trench, this paper views that Core JL7KGC05 diatomaceous ooze could be formed in or near the LGM. The ooze formation of the studied site at Pacific Ocean low latitudes is controlled by global scale climate and thermohaline circulations. Cold climate conditions

near the LGM caused stronger Southern Ocean silica acid leakage effect via the Antarctic Intermediate Water conveyor belt. Strong northern forward invasion of the AAIW to the Northern Pacific Ocean influenced regional diatom ecological status in the Mariana Trench, in terms of climate change driving and silica leakage interpretation. The surface Northwest Pacific Gyre migration may have created oligotrophic conditions that resulted in competitive advantage for *Ethmodiscus rex* blooms, matching up with greater silica acid leakage. Meanwhile, the local character of the extreme Mariana Trench water depth promoted high dissolution of diatom frustules and precipitated *Ethmodiscus rex* blooms forming the ooze. There is no evidence to support slumping of the trench slope to accumulate ooze in the location studied.

CONCLUSIONS

1. *Ethmodiscus rex* ooze in the top section of Core JL7KGC05 is predominantly composed of large quantities of *Ethmodiscus rex* fragments and also contains a small group of open ocean, warm water diatom species characterized by strongly silicified valves, such as *Azpeitia nodulifera* and *Alveus marinus*. Diatoms are not observed in the pelagic red clay section that underlies the ooze.

2. Comparison to well-dated diatomaceous oozes enabled us to estimate that the studied *Ethmodiscus rex* ooze formed during the last glacial stage, likely MIS 2 at about the LGM. The formation model could be analogous to the hypothesis of Mikkelsen (1977) involving a combination of several factors: *Ethmodiscus rex* blooms, oligotrophic habitat and/or the differential dissolution of diatom species. The diatomaceous ooze formation was closely related to the multiple mechanisms that increased the intensity of deep Antarctic Intermediate Water currents and southward migration of surface circulations of the Northwest Pacific Gyre.

3. *Ethmodiscus rex* ooze in the deep sea oceanic subsurface provides useful paleoceanographic information. The occurrence of diatomaceous ooze records the *Ethmodiscus rex* bloom event and changes in paleoceanographic conditions in the Mariana Trench through geological time. This is related to the late Quaternary global glacial prevalence, which brought the Antarctic Intermediate Water flow into the Northwest Pacific Ocean to replenish silica and reduce diatom dissolution processes. At the same time, the contribution launched by regional surface current mi-

gration promoted the oligotrophic status to trigger *Ethmodiscus rex* competitive advantages. This research provides a case study of global climate and marine environment change influence on the evolution of siliceous microfossils in the low latitude trench area.

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REFERENCES

- Abrantes, F. 2001. Assessing the *Ethmodiscus* ooze problem: a new perspective from a study of an eastern equatorial Atlantic core. *Deep-Sea Research I*, **48**, 125–135.
- Abrantes, F., Cermeno, P., Lopes, C., Romero, O., Matos, L., Van Iperen, J., Rufino, M. and Magalhães, V. 2016. Diatoms Si uptake capacity drives carbon export in coastal upwelling systems. *Biogeosciences*, **13**, 4099–4109.
- Abrantes, F., Winn, K. and Sarnthein, M. 1994. Late Quaternary paleoproductivity variations in the NE and Equatorial Atlantic: Diatom and C_{org} evidence. In: Zahn, R., Pedersen, T.F., Kaminski, M.A., and Labeyrie, L. (Eds), Carbon Cycling in the Glacial Oceans. NATO ASI, V17, pp. 425–439. Springer; Berlin.
- Anderson, R.F., Ali, S. and Bradtmiller, L.I. 2009. Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO₂. *Science*, **323** (5920), 1443–1448.
- Bailey, J.W. 1856. Notice of microscopic forms in the soundings of the Sea of Kamtschatka. *American Journal of Science and Arts, Series 2*, **22**, 1–6.
- Bolli, H.M., Saunders, J.B. and Perch-Nielsen, K. 1985. Plankton stratigraphy. Volume 2: Radiolaria, diatoms, silicoflagellates, dinoflagellates and ichthyoliths, pp. 763–809. Cambridge University Press; Cambridge.
- Brébisson, A. 1857. Reffermant la description de quelques nouvelles Diatomées observées dans le Guano de Pérou, et formant genre *Spatangidium*. *Bulletin de la Société Linnéenne de Normandie, 1st series, Caen*, **2**, 292–298.
- Brightwell, T. 1858. Remarks on the genus *Rhizosolenia* of Ehrenberg. *Quarterly Journal of Microscopical Science*, **6**, 93–95.
- Broecker, W.S. 1991. The Great Ocean Conveyor. *Oceanography*, **4**, 79–89.
- Broecker, W.S., Clark, E., Lynch-Stieglitz, J., Beck, W., Stott, L.D., Hajdas, I. and Bonani, G. 2000. Late glacial diatom accumulation at 9°S in the Indian Ocean. *Paleoceanography*, **15**, 348–352.
- Brun, J. 1891. Diatomées espèces nouvelles marines, fossiles ou pélagiques. *Mémoires de la Société de Physique et d'Histoire Naturelle de Genève*, **31**, 1–4.
- Bullister, J.L., Rhein, M. and Mauritzen, C. 2013. Deepwater Formation. In: Siedler, G., Griffies S.M., Gould, J. and Church, J.A. (Eds), Ocean Circulation and Climate – A 21st Century Perspective. *International Geophysics*, **103**, 227–253.
- Burckle, L.H. 1977. Pleistocene and Pleistocene diatom datum levels from the equatorial Pacific. *Quaternary Research*, **7**, 330–340.
- Burckle, L.H. and Cirilli, J. 1987. Origin of diatom ooze belt in the Southern Ocean: Implication for late Quaternary paleoceanography. *Micropaleontology*, **33**, 82–86.
- Cleve, P.T. 1901. The seasonal distribution of Atlantic Plankton-organisms. *Göteborgs Kongliga Vetenskaps-och Vitterhets-Samhälles Handlingar*, **4** (3), 1–368.
- Cleve, P.T. and Grunow, A. 1880. Beiträge zur Kenntniss der Arctischen Diatomeen. *Kongliga Svenska Vetenskaps-Akademiens Handlingar*, **17** (2), 1–121.
- De Deckker, P. and Gingele, F.X. 2002. On the occurrence of the giant diatom *Ethmodiscus rex* in an 80-ka record from a deep-sea core, southeast of Sumatra, Indonesia: Implication for tropical oceanography. *Marine Geology*, **183**, 31–43.
- Delcroix, T., Hénin, C. and Porte, V. 1996. Precipitation and sea-surface salinity in the tropical Pacific Ocean. *Deep-Sea Research I*, **43** (7), 123–141.
- Dickens, G.R. and Owen, R.M. 1996. Sediment geochemical evidence for an early–middle Gilbert (early Pliocene) productivity peak in the North Pacific Red Clay Province. *Marine Micropaleontology*, **27**, 107–120.
- Dickens, G.R. and Owen, R.M. 1999. The Latest Miocene–Early Pliocene biogenic bloom: a revised Indian Ocean perspective. *Marine Geology*, **161**, 75–91.
- Diester-Haass, L., Meyers, P.A. and Bickert, T. 2004. Carbonate crash and biogenic bloom in the late Miocene: evidence from ODP Sites 1085, 1086, and 1087 in the Cape Basin, southeast Atlantic Ocean. *Paleoceanography*, **19**, 1–19.

- Ehrenberg, C.G. 1844. Mittheilung über 2 neue Lager von Gebirgsmassen aus Infusorien als Meeres-Absatz in Nord-Amerika und eine Vergleichung derselben mit den organischen Kreide-Gebilden in Europa und Afrik. *Bericht über die zur Bekanntmachung geeigneten Verhandlungen der Königlich-Preussischen Akademie der Wissenschaften zu Berlin*, **1844**, 57–97.
- Ferreira, M.L.D.C. and Kerr, R. 2017. Source water distribution and quantification of North Atlantic Deep Water and Antarctic Bottom Water in the Atlantic Ocean. *Progress in Oceanography*, **153**, 66–83.
- Filippelli, G.M. and Delaney, M.L. 1996. Phosphorus geochemistry of equatorial Pacific sediments. *Geochimica et Cosmochimica Acta*, **60** (9), 1479–1495.
- Fryxell, G.A., Sims, P.A. and Watkins, T.P. 1986. *Azpeitia* (Bacillariophyceae): Related genera and promorphology. *Systematic Botany Monographs*, **13**, 1–74.
- Gardner, J.V., Armstrong, A.A., Calder, B.R. and Beaudoin, J. 2014. So, how deep is the Mariana Trench? *Marine Geodesy*, **37**, 1–13.
- Gardner, J.V. and Burekle, L.H. 1975. Upper Pleistocene *Ethmodiscus rex* oozes from the eastern equatorial Atlantic. *Micropaleontology*, **21**, 236–242.
- Gran, H.H. and Angst, E.C. 1931. Plankton diatoms of Puget Sound. *Publications Puget Sound Biological Station*, **7**, 417–519.
- Gregory, W. 1857. On new forms of marine Diatomaceae found in the Firth of Clyde and in Loch Fyne, illustrated by numerous figures drawn by K.K., Greville, LL.D., F.R.S.E. *Transactions of the Royal Society of Edinburgh*, **21**, 473–542.
- Greville, R.K. 1860. A monograph of the genus *Asterolampra*, including *Asteromphalus* and *Spatangidium*. *Transactions of the Microscopical Society of London, New Series*, **8**, 102–124.
- Grunow, A. 1880. Bemerkungen zu den Diatomeen von Finnmark, dem Karischen Meere und vom Jenissey nebst Vorarbeiten für Monographie der Gattungen Nitzschia, Achnanthes, Pleurosigma, Amphiprora, Plagiotropis, Hyalodiscus, Podosira und einiger Navicula-Gruppen. *Kongliga Svenska Vetenskaps-Akademiens Handlingar, Series 4*, **17** (2), 16–121.
- Grunow, A. 1884. Die Diatomeen von Franz Josefs-Land. *Denkschriften der Kaiserlichen Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Classe*, **48**, 53–112.
- Grunow, A. and Kitton, F. 1879. New species and varieties of Diatomaceae from the Caspian Sea. *Journal of Royal Microscopical Society*, **2**, 677–691.
- Hanzawa, S. 1933. Diatom (*Ethmodiscus*) Ooze obtained from the tropical southwestern north Pacific Ocean. *Records of Oceanographic Work in Japan*, **7**, 37–44.
- Hasle, G.R. 1960. Phytoplankton and ciliate species from the tropical Pacific. *Skrifter utgitt av det Norske Videnskaps-Akademi i Oslo. I, Matematisk-naturvidenskapelig klasse*, **2**, 1–50.
- Hasle, G.R. and Fryxell, G.A. 1977. The genus *Thalassiosira*: some species with a linear areola array. In: Simonsen, R. (Ed.), Proceedings of the Fourth Symposium on Recent and Fossil Marine Diatoms, Oslo, August 30–September 3, 1976. *Beihefte zur Nova Hedwigia*, **54**, 15–66.
- Haywood, B.A.M., Dowsett, H.J., Valdes, P.J., Lunt, D.J., Francis, J.E. and Sellwood, B.W. 2009. Introduction. Pliocene climate, processes and problems. *Philosophical Transactions of the Royal Society A*, **367**, 3–17.
- Hussong, D.M. and Fryer, P.B. 1982. Structure and tectonics of the Mariana arc and fore-arc: drill site selection surveys. *Initial Reports of the Deep Sea Drilling Project. Scientific Results*, **60**, 33–44.
- Janecek, T.R. and Rea, D.K. 1985. Quaternary fluctuations in the Northern Hemisphere trade winds and westerlies. *Quaternary Research*, **24** (2), 150–163.
- Johnson, G.C. and Toole, J.M. 1993. Flow of deep and bottom waters in the Pacific at 10°N. *Deep-Sea Research I*, **40** (2), 371–394.
- Kaczmarek, I. and Fryxell, G.A. 1996. *Alveus*, gen. nov. (Bacillariaceae, Bacillariophyta), a heavily silicified diatom found in warm water oceans. *Microscopy Research and Technique*, **33**, 2–11.
- Kawabe, M., Fujio, S., Yanagimoto, D. and Tanaka, K. 2009. Water masses and currents of deep circulation southwest of the Shatsky Rise in the western North Pacific. *Deep-Sea Research I*, **56**, 1675–1687.
- Kemp, A.E.S. 1994. Laminated sediments from coastal and open ocean upwelling zones: What variability do they record? In: Summerhayes, C.P., Emeis, K.C., Angel, M.V., Smith, R.L. and Zeitzschel, B. (Eds), *Upwelling in the ocean: Modern processes and ancient records*, pp. 239–257. John Wiley; Hoboken, New Jersey.
- Kemp, A.E.S. and Baldauf, J.G. 1993. Vast Neogene laminated diatom mat deposits from the eastern equatorial Pacific Ocean. *Nature*, **362**, 141–144.
- Kemp, A.E.S., Baldauf, J.G. and Pearce, R.B. 1995. Origins and paleoceanographic significance of laminated diatom ooze from the eastern equatorial Pacific. *Proceedings of the Ocean Drilling Program. Scientific Results*, **138**, 641–645.
- Kemp, A.E.S., Pike, J., Pearce, R.B. and Lange, C.B. 2000. The “fall dump” – a new perspective on the role of a “shade flora” in the annual cycle of diatom production and export flux. *Deep-Sea Research II*, **47**, 2129–2154.
- Kemp, A.E.S. and Villareal, T.A. 2013. High diatom production and export in stratified waters – A potential negative feedback to global warming. *Progress in Oceanography*, **119**, 4–23.
- Koizumi, I. 1986. Pliocene and Pleistocene diatom datum levels reflected with paleoceanography in the Northwestern Pacific. *Marine Micropaleontology*, **10**, 309–325.

- Lange, C.B., Berger, W.H., Lin, H.L. and Wefer, G. 1999. The early Matuyama diatom maximum off SW Africa, Benguela Current System (ODP Leg 175). *Marine Geology*, **161**, 93–114.
- Lin, C.Y., Ho, C.R., Lee, Y.H., Kuo, N.J. and Liang, S.J. 2013. Thermal variability of the Indo-Pacific warm pool. *Global and Planetary Change*, **100**, 234–244.
- Luo, M., Algeo, T.J., Tong, H.P., Gieskes, J., Chen, L.Y., Shi, X.F. and Chen, D. F. 2018. More reducing bottom-water redox conditions during the Last Glacial Maximum in the southern Challenger Deep (Mariana Trench, western Pacific) driven by enhanced productivity. *Deep-Sea Research II: Topical Studies in Oceanography*, **155**, 70–82.
- Lyle, M. and Baldauf, J. 2015. Biogenic sediment regimes in the Neogene equatorial Pacific, IODP Site U1338: Burial, production, and diatom community. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **433**, 106–128.
- Martini, E. 1982. Pliocene and quaternary diatoms, silicoflagellates, sponge spicules, and endoskeletal dinoflagellates from the Philippine Sea, Deep Sea Drilling Project Legs 59 and 60. *Initial Reports of the Deep Sea Drilling Project. Scientific Results*, **60**, 565–574.
- Medlin, L.K. and Sims, P.A. 1993. The transfer of *Pseudoeunotia doliolus* to *Fragilariopsis*. In: Sims, P.A. (Ed.), Progress in diatom studies: contributions to taxonomy, ecology and nomenclature. Special volume in honour of Robert Ross on the occasion of his 80th Birthday. *Beihefte zur Nova Hedwigia*, **106**, 323–334.
- Mikkelsen, N. 1977. On the origin of *Ethmodiscus* ooze. *Marine Micropaleontology*, **2**, 35–46.
- NASA Ocean Biology. 2014. Sea-viewING Wide Field-of-view Sensor (SeaWiFS) Ocean Color Data, 2014.0. <http://oceanclor.gsfc.nasa.gov/cms/dataaccess>
- Ostenfeld, C.H. 1900. Plankton. In: M. Knudsen and C. Ostenfeld, Jagttagelser over Overfladevandets Temperatur, Saltholdighed og Plankton paa islandke og grønlandske Skibsruter i 1899, pp. 45–93. Bianco Lunos Bogtrykkeri; Kjøbenhavn.
- Pelletan, J. 1889. Les Diatomées. Histoire naturelle, préparation, classification et description des principales espèces. Part II. *Journal de Micrographie*, **1889**, 1–364.
- Peragallo, H. 1892. Monographie du genre *Rhizosolenia* et de quelques genres voisins. *Le Diatomiste*, **1** (79–82), 99–117.
- Picaut, J., Ioualalen, M., Menkes, C., Delacroix, T. and McPhaden, M.J. 1996. Mechanism of the Zonal Displacements of the Pacific Warm Pool: Implications for ENSO. *Science*, **274** (5292), 1486–1489.
- Pritchard, A. 1861. A history of infusoria, living and fossil. Arranged according to the “Infusionsthierchen” of C.G. Ehrenberg; containing coloured engravings, illustrative of all the genera, and descriptions of all the species in that work, with several new ones, to which is appended an account of those recently discovered in the chalk formations, 968 p. Whittaker and Co.; London.
- Rackebrandt, N., Kuhnert, H., Groeneveld, J. and Bickert, T. 2011. Persisting maximum Agulhas leakage during MIS 14 indicated by massive *Ethmodiscus* oozes in the subtropical South Atlantic. *Paleoceanography*, **26**, PA3202, 1–13.
- Rahmstorf, S. 2002. Ocean circulation and climate during the past 120000 years. *Nature*, **419**, 207–214.
- Rahmstorf, S. 2003. Thermohaline circulation: The current climate. *Nature*, **421**, 699.
- Rattray, J. 1890. A Revision of the Genus *Coscinodiscus* Ehrb., and some Allied Genera. *Proceedings of the Royal Society of Edinburgh*, **16**, 449–692.
- Ravelo, A.C., Andreasen, D.H., Lyle, M., Lyle, A.O. and Wara, M.W. 2004. Regional climate shifts caused by gradual global cooling in the Pliocene epoch. *Nature*, **429**, 263–267.
- Rea, D.K., Basov, I.A., Janecek, T.R., Palmer-Julson, A. et al. 1993. Site 882. *Proceedings of the Ocean Drilling Program, Initial Reports*, **145**, 85–119.
- Riedel, W.R. 1954. The age of the sediment collected at Challenger (1875) station 225 and the distribution of *Ethmodiscus rex* (Rattray). *Deep-Sea Research I*, **1**, 170–175.
- Romero, O. and Schmieder, F. 2006. Occurrence of thick *Ethmodiscus* oozes associated with a terminal Mid-Pleistocene Transition event in the oligotrophic subtropical South Atlantic. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **235**, 321–329.
- Roper, F.C.S. 1858. Notes on some new species and varieties of British marine Diatomaceae. *Quarterly Journal of Microscopical Science*, **6**, 17–25.
- Round, F.E., Crawford, R.M. and Mann, D.G. 2007. The diatoms, biology and morphology of the genera, 747 p. Cambridge University Press; Cambridge.
- Sarmiento, J.L., Gruber, N., Brzezinski, M.A. and Dunne, J.P. 2004. High-latitude controls of thermocline nutrients and low latitude biological productivity. *Nature*, **427**, 56–60.
- Schmidt, A. 1878. Atlas der Diatomaceen-kunde, Heften 15–16, Tafeln 57–64. Verlag von Ernst Schlegel; Aschersleben.
- Shadbolt, G. 1854. A short description of some new forms of Diatomaceae from Port Natal. *The Transactions of the Microscopical Society of London, New Series*, **2**, 13–18.
- Shen, L., Chen, M., Lan, B., Qi, H., Zhang, A., Lan, D. and Fang, Q. 2017. Diatom distribution as an environmental indicator in surface sediments of the West Philippine Basin. *Chinese Journal of Oceanology and Limnology*, **35** (2), 431–443.
- Simonsen, R. 1979. The diatom system: ideas on phylogeny. *Bacillaria*, **2**, 9–71.
- Smetacek, V. 2009. The giant diatom dump. *Nature*, **406**, 574–575.
- Stabell, B. 1986. Variations of diatoms flux in the Eastern Equatorial Atlantic during the last 400,000 years (“METEOR” Cores 13519 and 13521). *Marine Geology*, **72**, 305–323.
- Tempère, J. and Peragallo, H. 1910. Diatomées du Monde En-

- tier, Edition 2, 30 fascicules. Fascicule 13–16, 209–256. Chez J. Tempère; Arcachon, Gironde.
- Tréguer, P.J. 2014. The Southern Ocean Silica Cycle. *Comptes Rendus Geoscience*, **346**, 279–286.
- Tréguer, P.J. and De La Rocha, C.J. 2013. The World Ocean Silica Cycle. *Annual Review of Marine Science*, **5**, 477–501.
- Tréguer, P.J., Nelson, D.M., Van Bennekom, A.J., DeMaster, D.J., Leynaert, A. and Quéguiner, B. 1995. The Silica Balance in the World Ocean: A Reestimate. *Science*, **268** (5209), 375–379.
- Van Heurck, H. 1883. Synopsis des Diatomées de Belgique. Atlas, plates 104–132. Ducaju & Cie.; Anvers.
- Villareal, T.A. 1992. Buoyancy properties of the giant diatom *Ethmodiscus*. *Journal of Plankton Research*, **14**, 459–463.
- Villareal, T.A. 1993. Abundance of the giant diatom *Ethmodiscus* in the southwest Atlantic Ocean and Central Pacific Gyre. *Diatom Research*, **8** (1), 171–177.
- Villareal, T.A., Adornato, L., Wilson, C. and Schoenbaechler, C.A. 2011. Summer blooms of diatom diazotroph assemblages and surface chlorophyll in the North Pacific gyre: a disconnect. *Journal of Geophysical Research*, **116**, 1–15.
- Villareal, T.A., Joseph, L., Brzezinski, M.A., Shipe, R.F., Lipschultz, F. and Altabet, M.A. 1999a. Biological and chemical characteristics of the giant diatom *Ethmodiscus* (Bacillariophyceae) in the Central North Pacific Gyre. *Journal of Phycology*, **35**, 896–902.
- Villareal, T.A., McKay, R.M.L., Al-Rshaidat, M.M.D., Boyanapalli, R. and Sherrell, R.M. 2007. Compositional and fluorescence characteristics of the giant diatom *Ethmodiscus* along a 3000 km transect (28°N) in the central North Pacific gyre. *Deep-Sea Research I*, **54**, 1273–1288.
- Villareal, T.A., Pilskaln, C., Brzezinski, M., Lipschultz, F., Dennet, M. and Gardner, G.B. 1999b. Upward transport of oceanic nitrate by migrating diatom mats. *Nature*, **397**, 423–425.
- Wallich, G.C. 1860. On the siliceous organisms found in the digestive cavities of the Salpae, and their relation to the Flint nodules of the Chalk Formation. *The Transactions of the Microscopical Society of London, New Series*, **8**, 36–55.
- Wallich, G.C. 1868. Proceeding of Societies. *Quarterly Journal of Microscopical Science, New Series*, **8**, 115.
- Wiseman, J.D.H. and Hendey, N.I. 1953. The significance and diatom content of a deep-sea floor sample from the neighborhood of the greatest oceanic depth. *Deep-Sea Research*, **1**, 47–59.
- Xiong, Z.F., Li, T.G., Algeo, T., Nan, Q.Y., Zhai, B. and Lu, B. 2012. Paleoproductivity and paleoredox conditions during late Pleistocene accumulation of laminated diatom mats in the tropical West Pacific. *Chemical Geology*, **334**, 77–91.
- Xiong, Z.F., Li, T.G., Crosta, X., Algeo, T., Chang, F.M. and Zhai, B. 2013. Potential role of giant marine diatoms in sequestration of atmospheric CO₂ during the Last Glacial Maximum: δ¹³C evidence from laminated *Ethmodiscus* mats in tropical West Pacific. *Global and Planetary Change*, **108**, 1–14.
- Zenk, W., Siedler, G., Ishida A., Holfort, J., Kashino, Y., Kuroda, Y., Miyama, T. and Mueller, J.T. 2005. Pathways and variability of the Antarctic Intermediate Water in the western equatorial Pacific Ocean. *Progress in Oceanography*, **67**, 245–281.
- Zhai, B., Li, T.G., Chang, F.M. and Cao, Q.Y. 2010. Vast laminated diatom mat deposits from the west low-latitude Pacific Ocean in the last glacial period. *Chinese Science Bulletin*, **55** (2), 171–175. [In Chinese with English abstract]
- Zhai, B., Li, T.G., Xiong, Z.F. and Li, J. 2012. Diatom records inferred from the diatom mat deposits from low-latitude Western Pacific in the last glacial period. *Journal of Tropical Oceanography*, **31** (4), 75–82. [In Chinese with English abstract]
- Zhang, J., Deng, X., Yang, S. and He, G. 2015. Diatom ooze found in 7000 m submarine area of Challenger Depth in Mariana Trench. *Geological Bulletin of China*, **34** (12), 2352–2354. [In Chinese with English abstract]
- Zhang, K., Chai, F.H., Zhang, R.J. and Xue, Z.G. 2010. Source, route and effect of Asian sand dust on the environment and the oceans. *Particuology*, **8**, 319–324.
- Zhang, W.F., Chen, J., Ji, J.F. and Li, G.J. 2016. Evolving flux of Asian dust in the North Pacific Ocean since the late Oligocene. *Aeolian Research*, **23**, 11–20.

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