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Enhanced marine productivity in the Kuroshio region off Shikoku during the last glacial period inferred from the accumulation and carbon isotopes of sedimentary organic matter

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ABSTRACT: We obtained marine primary production records from cores MD01-2422 and KH06-3-PC8 in the modern Kuroshio flow region in the western North Pacific for the last 35 ka. The organic carbon content of marine sediments is commonly used as a proxy for export production from the surface ocean. Most sedimentary organic carbon was derived from marine organisms, because carbon isotopes of organic matter ($\delta^{13}C_{org}$) in sediments were approximately −21‰, which is close to the typical marine $\delta^{13}C_{org}$ value. The quantities of marine and terrestrial organic matter were reconstructed from the mass balance of $\delta^{13}C_{org}$ in bulk total organic carbon. The accumulation of marine organic carbon, and presumably marine production, was enhanced during the latter half of the last glacial period in the subtropical gyre in the western North Pacific. Terrestrial organic matter varied synchronously with marine organic carbon changes, suggesting that both increased in late Marine Isotope Stage (MIS) 2. We conclude that in addition to aeolian dust supplied by the East Asia monsoon, the lateral transport of nutrients from the East China Sea to the subtropical gyre as a result of a sea-level rise at the last deglaciation played an essential role in enhancing palaeoproductivity during the last glacial period. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: marine productivity; organic carbon; carbon isotope of organic matter; Kuroshio; North Pacific Subtropical Gyre.

Introduction

The Kuroshio Current is one of the warmer and stronger currents of the world's oceans. The Kuroshio diverges from the North Equatorial Current (NEC) east of the Philippine Islands and forms the western boundary current in the North Pacific, flowing along the western margin of the North Pacific Subtropical Gyre. Along the Okinawa Trough and off Shikoku Island, the Kuroshio Current flows northeastward, paralleling the southern margin of the Japanese islands (Fig. 1). The Kuroshio plays a main role in heat transport from the tropical ocean to the subarctic North Pacific.

The North Pacific Subtropical Gyre is composed of clockwise circulating currents in the northern Pacific Ocean. The western subtropical gyre is a unique region in the North Pacific because it is adjacent to the several marginal seas, and also is in the East Asian monsoon zone. This region is strongly influenced by atmospheric forcing from winter to spring. A vertically homogeneous water mass, the North Pacific Subtropical Mode Water, is formed every winter as a result of intense ocean–atmosphere heat fluxes (e.g. Suga and Hanawa, 1995; Yasuda and Hanawa, 1999). During the severe and windy winter, a large amount of nutrients is supplied to the euphotic zone by deep convection in the mixed layer. In the past decade, many observations and studies have revealed the relationship between biological production and nutrient supply processes in the oligotrophic subtropical gyre (e.g. Goes *et al.*, 2001; Limsakul *et al.*, 2001; Li *et al.*, 2004). Despite the importance of the extensive subtropical gyre area in the western North Pacific, no palaeoceanographic studies based on deep-sea sediment cores in the western North Pacific Subtropical Gyre, including the Shikoku Basin and the Kyushu–Palau Ridge, have been conducted. The Shikoku Basin and the Kyushu–Palau Ridge are also east of the Asian continent, where they can be affected by westerly winds, which transport Asian dust to the North Pacific mainly in spring. Therefore, the palaeoceanographic investigation of the subtropical gyre is important for understanding changes in the past land–atmosphere–ocean system, including marine production, dust transport and nutrient supply over East Asia and the western North Pacific.

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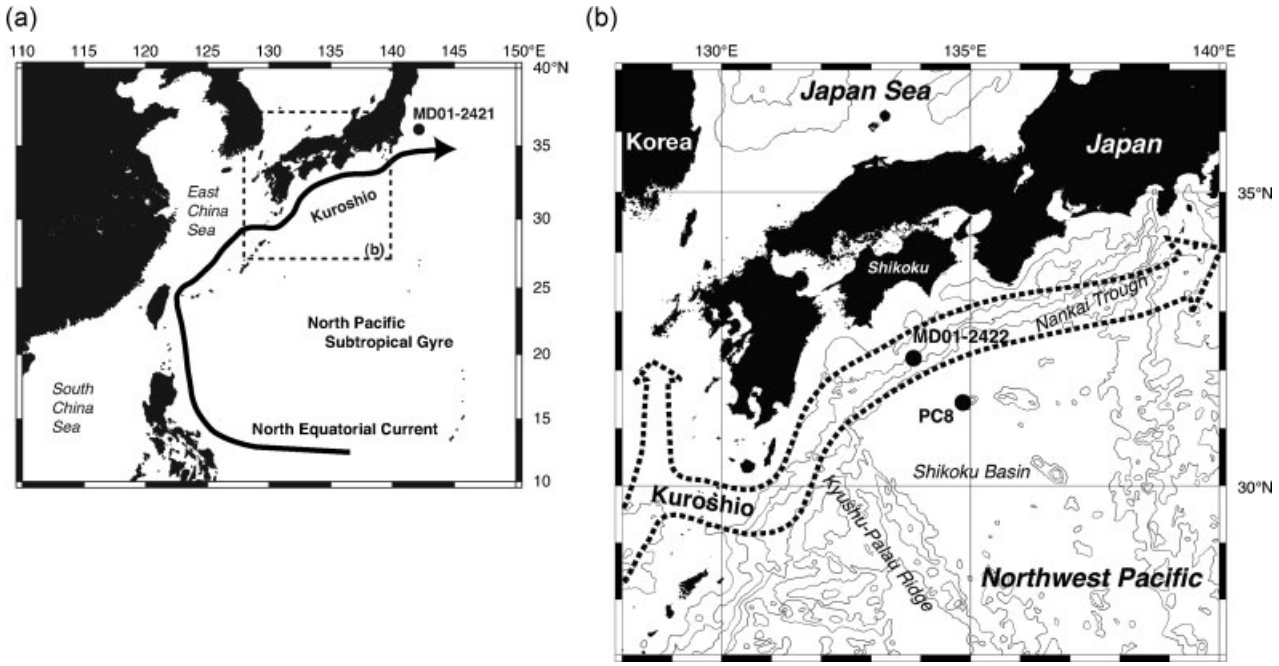

Figure 1 (a) The Kuroshio Current in the western North Pacific. A reference site MD01-2421 is shown by a solid circle. (b) Coring sites: MD01-2422 was collected from the continental slope off Shikoku. KH06-3 PC8 (PC8) was taken from the northern edge of the Shikoku Basin

Organic carbon fluxes in marine sediments have been used to estimate carbon budgets in the geological past, and the total organic carbon (TOC) content of sediments has been used as a clue to estimate marine productivity (e.g. Sarnthein *et al.*, 1988; Sicre *et al.*, 2000). In the middle latitudes of the western North Pacific, primary productivity has been estimated from TOC, and marine productivity variations have been reconstructed for the last 300 ka above the Shatsky Rise (Kawahata *et al.*, 1999). Fluxes of marine organic carbon were higher during glacial periods owing to enhanced marine production above the Shatsky Rise (Amo and Minagawa, 2003). However, marine productivity changes around the Japanese Islands have been poorly reconstructed. Recently, Ueshima *et al.* (2006) reported a pronounced TOC variation with a 41 ka periodicity off central Japan during the past 145 ka. They also showed that primary productivity in the Kuroshio–Oyashio mixing zone is related to the intensity of the winter Aleutian Low. In addition, several studies have used the mass balance of organic carbon isotopes ($\delta^{13}C_{org}$) in sediments to estimate the amount of marine and terrestrial organic carbon in deep-sea sediment and to reconstruct variations in past marine production in the western North Pacific (e.g. Amo and Minagawa, 2003; Ueshima *et al.*, 2006) and the eastern North Pacific (McKay *et al.*, 2004). Therefore, we sought to reconstruct marine productivity variations during past climate changes in the region of the modern Kuroshio Current and the adjacent North Pacific Subtropical Gyre. For this purpose, we analysed the oxygen isotopes of planktonic foraminifera, TOC and $\delta^{13}C_{org}$ in two piston cores from sites south of southwestern Japan forming a latitudinal transect from the continental slope off Shikoku.

Materials and methods

A giant piston core MD01-2422 was collected from the continental slope off Shikoku (Table 1 and Fig. 1) during the WEPAMA2001 cruise of R/V *Marion Dufresne*. The core was recovered to 47.3 m depth, and its sediments are composed mainly of homogeneous silty clay. Piston core KH06-3-PC8 (PC8) was collected from the northern Shikoku Basin (Table 1 and Fig. 1) during the KH06-3 cruise of R/V *Hakuho-maru*. PC8 sediments are composed of homogeneous silty clay with several ash layers.

Sediments were sampled from each of the cores with about 10 cm interval for MD01-2422 and 4.5 cm interval for PC8, respectively. Sediments were washed with water through a 63 μm mesh sieve and the residual samples on the sieve were dried at 50°C. Tests of the planktonic foraminifer *Globorotalia inflata* between 250 and 355 μm in size were then picked for isotope analysis. These tests (20 specimens per sample) were cleaned with methanol by ultrasonicator, slightly crushed in a glass vial and weighed, and then approximately 100 μg of the crushed specimens was reacted with 100% phosphoric acid at 90°C in a vacuum. The released CO_2 was purified and analysed for $\delta^{18}O$ and $\delta^{13}C$ using an IsoPrime isotope ratio mass spectrometer (IRMS) with a MultiPrep automated sample preparation module (GV Instruments Ltd) at Kochi University. The results are expressed in relation to the VPDB (Vienna PeeDee Belemnite) standard. The estimated analytical precision was better than ±0.05‰ for both $\delta^{18}O$ and $\delta^{13}C$ measurements.

Table 1 Core locations

Core	Cruise	Latitude	Longitude	Water depth (m)	Recovery (m)	Area
MD01-2422	WEPAMA	32° 08.7′ N	133° 51.8′ E	2737	47.3	Continental slope
PC8	KH06-3	31° 23.94′ N	134° 49.86 E	4002	3.16	Northern Shikoku Basin

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Table 2 Radiocarbon ages of planktonic foraminifera in core MD012422 (after Ikehara *et al.*, 2006)

Sample depth (m)	Mid-depth (m)	Species	Conventional age (a)	Reservoir corrected age (−400 a)	Error (a)	Calibrated age (a)	Lab no.
0.075–0.149	0.11	*G. inflata*	405	5	±25	Modern	KIA 18289
0.572–0.646	0.61	*G. inflata*	2 955	2 555	±30	2 730	KIA 18290
1.367–1.441	1.40	*G. inflata*	4 795	4 395	±35	5 040	KIA 18291
2.069–2.143	2.11	*G. inflata*	5 775	5 375	±40	6 190	KIA 18292
3.570–3.644	3.61	*G. inflata*	10 720	10 320	±70	11 940	KIA 18293
3.867–3.941	3.90	*G. inflata*	11 140	10 740	±70	12 720	KIA 18294
4.770–4.844	4.81	*G. inflata*	12 870	12 470	±90	14 330	KIA 18295
5.382–4.431	5.41	*G. inflata*	13 380	12 980	±90	15 510	KIA 18296
6.072–6.146	6.11	*G. inflata*	14 290	13 890	+100/−90	16 550	KIA 18298
7.600–7.649	7.62	*G. inflata*	16 370	15 970	±120	18 940	KIA 18300
9.027–9.102	9.06	*G. inflata*	18 280	17 880	±150	21 140	KIA 18301
11.271–11.346	11.31	*G. inflata*	22 490	22 090	±240	26 010	KIA 18302
13.467–13.529	13.50	*G. inflata*	28 770	28 370	+360/−340	33 160	KIA 18936
15.028–15.052	15.04	*G. inflata*	35 060	34 660	+800/−730	40 070	KIA 18937

Accelerator mass spectrometry (AMS) ^{14}C ages of *G. inflata* (test size, 250–355 μm) from MD01-2422 were measured at the AMS facility of Christian-Albrechts-University, Kiel, Germany (Table 2) (Ikehara *et al.*, 2006). AMS ^{14}C ages were calculated using a half-life of 5568 a. All dates were corrected for the reservoir age (400 a) in the Northwest Pacific (Bard, 1988) and converted to calendar years (a BP) using the calibration program CALIB 4.2 (Stuiver *et al.*, 1998) for ^{14}C ages younger than 24 000 cal. a BP and the calibration equation of Bard *et al.* (1998) for ^{14}C ages older than 24 000 cal. a BP.

To determine the tephrochronology, recovered volcanic ash layers by visual core description and microscope observations were examined under a stereo microscope and the refractive indices (RIs) of volcanic glass shards were measured. Tephra samples were prepared by washing them in an ultrasonic cleaner and then sieving to recover the >63 μm size fraction. The volcanic grains in that fraction were separated and classified under a stereo microscope. The RIs of volcanic glass shards in each tephra sample were analysed by the thermal immersion method, as described by Danhara *et al.* (1992), using a RIMS-2000 system (Kyoto Fission-Track Co.) to correlate the several ash layers in cores with known widespread tephras around the Japanese Islands.

To measure organic carbon, samples were collected from each of the cores and dried in a oven at 50°C, and dried samples were ground to a fine powder and treated with 3 M HCl in an Ag cup for 2 days to remove carbonate carbon. Carbonate-free samples were dried in a desiccator for 2 days. Residual samples were analysed by measurement of TOC content and the carbon isotope ratios of organic matter, with an elemental analyser (FlashEA1500) coupled to a Finnigan MAT DeltaPlus isotope ratio mass spectrometer at Hokkaido University for MD01-2422, and with a FlashEA1112 coupled to a Thermo Finnigan DeltaPlus Advantage IRMS at Kochi University for PC8. The analytical error for determination of organic carbon by this method was within 0.01 wt%. The precision of the $\delta^{13}C_{org}$ determinations was better than 0.1‰.

Results and discussion

Age models of cores MD01-2422 and PC8

The age model of MD01-2422 was established from the planktonic δ^{18}O record and AMS ^{14}C ages (Ikehara *et al.*, 2006). Fourteen AMS ^{14}C ages on monospecific samples of *G. inflata* were obtained from the upper section of the core, above 15 m core depth (Table 2 and Fig. 2(a)). In addition, high-resolution oxygen isotope analyses of *G. inflata* were conducted to obtain the detailed δ^{18}O record from Marine Isotope Stage (MIS) 3 to the present in the modern Kuroshio flow region off Shikoku, southwest Japan (Fig. 2(a)). Two volcanic ash zones at 1.47–2.24 and 11.87–12.05 m depth in the core were identified as the Kikai–Akahoya (K-Ah) and the Aira–Tanzawa (AT) tephras (Ikehara *et al.*, 2006). Volcanic glass shards from each tephra were broadly distributed in the MD01-2422 core sediments. The eruption age of the K-Ah tephra is 7 325 cal. a BP (Fukusawa, 1995), determined by the varve counting method in Japanese lake sediments. On the other hand, the most probable eruption age of the AT tephra has been estimated to be 28.3 cal. ka BP, based on ^{14}C ages in core MD01-2422 (Ikehara *et al.*, 2006).

Core PC8 contains two distinct ash layers, from 0.515 to 0.72 m and from 3.09 to 3.10 m. According to the RIs of the volcanic glass, the upper ash layer corresponds to the K-Ah tephra and the lower to the AT tephra (Fig. 2(b)). Unfortunately, δ^{18}O records could not be obtained from the upper 1.2 m of core PC8, because few planktonic foraminiferal tests were present owing to poor carbonate preservation. When the planktonic δ^{18}O curve of core PC8 was compared with the detailed δ^{18}O curve of MD01-2422 (Figs 2(a) and (b) and 3(a)), it was possible to correlate seven horizons, including the two ash layers. The age model indicated that the bottom of core PC8 dated to late MIS 3 (28.6 cal. ka BP). The average sedimentation rate of core PC8, including the two ash layers, was 11 cm ka^{-1}. Hence an analytical interval of 4.6 cm corresponds to about 410 a.

Marine and terrestrial organic carbon estimates

The TOC content of PC8 varied between 0.22% and 0.96% of $CaCO_3$ free dry sediment (average, 0.66%) (Fig. 3(b)). TOC contents of MD01-2422 ranged from 0.24% to 0.74% (average, 0.47%) (Fig. 3(b)). The variation pattern of TOC content was similar in both cores, and higher TOC contents were observed in the 15–14 cal. ka BP interval (Fig. 3(b)). Relatively lower TOC contents were observed in the 7–6 cal. ka BP interval in cores PC8 and MD01-2422 because the sediment samples in that interval were diluted by K-Ah volcanic ash.

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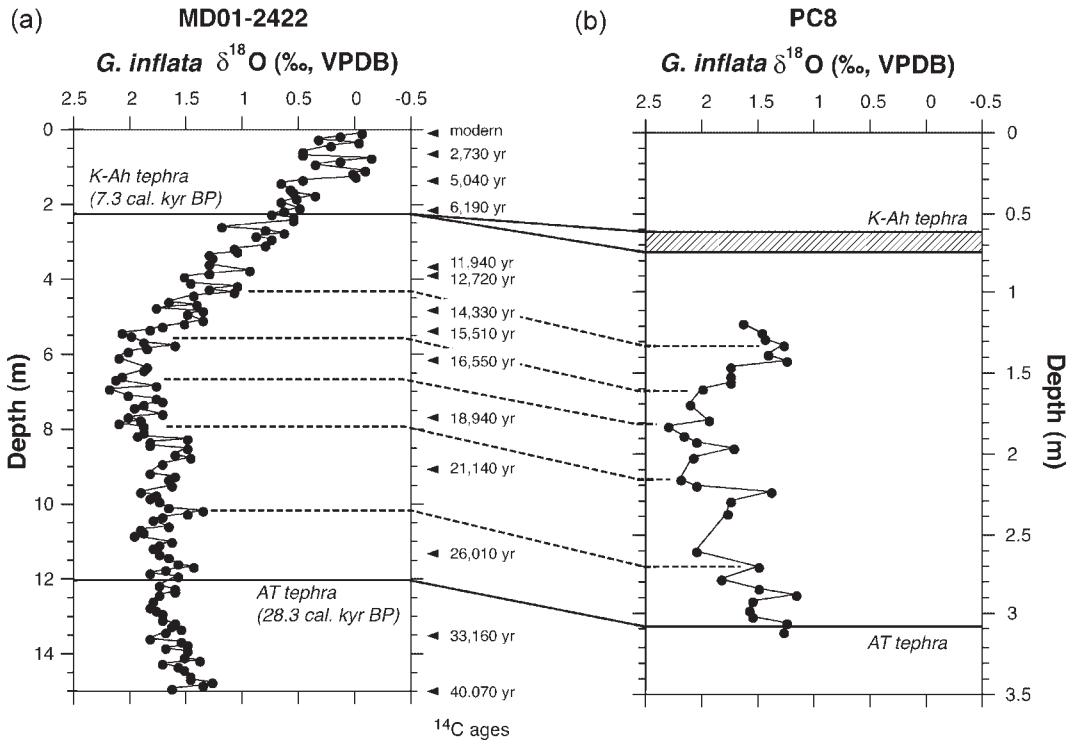

Figure 2 Age models of the two cores MD01-2422 and PC8. (a) Oxygen isotope ($\delta^{18}O$) profile of the planktonic foraminifer *Globorotalia inflata* in core MD01-2422. Fourteen AMS ^{14}C ages are also shown (Ikehara *et al.*, 2006). (b) $\delta^{18}O$ profile of *G. inflata* in core PC8. Correlations of $\delta^{18}O$ between PC8 and MD01-2422 are shown by dotted lines

The $\delta^{13}C$ of organic matter in MD01-2422 varied between −21.3‰ and −20.0‰, with an average of −20.7‰ (Fig. 3(c)). The $\delta^{13}C$ of organic matter in PC8 varied between −22.1‰ and −20.3‰, with an average of −21.0‰ (Fig. 3(c)). These ranges overlapped the range typical of marine organic matter (−22‰ to −20‰) (Meyers, 1994), suggesting that the organic matter was derived mostly from marine organisms, with a minor contribution from terrestrial C_3 plants. This inference is also supported by the TOC to total nitrogen (C/N) weight ratio. The C/N ratio in the two cores varied between 4.4 and 10.9 during the past 35 ka. These values also fall within the range typical of marine organic matter (4–10) (Meyers, 1994). In addition, these records indicate that the $\delta^{13}C$ of organic matter did not show any variation corresponding to the climate changes from the last glacial to the Holocene (Fig. 3). Therefore, the origin of sedimentary organic carbon in the study area hardly changed over the last glacial cycle.

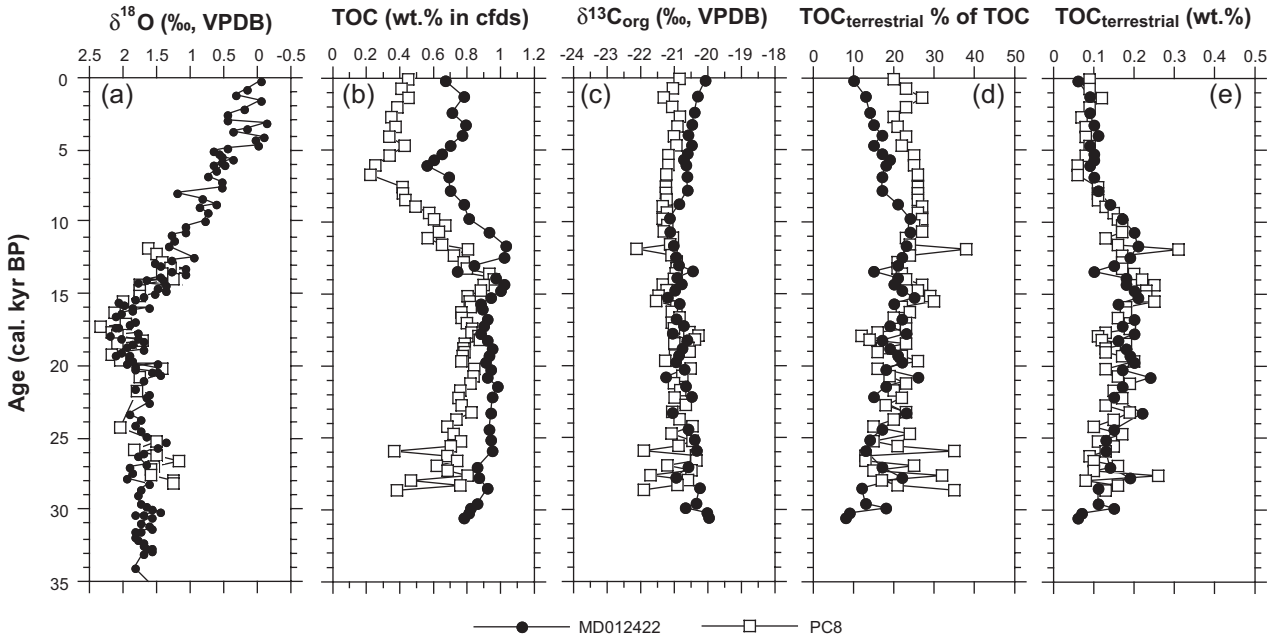

Figure 3 Profiles of the geochemical data from the two cores MD01-2422 (solid circles) and PC8 (open squares) over the past 35 ka BP: (a) oxygen isotopes ($\delta^{18}O$) in planktonic foraminifera; (b) total organic carbon (TOC) content as normalised by the weight of $CaCO_3$ free dry sediment (cfds); (c) carbon isotope of bulk organic carbon ($\delta^{13}C_{org}$); (d) the fraction of terrestrial organic matter in TOC ($TOC_{terrestrial}$ % of TOC), and terrestrial organic carbon concentrations ($TOC_{terrestrial}$)

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The terrestrial organic carbon ($TOC_{terrestrial}$, %) and marine organic carbon (TOC_{marine}, %) contents in marine sediments can be estimated by using the following equations:

$$TOC_{terrestrial}(\%) = \{(\delta^{13}C_{marine} - \delta^{13}C_{sediment})/(\delta^{13}C_{marine} - \delta^{13}C_{terrestrial})\} \times TOC_{bulk}$$

$$TOC_{marine}(\%) = TOC_{bulk} - TOC_{terrestrial}$$

where $\delta^{13}C_{marine}$ and $\delta^{13}C_{terrestrial}$ are the end-member values of carbon isotopic ratios of marine and terrestrial organic matter, and $\delta^{13}C_{sediment}$ is the value of the bulk sediment sample. We assumed terrestrial and marine end-member values of −26.5‰ and −19.4‰, respectively. These end members were calculated using case study results for the carbon isotopes of sedimentary organic matter. The $\delta^{13}C$ composition of terrestrial organic matter derived from vascular C_3 plants is between −29.3‰ and −25.5‰, with an average of −27‰ (Tyson, 1995). The end-member composition of $\delta^{13}C_{terrestrial}$ has also been calculated to be −26.5‰ in Otsuchi Bay, northeastern Japan (Wada *et al.*, 1990). These values are similar to the $\delta^{13}C_{terrestrial}$ estimates from Changjiang estuary sediments in the East China Sea (−26‰) (Gao *et al.*, 2008). A $\delta^{13}C_{terrestrial}$ value of −26.5‰ was therefore used to calculate past variation in terrestrial TOC%.

The $\delta^{13}C$ values of particulate organic matter between 40° N and 40° S in the whole ocean range from −22‰ to −18‰ (Goericke and Fry, 1994), and the $\delta^{13}C$ composition of marine organic matter in low and middle latitudes ranges from −21.5‰ to −17.5‰, with an average of approximately −20‰ (Tyson, 1995). The marine end-member $\delta^{13}C$ composition in the Changjiang estuary was estimated as −20‰ (Gao *et al.*, 2008). Surface sediments deposited on the continental slope and in the Shikoku Basin are characterised by similar values (−20.0‰ to −20.8‰), suggesting that the isotopic composition of organic matter is not altered as it settles through the water column. Furthermore, there is no change in the $\delta^{13}C$ composition in the upper 20 cm of slope deposits, so post-depositional diagenesis is of little concern in this study. In the $\delta^{13}C$ records from the cores, the heaviest $\delta^{13}C$ value of −19.4‰ was observed in glacial sediments of core KPR-3PC from the Kyushu–Palau Ridge in the North Pacific Subtropical Gyre, so this value is most applicable for estimating the marine contribution to TOC in subtropical gyre sediments, including in MD01-2422 and PC8 in the study area.

The proportion of $TOC_{terrestrial}$ in TOC in cores MD01-2422 and PC8 ranged from 8% to 26% and from 12% to 38%, with an average of 18% and 23%, respectively. These results indicate that the organic matter in the two cores consisted mainly of marine organic matter, and that the contribution of terrestrial organic matter was extremely low far south of Japan and the Asian continent during the glacial period. Terrestrial TOC contents increased during the last glacial, MIS 2, whereas they decreased during the Holocene (Fig. 3(e)), indicating that the supply of terrestrial organic matter to the continental slope and the northern Shikoku Basin was much larger during the Last Glacial Maximum (LGM) than during the Holocene. Based on the preliminary results of biomarker analysis, concentrations of high molecular weight (C_{25} to C_{35}) *n*-alkanes, which are known as a typical terrestrial biomarker, were significantly increased during the LGM at core MD01-2422 (Ikehara *et al.*, unpublished data).

Palaeoproductivity changes in the western North Pacific Subtropical Gyre

Concentrations of marine-derived TOC in cores MD01-2422 and PC8 increased during glacial periods, from late MIS 3 to MIS 2 (Fig. 4(b)). To quantify the variability of the sediment flux of marine organic carbon, we determined the mass accumulation rate (MAR), using the following equation:

$$MAR(mg\ cm^{-2}\ ka^{-1}) = TOC_{marine}(\%) \times DBD \times LSR/100 \times 1000$$

where DBD is dry bulk density (g cm^{-3}) and LSR is linear sedimentation rate (cm ka^{-1}). Unfortunately, the MAR of

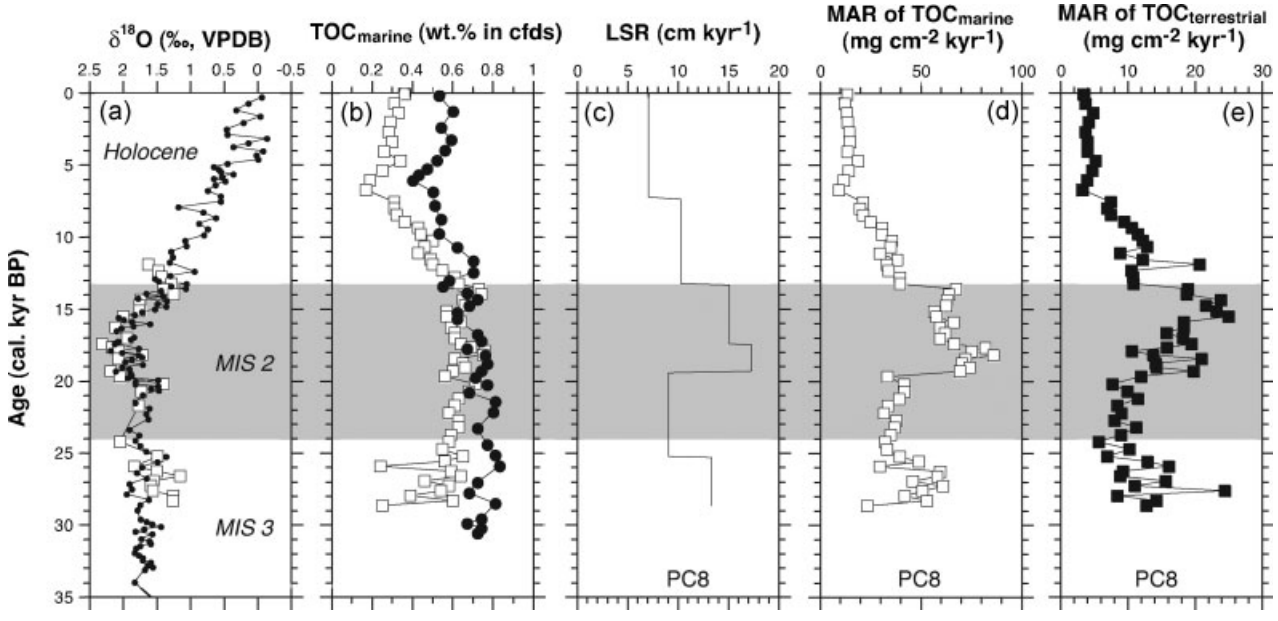

Figure 4 (a) $\delta^{18}O$ profiles of cores MD01-2422 (solid circles) and PC8 (open squares); (b) contents of marine organic carbon (TOC_{marine}) as normalised by the weight of $CaCO_3$ free dry sediment (cfds) of cores MD01-2422 (solid circles) and PC8 (open squares); (c) linear sedimentation rate (LSR) in core PC8; (d) mass accumulation rate (MAR) of marine TOC (mg cm^{-2} ka^{-1}) in core PC8; and (e) MAR of terrestrial TOC (mg cm^{-2} ka^{-1}) in core PC8

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TOC_{marine} in core MD01-2422 was not calculated in the studied interval, because LSR overestimating is highly likely to occur with the Calypso corer due to core-top expansion (e.g., Széréméta *et al.*, 2004). We found that the sediment above 6 m depth of MD01-2422 was about three times thicker than the gravity core (KR02-06-GC2), which was recovered from the same site, by correlation of colour indices and magnetic susceptibility (Ikehara *et al.*, unpublished data). According to the magnetic fabric analyses, the upper 14 m part of MD01-2422 was affected by a significant mechanical extension (Ikehara *et al.*, 2006). The uppermost 14 m interval corresponds to the past 40 cal. ka. Thus we calculated the MAR of TOC_{marine} for core PC8 only. In PC8, MAR of TOC_{marine} varied between 9.3 and 86.0 mg cm^{-2} ka^{-1}, with an average of 41.6 mg cm^{-2} ka^{-1}. These MAR values are about 10 times those from the Shatsky Rise in the western North Pacific, where Amo and Minagawa (2003) reported that the MAR of bulk TOC ranged from 1.1 to 9.6 mg cm^{-2} ka^{-1} and where marine organic carbon comprised more than 86% of TOC in the core.

The MAR of TOC_{marine} was highest during late MIS 2 and noticeably lower during the Holocene (Fig. 4(c)). A relative small MAR peak also occurred during MIS 3, and MAR decreased gradually from 14 to 7 cal. ka BP. These results suggest that marine productivity was higher during late MIS 2 and MIS 3. If plankton productivity was enhanced in late MIS 2, then the nutrient concentrations in the euphotic zone must have increased at that time in the western subtropical ocean. One possible cause of such an increase is a southward shift of the Kuroshio. The Kuroshio is a typical oligotrophic western boundary current, whereas the coastal water mass north of the modern Kuroshio is characterised by high nutrient concentrations and low temperature (e.g. Taft, 1978; Shiomoto and Matsumura, 1992).

A previous study of the planktonic foraminiferal assemblages in the Okinawa Trough and the Ryukyu Trench slope (Ujiié and Ujiié, 1999) reported a southern shift of the Kuroshio. According to Ujiié and Ujiié (1999), during the glacial period a Ryukyu–Taiwan land bridge prevented the inflow of the Kuroshio main flow into the Okinawa Trough, causing the Kuroshio to turn eastward south of the Ryukyu Arc. In addition, they proposed that the Kuroshio may have flowed far south of the Japanese islands during the LGM. However, the sea surface temperatures (SSTs), determined by alkenone palaeothermometer, during the LGM were 2–3°C lower than at present in the Kuroshio region of the Nishishichitou Ridge off central Japan (Sawada and Handa, 1998). According to our preliminary alkenone SST reconstruction results, SSTs during the LGM were decreased about 3–4°C in cores MD01-2422 compared with the present (Ikehara *et al.*, unpublished data). This SST lowering in the region of the modern Kuroshio flow south of Japan corresponded to glacial cooling of the western Pacific warm pool (Lea *et al.*, 2000) and the Sulu Sea (Rosenthal *et al.*, 2003), which are the source regions of the Kuroshio. Thus the SST in the modern Kuroshio flow region off central Japan was mainly affected by a decrease in the SST of the Kuroshio Current itself, indicating that the Kuroshio might not have shifted to the south of its modern flow axis off the Japanese islands. Hence our TOC_{marine} MAR results suggest that the enhancement of productivity during MIS 2 could not have been caused by the southward shift of the Kuroshio current and coastal waters.

This hypothesis is also supported by the carbon isotopes of planktonic foraminifers. The variation in $\delta^{13}C$ of organic matter is approximately 1‰ between Holocene and LGM. Such a small shift is likely attributed to changes in isotopic composition of dissolved inorganic carbon (DIC), if there was influence from the Oyashio or Oyashio-like water. Oba *et al.* (2006) showed the vertical profiles of $\delta^{13}C$ of the sea water at three stations off the east coast of Japan: SK4 in the Oyashio Current, LM9 in the mixed water mass and LM6 in the Kuroshio Current. According to the $\delta^{13}C$ profiles, the $\delta^{13}C$ values of subsurface and intermediate waters from 100 m to 1000 m at station LM6 in the Kuroshio are significantly heavier (up to 1‰) than those at stations SK4 and LM9. If the Oyashio-like water was influenced to our core sites off Shikoku, it is expected that the $\delta^{13}C$ values of planktonic foraminifera at core MD01-2422 were shifted to the lighter values during the last glacial period. We compared the $\delta^{13}C$ values of *G. inflata* in core MD01-2422 with those of a reference core MD01-2421 (Oba *et al.*, 2006), which is located at the south of the modern mixed water mass between the Oyashio and the Kuroshio. *G. inflata* is known as a deep-dwelling species (Bé, 1977; Hemleben *et al.*, 1989). Oba and Hattori (1992) found peak abundances of *G. inflata* in plankton nets deeper than 100 m water depth at the mixed water mass region in November and February. Therefore, carbon isotope values of *G. inflata* provide useful information of the subsurface and intermediate waters. The $\delta^{13}C$ values of *G. inflata* in core MD01-2422 are about 0.4‰ heavier than those of core MD01-2421 during the Holocene (Fig. 5). On the other hand, the *G. inflata* $\delta^{13}C$ differences between MD01-2422 and MD01-2421 are slightly increased during the LGM (Fig. 5). The $\delta^{13}C$ of MD01-2421 was significantly decreased during the glacial period, suggesting that the water chemistry of the southern mixed water mass was strongly affected by the Oyashio water during the glacials. However, the Oyashio-like water might not have influenced core sites off Shikoku, which is the modern Kuroshio flow axis off the Japanese islands.

Organic carbon accumulation rates were higher during the last glacial period. If this pattern is attributed to preservation, it implies that glacial deep water in the Northwest Pacific was less well ventilated (lower O_2 concentration) than during the Holocene. However, such an interpretation does not agree with the pattern of carbonate deposition in this region. In core PC8, carbonate content was slightly increased to approximately 5% during the LGM, whereas that of the Holocene was decreased by a few per cent (Ikehara *et al.*, unpublished data). The records

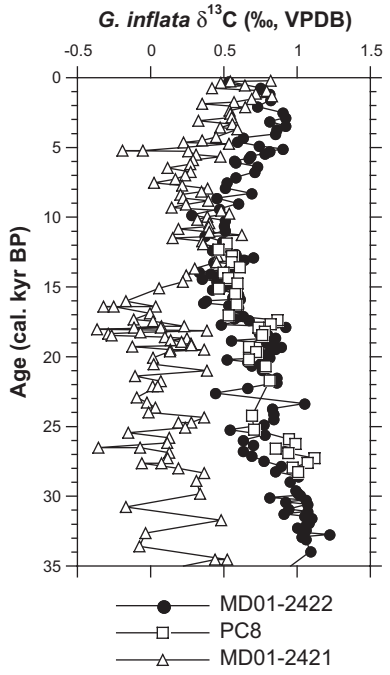

Figure 5 $\delta^{13}C$ profiles of the planktonic foraminifer *Globorotalia inflata* from the three cores MD01-2422 (solid circles), PC8 (open squares) and MD01-2421 (open triangles) (Oba *et al.*, 2006) over the past 35 ka BP

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showed that carbonate preservation in the northern Shikoku Basin was slightly better during the glacial, and this is attributed to the presence of more nutrient-depleted deep waters with lower CO_2 content during this period. On the other hand, the amount of carbonate components in the MD01-2422 where water depth is shallower than at PC8 was decreased in the glacial period. Thus it is suggested that the character of deep-water masses was different between a water depth of ~2700 m (MD01-2422) and 4000 m (PC8). However, the variation pattern of TOC of both MD01-2422 and PC8 are similar (Fig. 3). These results indicate that the organic carbon burial was not mainly controlled by deep-water chemistry in the Northwest Pacific; the evidence also suggests that bottom oxygen does not play a primary role in promoting organic matter preservation (e.g. Calvert and Pedersen, 1992). On the basis of this we conclude that water mass chemistry-controlled preservation is not the primary factor controlling the organic carbon accumulation pattern.

Another possible cause of the glacial increase in TOC_{marine} MAR is the nutrient supply to the euphotic layer in the subtropical gyre. Terrestrial organic carbon also accumulated during late MIS 2, similar to TOC_{marine} MAR (Fig. 4(e)). Such an increase in terrestrial input might cause higher primary production because trace nutrients in the terrestrial fraction are regarded as a limiting factor on phytoplankton growth (Martin and Fitzwater, 1988). The terrestrial material would have reached the study area via atmospheric deposition, because the northwestern North Pacific is downwind of aeolian dust carried from the Asian continent. Seasonal variations in settling fluxes of major components have been analysed using a time series of sediment traps, deployed at station SHIBT (29° 30′ N, 135°15′ E) near the centre of the oligotrophic subtropical gyre in the Shikoku Basin (Li *et al.*, 2004). On the basis of the distributions of strontium isotopes and the clay-sized fraction, Li *et al.* (2004) concluded that many of the clay minerals in the sediment traps in spring were derived mainly from Asian dust via aeolian transport. In addition, they suggested that the organic carbon flux increased in spring, and that a high biogenic flux followed the deposition of Asian dust in early spring of 1999. Therefore, high biological production in the oligotrophic subtropical Shikoku Basin might be caused by the Asian dust supply in spring (Li *et al.*, 2004).

On the other hand, a change in the nutrient supply from the East China Sea via the surface water is another possibly important factor. Oguri *et al.* (2000) studied the organic carbon MAR in two piston cores from the central Okinawa Trough in the East China Sea covering the last 18 cal. ka, and showed that the TOC MAR decreased gradually from 18 to 11 cal. ka after the LGM. They also reported that $\delta^{13}C_{org}$ became depleted at around 16 cal. ka (17.5–13 cal. ka) owing to large terrestrial material inputs from the continental shelf. Sea-level change is the most important factor controlling the nutrient cycle in this marginal sea, which has an extensive continental shelf. Oguri *et al.* (2000) therefore concluded that the offshore transport of terrestrial organic matter was increased significantly by meltwater pulse 1A, caused by the sea-level rise during the last deglaciation. During the LGM, large amounts of lithogenic matter were transported mainly from the coastal lowlands created by the large drop in sea level of the northeastern East China Sea (Kawahata *et al.*, 2006). We thus hypothesised that the higher accumulation rates of marine organic carbon resulted from efficient biological production, which might have been enhanced by increases in the aeolian dust supply from China or by enhanced discharge of terrestrial materials from the East China Sea to the oligotrophic subtropical Pacific. Similar phenomena were recently reported in the Atlantic Ocean based on the general circulation model experiments and observations, where there is a northward transport of inorganic nutrients and dissolved organic nitrogen and phosphorus from the tropics into the northern subtropical gyre associated with the western boundary currents (Roussenov *et al.*, 2006; Williams *et al.*, 2006).

Conclusions

This study investigated variations in TOC accumulation rates and their $\delta^{13}C$ values in the western North Pacific Subtropical Gyre, including the modern Kuroshio Current. On the basis of marine and terrestrial organic carbon accumulations estimated from the mass balance of $\delta^{13}C_{org}$, marine organic carbon was estimated to account for more than 62% of TOC over the continental slope and northernmost Shikoku Basin. C_{marine} MAR was highest, 86 mg cm^{-2} ka^{-1}, in late MIS 2 in the Kuroshio and North Pacific Subtropical Gyre regions. Averaged TOC_{marine} MAR during late MIS 2 was about five times that during the late Holocene. We inferred that these higher accumulation rates resulted from efficient biological production, which might have been enhanced by increases in the aeolian dust supply from China or by enhanced discharge of terrestrial materials from the East China Sea to the oligotrophic subtropical Pacific.

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References

Amo M, Minagawa M. 2003. Sedimentary record of marine and terrigenous organic matter delivery to the Shatsky Rise, western North Pacific, over the last 130 kyr. *Organic Geochemistry* **34**: 1299–1312.

Bard E. 1988. Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic foraminifera: paleoceanographic implications. *Paleoceanography* **3**: 635–645.

Bard E, Arnold M, Hamelin B, Tisnerat-Laborde N, Cabioch G. 1998. Radiocarbon calibration by means of mass spectrometric $^{230}Th/^{234}U$ and ^{14}C ages of corals: an updated database including samples from Barbados, Mururoa and Tahiti. *Radiocarbon* **40**: 1085–1092.

Bé AWH. 1977. An ecological, zoogeographical and taxonomic review of recent planktonic foraminifer. In *Oceanic Micropaleontology*, Ramsey ATS (ed.) Academic Press: New York.

Calvert SE, Pedersen TF. 1992. Organic carbon accumulation and preservation in marine sediments: how important is anoxia. In *Organic Matter: Productivity Accumulation and Preservation of Organic Matter in Recent and Ancient Sediments*, Whelan JK, Farrington JW (eds). Columbia University Press: New York; 231–263.

Danhara T, Yamashita H, Kasuya M. 1992. An improved system for measuring refractive index using the thermal immersion method. *Quaternary International* **13–14**: 89–91.

Fukusawa H. 1995. Non-glacial varved lake sediment as a natural timekeeper and detector on environmental changes. *Quaternary Research* **34**: 135–149 (in Japanese with English abstract).

Gao J, Wang Y, Pan S, Zhang R, Li J, Bai F. 2008. Spatial distributions of organic carbon and nitrogen and their isotopic compositions in sediments of the Changjiang Estuary and its adjacent sea area. *Journal of Geographical Sciences* **18**: 46–58.

Goericke R, Fry B. 1994. Variations of marine plankton $\delta^{13}C$ with latitude, temperature, and dissolved CO_2 in the world ocean. *Global Biogeochemical Cycles* **8**: 85–90.

Goes JI, Gomes HDR, Limsakul A, Balch WM, Saino T. 2001. El Niño related interannual variations in biological production in the North Pacific as evidenced by satellite and ship data. *Progress in Oceanography* **49**: 211–225.

Hemleben C, Spindler M, Anderson OR. 1989. *Modern Planktonic Foraminifer*. Springer: New York.

Ikehara M, Murayama M, Tadai O, Hokanishi N, Daido N, Kawahata H, Yasuda H. 2006. Late Quaternary tephrostratigraphy of two IMAGES cores taken from the off Shikoku in the Northwest Pacific. *Fossils* **79**: 60–76 (in Japanese with English abstract).

Kawahata H, Ohkushi K, Hatakeyama Y. 1999. Comparative Late Pleistocene paleoceanographic changes in the mid latitude boreal and austral western Pacific. *Journal of Oceanography* **55**: 747–761.

Kawahata H, Nohara M, Aoki K, Minoshima K, Gupta LP. 2006. Biogenic and abiogenic sedimentation in the northern East China Sea in response to sea-level change during the Late Pleistocene. *Global and Planetary Change* **53**: 108–121.

Lea DW, Pak DK, Spero HJ. 2000. Climate impact of late Quaternary equatorial Pacific sea surface temperature variations. *Science* **289**: 1719–1724.

Li T, Masuzawa T, Kitagawa H. 2004. Seasonal variations in settling fluxes of major components in the oligotrophic Shikoku Basin, the western North Pacific: coincidence of high biogenic flux with Asian dust supply in spring. *Marine Chemistry* **91**: 187–210.

Limsakul A, Saino T, Midorikawa T, Goes JI. 2001. Temporal variations in lower trophic level biological environments in the northwestern North Pacific Subtropical Gyre from 1950 to 1997. *Progress in Oceanography* **49**: 129–149.

Martin JH, Fitzwater SE. 1988. Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic. *Nature* **331**: 341–343.

McKay JL, Pedersen TF, Kienast SS. 2004. Organic carbon accumulation over the last 16 kyr off Vancouver Island, Canada: evidence for increased marine productivity during the deglacial. *Quaternary Science Reviews* **23**: 261–281.

Meyers PA. 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. *Chemical Geology* **114**: 289–302.

Oba T, Hattori T. 1992. Living planktonic foraminiferal assemblages at the Japan Trench off Boso Peninsula. *Fossils* **52**: 12–19 (in Japanese with English abstract).

Oba T, Irino T, Yamamoto M, Murayama M, Takamura A, Aoki K, Kawahata H. 2006. Paleoceanographic change off central Japan since the last 144,000 years based on high-resolution oxygen and carbon isotope records. *Global and Planetary Change* **53**: 5–20.

Oguri K, Matsumoto E, Saito T, Honda M, Harada N, Kusakabe M. 2000. Evidence for the offshore transport of terrestrial organic matter due to the rise of sea level: the case of the East China Sea continental shelf. *Geophysical Research Letters* **27**: 3893–3896.

Rosenthal Y, Oppo DW, Linsley BK. 2003. The amplitude and phasing of climate change during the last deglaciation in the Sulu Sea, western equatorial Pacific. *Geophysical Research Letters* **30**: 11.1–11.4.

Roussenov V, Williams RG, Mahaffey C, Wolff GA. 2006. Does the transport of dissolved organic nutrients affect export production in the Atlantic Ocean? *Global Biogeochemical Cycles* **20**: GB3002.

Sarnthein M, Winn K, Duplessy J-C, Fontugne MR. 1988. Global variations of surface ocean productivity in low and mid latitudes: influence on CO_2 reservoirs of the deep ocean and atmosphere during the last 21,000 years. *Paleoceanography* **3**: 361–399.

Sawada K, Handa N. 1998. Variability of the path of the Kuroshio ocean current over the past 25,000 years. *Nature* **392**: 592–595.

Shiomoto A, Matsumura S. 1992. Primary productivity in a cold water mass and the neighborhood area occurring off Enshu-Nada in the late summer of1989. *Journal of Oceanography* **48**: 105–115.

Sicre M-S, Ternois Y, Paterne M, Boireau A, Beaufort L, Martinez P, Bertrand P. 2000. Biomarker stratigraphic records over the last 150 kyears off the NW African coast at 25°N. *Organic Geochemistry* **31**: 577–588.

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac G, van der Plicht J, Spurk M. 1998. INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. *Radiocarbon* **40**: 1041–1083.

Suga T, Hanawa K. 1995. Subtropical Mode Water south of Honshu, Japan in spring of 1988 and 1989. *Journal of Oceanography* **51**: 1–19.

Széréméta N, Bassinot F, Balut Y, Labeyrie L, Pagel M. 2004. Oversampling of sedimentary series collected by giant piston corer: evidence and corrections based on 3.5-kHz chirp profile. *Paleoceanography* **19**: PA1005.

Taft B. 1978. Structure of Kuroshio south of Japan. *Journal of Marine Research* **36**: 77–117.

Tyson RV. 1995. *Sedimentary Organic Matter: Organic Facies and Palynofacies*. Chapman & Hall: London.

Ueshima T, Yamamoto M, Irino T, Oba T, Minagawa M, Narita H, Murayama M. 2006. Long term Aleutian Low dynamics and obliquity-controlled oceanic primary production in the mid-latitude western North Pacific (Core MD01-2421) during the last 145,000 years. *Global and Planetary Change* **53**: 21–28.

Ujiié H, Ujiié Y. 1999. Late Quaternary course changes of the Kuroshio Current in the Ryukyu Arc region, northwestern Pacific Ocean. *Marine Micropaleontology* **37**: 23–40.

Wada E, Kabaya Y, Tsuru K, Ishiwatari R. 1990. ^{13}C and ^{15}N abundance of sedimentary organic matter in estuarine areas of Tokyo Bay, Japan. *Mass Spectroscopy* **38**: 307–318.

Williams RG, Roussenov V, Follows MJ. 2006. Nutrient streams and their induction into the mixed layer. *Global Biogeochemical Cycles* **20**: GB1016.

Yasuda T, Hanawa K. 1999. Composite analysis of North Pacific subtropical mode water properties with respect to the strength of the wintertime East Asian monsoon. *Journal of Oceanography* **55**: 531–541.

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