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| Title            | Biomarker records from core GH02-1030 off Tokachi in the northwestern Pacific over the last 23,000 years: Environmental changes during the last deglaciation |
| Author(s)        | Inagaki, Masaki; Yamamoto, Masanobu; Igarashi, Yaeko et al.                                                                                                  |
| Citation         | Journal of Oceanography, 65(6), 847-858<br><a href="https://doi.org/10.1007/s10872-009-0070-4">https://doi.org/10.1007/s10872-009-0070-4</a>                 |
| Issue Date       | 2009-12                                                                                                                                                      |
| Doc URL          | <a href="https://hdl.handle.net/2115/51231">https://hdl.handle.net/2115/51231</a>                                                                            |
| Type             | journal article                                                                                                                                              |
| File Information | Inagaki 2009 JO.pdf                                                                                                                                          |



**Biomarker Records from Core GH02-1030 off Tokachi in the  
Northwestern Pacific over the Last 23,000 Years; Environmental  
Changes during the Last Deglaciation**

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Short title: Paleoenvironment in the NW Pacific

**Abstract:**

We investigated marine and terrestrial environmental changes at the northern  
Japan margin in the northwestern Pacific during the last 23,000 years by analyzing  
biomarkers (alkenones, long-chain *n*-alkanes, long-chain *n*-fatty acids, and  
lignin-derived materials) in Core GH02-1030. The  $U_{37}^{K'}$ -derived temperature in the last

glacial maximum (LGM) centered at 21 ka was  $\sim 10^{\circ}\text{C}$ , which was  $2^{\circ}\text{C}$  lower than the core-top temperature ( $\sim 12^{\circ}\text{C}$ ). This small temperature drop does not agree with pollen evidence of a large air temperature drop (more than  $4^{\circ}\text{C}$ ) in the Tokachi area. This disagreement might be attributed to a bias of  $U_{37}^{\text{K}}$ -derived temperature within  $2.5^{\circ}\text{C}$  by a seasonal shift in alkenone production. The  $U_{37}^{\text{K}}$ -derived temperature was significantly low during the last deglaciation. Because this cooling was significant in the Kuroshio-Oyashio transition zone, the temperature drops are attributable to the southward displacement of the Kuroshio-Oyashio boundary. Abundant lignin-derived materials, long-chain *n*-alkanes and long-chain *n*-fatty acids indicate a higher contribution of terrigenous organic matter from 17 to 12 ka. This phenomenon might have resulted from an enhanced coastal erosion of terrestrial soils due to marine transgression and/or an efficient inflow of higher plant debris to river waters from 17 to 12 ka.

Keywords: North Pacific, Japan, East Asia, biomarker, glacial, deglacial, paleoenvironment, paleotemperature.

## 1. Introduction

The last glacial period ( $\sim 117\text{--}12$  ka) ended with the last deglaciation (Termination I;  $\sim 19\text{--}7$  ka). The onset of sea-surface warming varied in different regimes (in the Pacific, reviewed by Kiefer and Kienast, 2005). The mid-latitude northwestern Pacific is one of the regions of the globe where deglacial warming occurred latest at Termination I (e.g., Oba and Murayama, 2004; Yamamoto *et al.*, 2004; 2005b). A pollen study demonstrated the southward expansion of open taiga vegetation known as the

“Kenbuchi Stadial” on the central Hokkaido Island during the last deglaciation (Igarashi, 1996). An earlier study also showed several cooling events during the last deglaciation on southwestern Hokkaido (Sakaguchi, 1989).

The region contains the subarctic boundary between the subtropical Kuroshio and subarctic Oyashio currents (Fig. 1) and is sensitive to global climate changes (e.g., Chinzei *et al.*, 1987; Isono *et al.*, 2009). Early studies have roughly reconstructed that the Kuroshio-Oyashio boundary shifted southward during the last glacial period and northward during the last interglacial period from ~129 to ~117 ka (e.g., Moore *et al.*, 1980; Thompson and Shackleton, 1980; Chinzei *et al.*, 1987; Harada *et al.*, 2004). Yamamoto *et al.* (2005b), however, demonstrated drops in  $U_{37}^K$ -derived temperature in Core MD01-2421 off the coast of central Japan from ~17 to ~12 ka during the last deglaciation, which was attributed to a southward shift of the summer position of Kuroshio-Oyashio boundary due to the weaker North Pacific High and stronger Okhotsk High. These cooling intervals were not consistent with a global warming trend during the last deglaciation.

We generated the records of  $U_{37}^K$ -derived temperatures and terrestrial and marine biomarkers during the last 23 kyr from Core GH02-1030 taken off the southeastern coast of Hokkaido Island in the northwestern Pacific. We examined both marine and terrestrial environmental changes at the northern Japan margin in order to elucidate the climate linkage between the ocean and land. The high sedimentation rate (average 29 cm/kyr) allowed us to perform a much higher resolution analysis than in previous studies.

## 2. Study site

The study site is located at the northern edge of the mixing zone between Oyashio and Kuroshio waters (Fig. 1). Cold and warm mesoscale eddies from the Oyashio and Kuroshio develop in the mixing zone. The Kuroshio-Oyashio boundary is displaced seasonally. The southern limit of the Oyashio stays at  $\sim 38.5^{\circ}\text{N}$  in April, gradually shifts northward to  $\sim 40^{\circ}\text{N}$  until October, and then moves more rapidly northward to  $\sim 41.5^{\circ}\text{N}$  to December before gradually returning southward until April (Data from Japan Meteorological Agency, <http://www.data.kishou.go.jp/kaiyou/db/hakodate/knowledge/oyashio.html>) The monthly mean sea-surface temperature (SST) ranges from  $2.4^{\circ}\text{C}$  in March to  $\sim 18.6^{\circ}\text{C}$  in August and averages  $\sim 9.7^{\circ}\text{C}$  (Reynolds *et al.*, 2002). The seasonal SST change reflects both the latitudinal displacement of the Kuroshio-Oyashio boundary and the development of thermal stratification. Thermal stratification develops from summer to fall in this region.

The SST in the Kuroshio-Oyashio transition zone is also influenced by decadal oscillations of two oceanic gyre circulations: the Pacific Decadal Oscillation (PDO; Mantua *et al.*, 1997; Minobe, 1997) and the North Pacific Gyre Oscillation (NPGO; Di Lorenzo *et al.*, 2008). The PDO and NPGO modes of climate variability emerge from analyses of North Pacific SST anomalies (the leading principal component) and sea-surface height anomalies (the second principal component), respectively (Mantua *et al.*, 1997; Di Lorenzo *et al.*, 2008). The PDO represents changes in the subpolar gyre circulation, while the NPGO represents changes in the subtropical gyre and the northernmost Alaskan gyre circulation (Di Lorenzo *et al.*, 2008). Both oscillations show El Niño-like spatial patterns of SSTs, and are linked to El Niño-Southern Oscillation (Dettinger *et al.*, 2001; Di Lorenzo *et al.*, 2008).

The spatial distribution of organic matter in surficial sediments off Tokachi

(42°–43°N, 143.5°–145°E) was described in Usui *et al.* (2006). According to Usui *et al.* (2006), total organic carbon (TOC) content is variable on the continental shelf and depends on the influx of terrigenous organic matter from the Tokachi River (Usui *et al.*, 2006). The Tokachi River (156 km length) flows through the Tokachi plains and empties into the northwestern Pacific. River flow increases in spring and early fall due to snowmelt and an increase of precipitation, respectively. On the continental slope, the organic matter derives mainly from marine organisms. The TOC increases with increasing depth, is maximized at ~1100 m, and then decreases to 2000 m. The TOC was significantly correlated with silt and clay content, suggesting that transport and deposition of organic-rich fine sediment particles by hydrodynamic processes were major factors controlling TOC off Tokachi (Usui *et al.*, 2006).

### 3. Materials and methods

A piston core GH02-1030 (8.14 m long) was collected offshore of the southeastern coast of Hokkaido Island at 42°13.77'N, 144°12.53'E at a water depth of 1212 m in 2002 during the *R/V Daini-Hakurei-Maru* GH02 cruise (Fig. 1). Sediments in this core consisted of olive-gray silty clay and clayey silt with sand seams at 454.5–456.5 and 609–611 cm (Fig. 2). The uppermost and middle parts of the core were diatomaceous. Visual observation and soft-X-ray radiographs revealed no clear erosion surface in the core. Very weak lamination was found at two horizons in the middle part of the core, and coarser sandy silt existed between the two laminated horizons (Ikehara *et al.*, 2006).

The age model was established using data from Ikehara *et al.* (2006). The age model between 10.31 and 21.84 ka was created by the AMS <sup>14</sup>C ages of 13 samples of planktonic foraminifera; *Neoglobobulimina pachyderma* or mixed planktonic

foraminifera, mainly *N. pachyderma* with minor portions of *Globigerina bulloides*. The age model after 10.31 ka was created by the AMS  $^{14}\text{C}$  ages of four samples of mixed benthic foraminifera. The conventional age of benthic foraminifera was converted to the planktonic value by subtracting  $700\pm151$  years, which is equivalent to the average difference in conventional ages between planktonic and benthic foraminifera in samples at depths of 2.10, 2.20, and 2.35 m (Ikehara *et al.*, 2006). The calendar age was converted using the CALIB5.0 program and the Marine04.14C dataset (Reimer *et al.*, 2004) with a 776-year reservoir correction ( $\text{DR} = 376\pm46$  years; Kuzmin *et al.*, 2001) (Fig. 3).

The analysis of alkenones and *n*-alkanes was conducted following the modified method of Yamamoto *et al.* (2000). Sediment sample (2 g in dry weight) was extracted twice at  $100^{\circ}\text{C}$  under 1000 psi with 11 mL of dichloromethane/methanol (6/4 v/v) using a DIONEX accelerated solvent extractor ASE-200. The lipid extract was separated into four fractions (F1: 3 mL of hexane; F2: 3 mL of hexane/toluene [3/1 v/v]; F3: 4 mL of toluene; F4: 3 mL of toluene/methanol [3/1 v/v]) by column chromatography ( $\text{SiO}_2$  with 5% distilled water, 5.5 mm ID  $\times$  45 mm long). *n*- $\text{C}_{24}\text{D}_{50}$  and *n*- $\text{C}_{36}\text{H}_{74}$  were added as internal standards into the F1 and F3 fractions, respectively. Gas chromatography for the F1 and F3 fractions was conducted using a Hewlett Packard 6890 gas chromatograph (GC) with on-column injection and electronic pressure control systems and a flame ionization detector. The column used was a capillary column coated with Chrompack CP-Sil5CB (60  $\mu\text{m}$  ID  $\times$  0.25 mm, 0.25  $\mu\text{m}$  coating). The oven temperature was programmed from 70 to  $130^{\circ}\text{C}$  at  $20^{\circ}\text{C}/\text{min}$ , from 130 to  $310^{\circ}\text{C}$  at  $4^{\circ}\text{C}/\text{min}$ , and then was held at  $310^{\circ}\text{C}$  for 30 min in the analysis of the F1 fraction. The oven temperature was programmed from 70 to  $290^{\circ}\text{C}$  at  $20^{\circ}\text{C}/\text{min}$ , from 290 to  $310^{\circ}\text{C}$

at 0.5°C/min, and then was held at 310°C for 60 min in the analysis of the F3 fraction. Helium was used as a carrier gas, and the flow velocity was maintained at 30 cm/s. The alkenone unsaturation index  $U_{37}^{K'}$  was calculated from the concentrations of di- and tri-unsaturated C<sub>37</sub> alken-2-ones (C<sub>37</sub>MK) using the expression (Brassell *et al.*, 1986):  $U_{37}^{K'} = [C_{37:2}MK]/([C_{37:2}MK] + [C_{37:3}MK])$ . The calculation of temperature was conducted according to the equation: Temperature (°C) = ( $U_{37}^{K'} - 0.039$ )/0.034, based on an experimental result for cultured strain 55a of *Emiliania huxleyi* (Prahl *et al.*, 1988), within an analytical accuracy of 0.24°C.

The fatty acids and lignin were analyzed following the methods of Yamamoto *et al.* (2001) and Yamamoto *et al.* (2005a) modified after S. Yamamoto (2000), respectively. Pyrolysis gas chromatography-mass spectrometry with *in situ* methylation with tetramethylammonium hydroxide (TMAH-pyrolysis-GC/MS) was carried out using a Japan Analytical Industry JHP-5 Curie point pyrolyzer that was directly connected to the injection port of a Hewlett Packard 5973 gas chromatograph-mass selective detector. The column used was a Chrompack CP-Sil5CB (length, 30 m; i.d., 0.25 mm; thickness, 0.25 µm). The sediment sample (ca. 20 mg) was placed on a Ni-Co pyrofoil plate with 30 µl of 5% TMAH in methanol and 20 µl of internal standard solution (0.1 g/L *n*-nonadecanoic acid in hexane). The methanol and hexane were dried in room temperature, and the sample was wrapped in pyrofoil. The sample was heated at 590°C for 20 sec in the pyrolyzer, and the generated compounds were transferred to the GC splitless injection system at 300°C with a helium carrier gas. The oven temperature was programmed from 70 to 310°C at 4°C/min after the initial hold time of 1 min, and then it was held isothermally at 310°C for 30 min. The mass spectrometer was run in the full scan ion-monitoring mode (*m/z* 50–650). Electron impact spectra

were obtained at 70 eV. Identification of *n*-fatty acids and lignin phenols was achieved by comparison of their mass spectra and retention times with those of authentic standards. The standard deviations in three duplicate analyses averaged 13% of the concentration for total fatty acids. The standard deviations in replicate analysis (five times) were 10, 7, 15, and 8% of the concentration for total syringyl phenol (S), total vanillyl phenols (V), total cinnamyl phenol (C), and total eight lignin ( $\Sigma 8$ ; S+V+C), respectively, and they were 0.01, 0.03, and 0.06 for S/V and C/V ratios and the ratio of acid to aldehyde of vanillyl phenol [(Ad/Al)<sub>v</sub> ratio], respectively.

Total organic carbon content was measured following the method of Yamamoto (2004) using a LECO WR-112 carbon analyzer. The analyzer was attached to a halogen trap (antimony and potassium iodide). To remove carbonate carbon, the sample was acidified according to the following procedure. The sample (~0.1 g) was soaked in 1-M HCl solution in a ceramic crucible overnight and was heated at 110°C for 3 hr after adding new 1-M HCl. The sample was rinsed to remove chlorides by twice adding pure water, and was heated again at 110°C for 3 hr. The precision of measurement was better than 0.01 wt%.

## **4. Results**

### **4.1. Total organic carbon contents**

Total organic carbon (TOC) content varied between 0.4 and 2.0 wt% of dry sediment, with an average of 1.1 wt% (Fig. 4A), and showed a decreasing trend with increasing depth. Maximal peaks of TOC content were observed at ~14.2 and ~4.4 ka.

### **4.2. Alkenones and $U_{37}^K$ -derived temperature**

Total concentration of C<sub>37:2</sub> and C<sub>37:3</sub> alkenones ranged from 0.06 to 2.09 mg/g-sediment, with an average of 0.67 mg/g-sediment. The concentration abruptly increased at ~14.5 ka (Fig. 4B). The average concentrations before and after 15 ka were 0.22 and 1.20 mg/g of sediment, respectively, and the concentration level rose 5.5 times at 15 ka.

The temperature varied between 7.4 and 14.4°C during the last 23 kyr (Fig. 4C). The temperature during the Last Glacial Maximum (LGM) centered at 21 ka was ~10°C, which was 2°C lower than the core-top temperature (~12°C) at the study site (Fig. 4C). The temperature decreased to ~8°C at 16 ka with a high fluctuation of ~1°C in amplitude, in correlation with the North Atlantic Oldest Dryas cold period. The temperature increased to ~12°C at 14.7 ka, in correlation with the North Atlantic Bølling-Allerød warm period. The temperature subsequently decreased and reached ~9°C at ~12.1 ka, which was correlated with the North Atlantic Younger Dryas cold period. The temperature abruptly increased to ~12°C at 11.3 ka, dropped to 9°C at 10.1 ka and then rose again to ~12°C at 9.6 ka. The temperature gradually increased and maximized at ~6.9 ka and then decreased up to the late Holocene.

#### **4.3. Normal fatty acids**

Total concentrations of short-chain C<sub>14</sub>-C<sub>18</sub> *n*-fatty acids, derived mainly from marine organisms, showed two maxima at 15 ka and 11 ka (Fig. 4D). The total concentrations of long-chain C<sub>26</sub>-C<sub>30</sub> *n*-fatty acids, derived predominantly from higher plants (Kvenvolden *et al.*, 1967), were significantly higher from 17.5 to 12 ka than those in other intervals (Fig. 4E). The abundance ratios of long-chain to short-chain fatty acids, an index of terrestrial organic matter contribution, showed a similar

variation as that of long-chain fatty acid concentration (Fig. 4F).

#### 4.4. Normal alkanes

Normal-alkanes showed a monomodal homologous distribution with a maximum at C<sub>29</sub>. Their homologous distribution is typical of terrestrial higher plant waxes (Eglinton and Hamilton, 1967). Total concentrations of long-chain *n*-C<sub>27</sub>, C<sub>29</sub> and C<sub>31</sub> alkanes, derived from higher plants, tended to be higher from 17.5 to 9 ka than in other intervals (Fig. 4G). The odd/even carbon preference index (CPI) of long-chain C<sub>24</sub>-C<sub>34</sub> *n*-alkanes, defined by Bray and Evans (1961), ranged from 2.2 to 6.3, with an average of 4.4. Most values were in the typical range of fresh *n*-alkanes from higher plants. We observed several spikes of low CPI from 17 to 11 ka (Fig. 4H), implying the contribution of mature (thermally altered) terrestrial organic matter.

#### 4.5. Lignin abundance and composition

Σ 8 (mg/10g-sediment, defined by Hedges and Mann, 1979a), which is the total amount of eight lignin phenols belonging to vanillyl (vanillin, acetovanillone, and vanillic acid), syringyl (syringaldehyde, acetosyringone, and syringic acid) and cinnamyl groups (*p*-coumaric acid and ferulic acid), varied between 0.009 and 0.202, with an average of 0.062 (Fig. 4I). Λ (mg/100mg-TOC), which is the total amount (in mg) of the above-mentioned eight lignin phenols in 100 mg of TOC (Hedges and Mann, 1979a), varied between 0.008 and 0.259, with an average of 0.063 (Fig. 4J). Σ8 and Λ were higher from 18.4 to 17.2 ka and from 15.4 to 12.5 ka than during the other intervals (Figs. 4I and 4J). The Σ8 and Λ were much smaller than those of riverine particles from the Tokachi River in Hokkaido onshore of the study site (Σ8 = 0.13–0.88

and  $\Lambda = 0.69\text{--}2.94$ ,  $n = 4$ , M. Inagaki, unpublished data), implying that the organic matter in the core is mainly of marine origin.

The ratios of syringyl (S) to vanillyl (V) phenols (S/V ratio) and of cinnamyl (C) to vanillyl (V) phenols (C/V ratio) were used for the assessment of paleovegetation (e.g., Hedges and Mann, 1979b; Goñi and Hedges, 1992). The S/V ratio, which is a contribution index of angiosperms relative to gymnosperms (Hedges and Mann, 1979b), ranged from 0.06 to 0.65, with an average of 0.29 (Fig. 4K). The values fell within the range of mixture of angiosperms and gymnosperms ( $S/V = 0.9\text{--}4$  and 0, respectively; Hedges and Mann, 1979b). The S/V ratios were generally higher in the LGM and the early Holocene than in the last deglaciation and the middle and late Holocene (Fig. 4K).

In Core GH02-1030, cinnamyl phenol was hardly detected in lignin-lean samples, only detected samples are shown in Fig. 4L. In the detected samples, the C/V ratio ranged from 0.19 to 0.88, with an average of 0.42. The C/V ratio is used as an index to present the contribution of nonwoody tissues and herbs (Hedges and Mann, 1979b). Recently, Ishiwatari *et al.* (2006) found high C/V ( $>1$ ) and Pc/Vc ( $>10$ ) ratios in sediments from Lake Baikal, which they attributed to the contribution of pollen lignin. In Core GH02-1030, no correlation was observed between the C/V ratio and pollen abundance (Y. Igarashi, unpublished data), and PC/Vc [p-coumaric acid/ferulic acid] ratios (0.1-0.7) were much lower than those of pollen ( $>10$ ; Ishiwatari *et al.*, 2006), implying that the contribution of pollen lignin was not important in the study core.

## 5. Discussion

### 5.1. Sea surface temperatures during the Last Glacial Maximum

The  $U_{37}^{K'}$ -derived temperature record from Core GH02-1030 is characterized by

relatively warm temperatures during the LGM (Fig. 5A). The temperature in the LGM centered at 21 ka was  $\sim 10^{\circ}\text{C}$ , which was  $2^{\circ}\text{C}$  lower than the core-top temperature ( $\sim 12^{\circ}\text{C}$ ). Even warmer temperatures during the LGM than the Holocene were observed at other locations in the subpolar region of northwestern Pacific margins such as the sites of Cores PC-2, PC-4, and MD01-2412 in the Sea of Okhotsk (Fig. 5B; Seki *et al.*, 2004; Harada *et al.*, 2006a), and Cores PC-9 and MD01-2408 in the Sea of Japan (Fig. 5B; Ishiwatari *et al.*, 2001). Ishiwatari *et al.* (2001) interpreted the warm temperatures during the LGM in the Sea of Japan as resulting from the combination of a shift of the alkenone production season and a well-developed thermal stratification. Seki *et al.* (2004) attributed warm temperatures at Cores PC-2 and PC-4 in the Sea of Okhotsk during the LGM partly to the shift of the alkenone production season from October to August. Recently, Fujine *et al.* (2006) found a shorter-chain alkenone ( $\text{C}_{36:2}$  ethylalkenone) and alkenoate ( $\text{C}_{36:2}$  ethylalkenoate) in Core MD01-2408 (the Sea of Japan) during the last two glacial periods ( $\sim 9\text{--}57$  and  $\sim 129\text{--}164$  ka). The occurrence of these unique compounds was associated with low salinity and anomalously high  $U_{37}^{\text{K}}$ -derived temperatures. This correspondence implies either physiological stress induced by low salinity or that a genotypic difference in alkenone producers caused the anomalously high  $U_{37}^{\text{K}}$  values during the last two glacial periods in the Sea of Japan (Fujine *et al.*, 2006). Our survey indicated an absence of these shorter-chain alkenone and alkenoate in samples from Core GH012-1030, which indicates that the temperatures during the LGM at the study site were not affected by low salinity events.

The study site is characterized by a large seasonal sea surface temperature (SST) variation. SST varies between  $2.4^{\circ}\text{C}$  in March and  $18.6^{\circ}\text{C}$  in August (Reynolds *et al.*, 2002). The core-top  $U_{37}^{\text{K}}$ -derived temperature at the study site was  $11.9^{\circ}\text{C}$  (Fig. 5A),

corresponding to the SST in June and was higher than the annual mean SST at the study site (9.7°C; Reynolds *et al.*, 2002). A time-series sediment-trap study demonstrated that alkenones are continuously produced from April to October and the production is optimal in July at 39°N, 147°E in the mid-latitude northwestern Pacific (Yamamoto *et al.*, 2007). The  $U_{37}^K$ -derived temperature in summer indicate a thermocline temperature that is at most 6°C lower than the SST (Yamamoto *et al.*, 2007). Lower  $U_{37}^K$ -derived temperatures than SST in summer were also observed at other locations in the mid-latitude North Pacific (Station JT-2; Sawada *et al.*, 1998, Stations KNOT, 40N and 50N; Harada *et al.*, 2006b).

We predicted a possible increase in the  $U_{37}^K$ -derived temperature when the onset of alkenone production was delayed based on the one-year sediment-trap data of the flux-weighted  $U_{37}^K$ -derived temperature at 39°N, 147°E in 1998 (Site WCT-2; Yamamoto *et al.*, 2007). The delay in the onset of alkenone production by 1 month (early May onset) induced only a 0.1°C rise and delays 2 (early June), 3 (late June), 4 (late July), 5 (late August), or 6 (late September) months resulted in a total increase in  $U_{37}^K$ -derived temperatures of 0.7°C, 0.9°C, 2.1°C, 2.2°C, and 2.5°C, respectively (Fig. 6). This calculation implies that  $U_{37}^K$ -derived temperature can be biased by up to 2.5°C when the onset of alkenone production shifts from April to September.

A sediment-trap study at a cooler site (50°N, 165°E) demonstrated a short period of alkenone production in October and November (Harada *et al.*, 2006b). The seasonal shift of haptophyte blooms is presumably caused by the temperature dependence of the growth rates of these algae, which was demonstrated by culture experiments (Conte *et al.*, 1998). These observations support our hypothesis that the  $U_{37}^K$ -derived temperature

during the LGM was biased within 2.5°C by a seasonal shift in alkenone production.

Pollen analysis indicated abundant *Larix* during the LGM in Core GH02-1030 (Y. Igarashi, unpublished data). The southern limit of *Larix* is south Sakhalin Island in the modern natural flora (e.g., Igarashi and Igarashi, 1998). The July temperature at Korsakov in south Sakhalin is 14.8°C (Japan Weather Association, 1982), but 18.3°C at Obihiro in the Tokachi area, onshore of the study site (National Astronomical Observatory, 2000); the temperature difference is thus ~4°C. This suggests that the summer air temperature in the Tokachi area during the LGM was more than 4°C lower than that at present. This air temperature drop was larger than the drop of the  $U_{37}^K$ -derived temperature (~ 2°C). If there was no seasonal shift of alkenone production, the difference suggests the mismatch of temperature changes between atmosphere and ocean surface. If there was a seasonal shift, the difference in SST between the LGM and present is possibly a maximum of 4.5°C, which agrees with the estimated difference in air temperature (>4°C).

## 5.2. Cooling during the last deglaciation

The  $U_{37}^K$ -derived temperature record from Core GH02-1030 is characterized by cooling events during the last deglaciation from 17 to 10 ka (Fig. 5A). The general trend in  $U_{37}^K$ -derived temperatures is consistent with that of foraminiferal Mg/Ca-based temperatures (Sagawa and Ikehara, 2008). The temperatures were even lower than those during the LGM. The seasonal shift in alkenone production less likely enhanced a temperature drop, because alkenone producers prefer warmer water (Conte *et al.*, 1998), but mutes the drop by shifting the production to a warmer season. The seasonal shift of alkenone production was, therefore, less likely to account for the cooling during the last

deglaciation.

Igarashi (1996) reported a cooling event in central Hokkaido Island during the last deglacial, based on abundant *Larix* pollen in terrestrial boring cores, which she called the “Kenbuchi Stadial”. This stadial was not precisely defined in age by Igarashi (1996). Pollen analysis for Core MD01-2421 indicated that the terrestrial vegetation was *Larix-Picea* forest in the LGM from 22 to 18.5 ka and changed to open *Larix-Picea* forest from 18.5 to 14.8 ka, *Betula* forest from 14.8 to 11.0 ka, mixed forest with *Larix* from 11.0 to 8.5 ka, and mixed forest after 8.5 ka (Fig. 4N). *Larix* dominated in the LGM and continued to be present from 18.5 to 8.5 ka. In contrast to terrestrial boring cores from central Hokkaido (Igarashi, 1996), pollen record from Core GH02-1030 did not show a “Kenbuchi stadial”-like cold reversal during the last deglaciation, but showed a slow and gradual warming from 15 to 9 ka (Yaeko Igarashi, unpublished data). Cooler sea surface temperatures during the last deglaciation at Core GH02-1030 might be related to this slow warming on land.

The variation of  $U_{37}^K$ -derived temperature in Core GH02-1030 during the last 23 kyr was nearly parallel to that in Core MD01-2421 (Yamamoto *et al.*, 2005b; Isono *et al.*, 2009) off central Japan and Core PC-6 (Minoshima *et al.*, 2007) off northeastern Japan (Fig. 5A). Since these sites are located in the Kuroshio-Oyashio transition, the temperature variations are attributable to the latitudinal displacement of the Kuroshio-Oyashio boundary. The southward displacement of the Kuroshio-Oyashio boundary resulted in cooler temperatures during the last deglaciation at the study site.

Yamamoto *et al.* (2005b) attributed a strong cooling at MD01-2421 off central Japan during the last deglaciation to both the depressed North Pacific High and the enhanced Okhotsk High. Recently Yamamoto (2009) revisited the data of Yamamoto *et*

*al.* (2004; 2005b) and interpreted that the cooling at the Japan margin during the last deglaciation was caused by the decline of subtropical gyre circulation which is linked to changes in tropical ocean-atmosphere dynamics.

In modern climate, the summer Okhotsk High is enhanced by the summer heating of northeastern Siberia, north of the Sea of Okhotsk, and the northerly cold air advection to the south of the Okhotsk High generates cold SST anomalies in the Kuroshio-Oyashio transition (Ogi *et al.*, 2004). The enhanced heating of the land surface over northeastern Siberia due to increasing summer insolation and atmospheric greenhouse gases, might have resulted in the stronger summer Okhotsk High during the last deglaciation (Yamamoto *et al.*, 2005b). This cooling by northerly winds from the Okhotsk High might contribute to low SST in addition to the southward displacement of the Kuroshio-Oyashio boundary during the last deglaciation.

### **5.3. Increased influx of terrigenous organic matter during the last deglaciation**

High abundance of lignin, long-chain *n*-alkanes, and long-chain *n*-fatty acids indicate the enhanced contribution of terrigenous organic matter during the last deglaciation from 17 to 12 ka (Figs. 4E, 4G and 4I). A similar phenomenon was observed in the Sea of Okhotsk (Ternois *et al.*, 2001; Seki *et al.*, 2003). This phenomenon was attributed to the enhanced transportation of terrigenous organic matter by ice rafts (Ternois *et al.*, 2001) and subsequently to the increase in reworked terrigenous organic matter from the continental shelves of the northern margin because ice rafts decreased during the last deglaciation in the Sea of Okhotsk (Seki *et al.*, 2003).

Ad/Al<sub>v</sub> [vanillic acid/vanillin] and Ad/Al<sub>s</sub> [syringic acid/acetosyringone] ratios are indices of aerobic microbial degradation in freshwater environment (Goñi *et al.*, 1993).

Fresh, moderately degraded, and highly degraded lignin have Ad/Al<sub>v</sub> ratios of ~0.5, ~3, and 7–12, respectively, in the TMAH procedure (Hatcher *et al.*, 1995). In Core GH02-1030, the Ad/Al<sub>v</sub> values ranged from 0.3 to 6.2, with an average of 2.3 (Fig. 4M). This suggests that the lignin was not highly degraded but slightly or moderately degraded by aerobic microbes. Relatively high values were observed from ~19 to ~7 ka (Fig. 4M), implying the transportation of more degraded terrigenous organic matter into the study site.

Spikes of low CPI appeared from 17 to 11 ka (Fig. 4H). Since CPI decreases with increasing thermal maturity in sedimentary rock (e.g., Philippi, 1965), the spikes of low CPI in the last deglacial samples indicate the contribution of mature sedimentary organic matter. This suggests that Tertiary sedimentary rocks exposed in the Tokachi district onshore of the study site were eroded and mature organic matter was transported to the study site during the last deglaciation.

Two possible processes may have increased the inflow of terrestrial organic matter during the last deglaciation. Firstly, an enhanced coastal erosion due to marine transgression likely increased terrestrial organic matter. The sea level rose more than 120 m from 19 to 6 ka (Fig. 4O, Lambeck *et al.*, 2002). Oguri *et al.* (2000) found a negative excursion of carbon isotopes of bulk organic matter in a core from the Okinawa Trough in the East China Sea. They attributed this phenomenon to enhanced coastal erosion during the last deglaciation. Seki *et al.* (2003) interpreted a similar phenomenon in the Sea of Okhotsk as being due to the same mechanism. The average rate of sea level rise was ~1 cm/yr during the last deglaciation, and such a rapid rise could have enhanced coastal erosion. This hypothesis is consistent with the increases in mature sedimentary organic matter and more degraded terrestrial organic matter during

the last deglaciation, which were observed in the study core.

Secondly, more likely, the development of an alluvial plain in the Tokachi area during the last deglaciation also could have increased the discharge of terrestrial organic matter to the study site (Fig. 7). Geomorphological studies of river terraces on the Tokachi district onshore of the study site demonstrated a contrast of fluvial accumulation-incision balance between the upper and lower reaches of the rivers during the LGM and the Holocene (Hirakawa and Ono, 1974; Hirakawa, 1977). Fluvial deposits accumulated in the upper and middle reaches of the rivers, and the plain was incised in the lower reaches due to low sea level stand during the LGM. During the Holocene, mountainous regions were incised, presumably due to increased precipitation, and thick sediments accumulated in the alluvial fan. Grain size analysis for Core GH02-1030 showed that the sand fraction was significant in the LGM interval and disappeared in the overlying intervals (Ikehara *et al.*, 2006). This change likely reflected the landward shift of the deposition center of terrestrial detrital matter as a result of sea level rise, which is also consistent with the change in mass balance from incision to accumulation in the lower reach of the Tokachi River.

The suspended organic matter in the rivers of Hokkaido Island, including the Tokachi River, is fed mainly by riverbank erosion (Alam *et al.*, 2007; Alam, personal communication). During the LGM, the Tokachi Plain was incised; since the rivers flowed within the valley, organic matter was not efficiently supplied from the vegetation on the plain (Fig. 7). Mountainous regions were less vegetated (Ono and Hirakawa, 1975) and could not supply substantial higher-plant debris to the river waters. During the last deglaciation, the alluvial plain developed as a result of sea level rise, and organic matter was efficiently fed to rivers from the bank erosion by meandering rivers

(Fig. 7). The presence of altered lignin and mature organic matter in this interval suggests that the reworking process of terrestrial organic matter was more important during this period than other periods. During the Holocene, the deposition center shifted landward, and the transportation of terrestrial organic matter to the study site decreased (Fig. 7).

## 6. Conclusions

The  $U_{37}^K$ -derived temperature record from Core GH02-1030 is characterized by relatively warm temperatures during the LGM. The temperature in the LGM centered at 21 ka was  $\sim 10^{\circ}\text{C}$ , which was  $2^{\circ}\text{C}$  lower than the core-top temperature ( $\sim 12^{\circ}\text{C}$ ). An evaluation based on modern sediment trap data suggests that  $U_{37}^K$ -derived temperature can be biased by up to  $2.5^{\circ}\text{C}$  when the onset of alkenone production shifts from April to September. If there was the seasonal shift of alkenone production, the difference in SST between the LGM and present is possibly a maximum of  $4.5^{\circ}\text{C}$ , which agrees with the difference in air temperature ( $>4^{\circ}\text{C}$ ) estimated from pollen assemblages.

The  $U_{37}^K$ -derived temperature record from Core GH02-1030 is characterized by cooling events during the last deglaciation (Fig. 5A). These cooling events are correlated with the “Kenbuchi Stadial” previously reported from pollen records of inland Hokkaido (Igarashi, 1996). The variation of  $U_{37}^K$ -derived temperature in Core GH02-1030 was nearly parallel to those off the coast of central and northeastern Japan. The southward displacement of the Kuroshio-Oyashio boundary resulted in cooler temperatures during the last deglaciation.

High abundance of lignin, long-chain *n*-alkanes and long-chain *n*-fatty acids indicate the enhanced contribution of terrigenous organic matter during the last

deglaciation from 17 to 12 ka. High Ad/Al<sub>v</sub> [vanillic acid/vanillin] and Ad/Al<sub>s</sub> [syringic acid/acetosyringone] ratios and the spikes of low CPI (odd/even carbon number preference of long-chain *n*-alkanes) indicate the contribution of more degraded and mature (thermally altered) organic matter. This presumably reflected an enhanced coastal erosion of terrestrial soils due to marine transgression and/or an efficient inflow of higher plant debris to river waters during this period.

## Acknowledgements

We thank Yutaka Ichikawa, Takuya Sagawa, Osamu Seki, Seiya Nagao, Masao Minagawa, Tomohisa Irino, Tadamichi Oba, Takeshi Nakatsuka, Kazuomi Hirakawa, Yugo Ono (Hokkaido University), Shuichi Yamamoto (Soka University), Takuya Itaki, Atsushi Noda, Hajime Katayama (Geological Survey of Japan, AIST), and the shipboard scientists of the GH02 cruise for their valuable input. Comments by Ryoshi Ishiwatari, Naomi Harada, and the anonymous reviewer improved this manuscript. This study was carried out under Grants-in-Aid for Scientific Research (B) No. 16340158 and Scientific Research (A) No. 19204051 of JSPS (MY).

## References

- Alam, M.J., S. Nagao, T. Aramaki, Y. Shibata and M. Yoneda (2007): Transport of particulate organic matter in the Ishikari River, Japan during spring and summer. *Nucl. Instr. Meth. Phys. Res. B*, **259**, 513–517.
- Bray, E.E. and E.D. Evans (1961): Distribution of *n*-paraffins as a clue to the recognition of source beds. *Geochim. Cosmochim. Acta*, **22**, 2–9.
- Chinzei, K., K. Fujioka, H. Kitazato, I. Koizumi, T. Oba, M. Oda, H. Okada, T. Sakai

479 and Y. Tanimura (1987): Postglacial environmental change of the Pacific Ocean off  
 480 the coasts of central Japan. *Mar. Micropal.*, **11**, 273–291.

481 Conte, M.H., A. Thompson, D. Lesley and R.P. Harris (1998): Genetic and  
 482 physiological influences on the alkenone/alkenoate versus growth temperature  
 483 relationship in *Emiliania huxleyi* and *Gephyrocapsa oceanica*. *Geochim.*  
 484 *Cosmochim. Acta*, **62**, 51-68.

485 Dettinger, M.D., D.S. Battisti, R.D. Garreaud, G.J. McCabe, Jr. and C.M. Bitz (2001):  
 486 Interhemispheric effects of interannual and decadal ENSO-like climate variations  
 487 on the Americas. p. 1-16. In *Interhemispheric Climate Linkages*, Academic Press,  
 488 San Diego.

489 Di Lorenzo, E., N. Schneider, K.M. Cobb, P.J.S. Franks, K. Chhak, A.J. Miller, J.C.  
 490 McWilliams, S.J. Bograd, H. Arango, E. Curchitser, T.M. Powell and P. Rivière  
 491 (2008): North Pacific Gyre Oscillation links ocean climate and ecosystem change.  
 492 *Geophys. Res. Let.*, **35**, L08607.

493 Eglinton, G. and R.J. Hamilton (1967): Leaf epicuticular waxes. *Science*, **156**,  
 494 1322-1355.

495 Fujine, K., M. Yamamoto, R. Tada and Y. Kido (2006): A salinity-related occurrence of  
 496 a novel alkenone and alkenoate in Late Pleistocene sediments from the Japan Sea.  
 497 *Org. Geochem.*, **37**, 1074-1084.

498 Goñi, M.A. and J.I. Hedges (1992): Lignin dimers: Structures, distribution, and  
 499 potential geochemical applications. *Geochim. Cosmochim. Acta*, **56**, 4025-4043.

500 Goñi, M.A., B. Nelson, R.A. Blanchette and J.I. Hedges (1993): Fungal degradation of  
 501 wood lignins: Geochemical perspectives from CuO-derived phenolic dimers and  
 502 monomers. *Geochim. Cosmochim. Acta*, **57**, 3985-4002.

503 Harada, N., N. Ahagon, M. Uchida and M. Murayama (2004): Northward and  
 504 southward migrations of frontal zones during the past 40 kyr in the  
 505 Kuroshio-Oyashio transition area. *Geochem. Geophys. Geosyst.*, **5**, Q09004.  
 506 Harada, N., N. Ahagon, T. Sakamoto, M. Uchida, M. Ikehara and Y. Shibahara (2006a):  
 507 Rapid fluctuation of alkenone temperature in the southwestern Okhotsk Sea during  
 508 the past 120 ky. *Global Planet. Change*, **55**, 29-46.  
 509 Harada, N., M. Sato, A. Shiraishi and M.C. Honda (2006b): Characteristics of alkenone  
 510 distributions in suspended and sinking particles in the northwestern North Pacific.  
 511 *Geochim. Cosmochim. Acta*, **70**, 2045-2062.  
 512 Hatcher, P.G., M.A. Nanny, R.D. Minard, S.D. Dible and D.M. Carson (1995):  
 513 Comparison of two thermochemolytic methods for the analysis of lignin in  
 514 decomposing gymnosperm wood: the CuO oxidation method and the method of  
 515 thermochemolysis with tetramethylammonium hydroxide (TMAH). *Org.*  
 516 *Geochem.*, **23**, 881-888.  
 517 Hedges, J.I. and D.C. Mann (1979a): The lignin geochemistry of marine sediments from  
 518 the southern Washington coast. *Geochim. Cosmochim. Acta*, **43**, 1809-1918.  
 519 Hedges, J.I. and D.C. Mann (1979b): The characterization of plant tissues by their  
 520 lignin oxidation products. *Geochim. Cosmochim. Acta*, **43**, 1803-1807.  
 521 Hirakawa, K. and Y. Ono (1974): The landform evolution of the Tokachi Plain.  
 522 *Geograph. Rev. Japan*, **47**, 607-632 (in Japanese).  
 523 Hirakawa, K. (1977): Chronology and evolution of landforms during the late  
 524 Quaternary in the Tokachi Plain and adjacent areas, Hokkaido, Japan. *Catena*, **4**,  
 525 255-288.  
 526 Igarashi, Y. (1996): A late glacial climate reversion in Hokkaido, Northeast Asia,

527       inferred from the *Larix* pollen record. *Quat. Sci. Rev.*, **15**, 989-995.

528   Igarashi, Y. and T. Igarashi (1998): Late Holocene vegetation history in south Sakhalin,  
529       northeast Asia. *Jpn. J. Ecol.*, **48**, 231-244 (in Japanese).

530   Ikehara, K., K. Ohkushi, A. Shibahara and M. Hoshiba (2006): Change of bottom water  
531       conditions at intermediate depths of the Oyashio region, NW Pacific over the past  
532       20,000 yrs. *Global Planet. Change*, **53**, 78-91.

533   Ishiwatari, R., M. Houtatsu and H. Okada (2001): Alkenone-sea surface temperatures in  
534       the Japan Sea over the past 36 kyrs: Warm temperatures at the last glacial  
535       maximum. *Org. Geochem.*, **32**, 57-67.

536   Ishiwatari, R., S. Yamamoto and S. Shimoyama (2006): Lignin and fatty acid records in  
537       Lake Baikal sediments over the last 130 kyr: A comparison with pollen records.  
538       *Org. Geochem.*, **37**, 1787-1802.

539   Isono, D., M. Yamamoto, T. Irino, T. Oba, M. Murayama, T. Nakamura and H.  
540       Kawahata (2009): The 1,500-year climate oscillation in the mid-latitude North  
541       Pacific during the Holocene. *Geology*, **37**, 591-594.

542   Japan Weather Association (1982): *Climate of Hokkaido*. Japan Weather Association,  
543       Hokkaido Headquater, Sapporo, 319p (in Japanese).

544   Kiefer, T. and M. Kienast (2005): Patterns of deglacial warming in the Pacific Ocean: a  
545       review with emphasis on the time interval of Heinrich event. *Quat. Sci. Rev.*, **24**,  
546       1063–1081.

547   Kuzmin, Y.V., G.S. Burr and A.J.T. Jull (2001): Radiocarbon reservoir correction ages in  
548       the Peter the Great Gulf, Sea of Japan, and eastern coast of the Kunasir, Southern  
549       Kurils (Northwestern Pacific). *Radiocarbon*, **43**, 477-481.

550   Kvenvolden, K.A. (1967): Normal fatty acids in sediments. *J Amer. Oil Chem. Soc.*, **44**,

551           628-636.

552   Lambeck, K., Y. Yokoyama and T. Purcell (2002): Into and out of the Last Glacial  
553           Maximum: sea level change during Oxygen Isotope Stages 3 and 2. *Quat. Sci. Rev.*,  
554           **21**, 343-360.

555   Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace and R.C. Francis (1997): A Pacific  
556           interdecadal climate oscillation with impacts on salmon production. *Bull. Amer.*  
557           *Meteorol. Soc.*, **78**, 1069-1079.

558   Minobe, S. (1997): A 50-70 year climate oscillation over the North Pacific and North  
559           America. *Geophys. Res. Let.*, **24**, 683-686.

560   Minoshima, K., H. Kawahata and K. Ikehara (2007): Changes in biological production  
561           in the mixed water region (MWR) of the northwestern North Pacific during the last  
562           27 kyr. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **254**, 430-447.

563   Moore, T.C., L.H. Burkle, K. Geitzenauer, K., *et al.* (1980): The reconstruction of sea  
564           surface temperatures in the Pacific Ocean of 18,000 B.P. *Mar. Micropal.*, **5**,  
565           215-247.

566   National Astronomical Observatory (2000): *Chronological Scientific tables 2001*.  
567           Maruzen, Tokyo, 1064p (in Japanese).

568   Oba, T. and M. Murayama (2004): Sea surface temperature and salinity changes in the  
569           northwest Pacific since the last glacial maximum. *J. Quat. Sci.*, **19**, 1-12.

570   Ogi, M., Y. Tachibana and K. Yamazaki (2004): The connectivity of the winter North  
571           Atlantic Oscillation (NAO) and the summer Okhotsk High. *J. Meteorol. Soc.*  
572           *Japan*, **82**, 905-913.

573   Oguri, K., E. Matsumoto, Y. Saito, M.C. Honda, N. Harada and M. Kusakabe (2000):  
574           Evidence for the offshore transport of terrestrial organic matter due to the rise of

575 sea level: The case of the East China Sea continental shelf. *Geophys. Res. Let.*, **27**,  
576 3893-3896.

577 Ono, Y. and K. Hirakawa (1975): Glacial and periglacial morphogenetic environments  
578 around the Hidaka Range in the Würm glacial age. *Geograph. Rev. Japan*, **48**,  
579 1-26.

580 Philipi, G.T. (1965): On the depth, time and mechanism of petroleum generation.  
581 *Geochim. Cosmochim. Acta*, **29**, 1021-1049.

582 Prahl, F.G., L.A. Muehlhausen and D.L. Zahnle (1988): Further evaluation of long-chain  
583 alkenones as indicators of paleoceanographic conditions. *Geochim. Cosmochim.*  
584 *Acta*, **52**, 2303-2310.

585 Reimer, P.J., *et al.* (2004): IntCal04 Terrestrial radiocarbon age calibration, 26 - 0 ka  
586 BP. *Radiocarbon*, **46**, 1029-1058.

587 Reynolds, R.W., N.A. Rayner, T.M. Smith, D.C. Stokes and W. Wang (2002): An  
588 improved in situ and satellite SST analysis for climate. *J. Climate* **15**, 1609-1625.

589 Sagawa, T. and K. Ikehara (2008): Intermediate water ventilation change in the  
590 subarctic northwest Pacific during the last deglaciation. *Geophys. Res. Let.*, **35**,  
591 L24702, doi:10.1029/2008GL035133.

592 Sakaguchi, Y. (1989): Some pollen records from Hokkaido and Sakhalin. *Bull. Dpt.*  
593 *Geography, Univ. Tokyo*, **21**, 1-17.

594 Sawada, K., N. Handa and T. Nakatsuka (1998): Production and transport of long-chain  
595 alkenones and alkyl alkenoates in a sea water column in the northwestern Pacific  
596 off central Japan. *Mar. Chem.*, **59**, 219-234.

597 Seki, O., K. Kawamura, T. Nakatsuka, K. Ohnishi, M. Ikehara and M. Wakatsuchi  
598 (2003): Sediment core profiles of long-chain *n*-alkanes in the Sea of Okhotsk:

599       Enhanced transport of terrestrial organic matter from the last deglaciation to the  
600       early Holocene. *Geophys. Res. Lett.*, **30**, 1001.

601       Seki, O, K. Kawamura, M. Ikehara, T. Nakatsuka and T. Oba (2004): Variation of  
602       alkenone sea surface temperature in the Sea of Okhotsk over the last 85 kyrs. *Org.*  
603       *Geochem.*, **35**, 347-354.

604       Ternois, Y., K. Kawamura, L. Keigwin, N. Ohkouchi and T. Nakatsuka (2001): A  
605       biomarker approach for assessing marine and terrigenous inputs to the sediments of  
606       Sea of Okhotsk for the last 27,000 years. *Geochim. Cosmochim. Acta*, **65**, 791-802.

607       Thompson, P.R. and N.J. Shackleton (1980): North Pacific paleoceanography: late  
608       Quaternary coiling variations of planktonic foraminifer *Neogloboquadrina*  
609       *pachyderma*. *Nature*, **287**, 829-833.

610       Usui, T., S. Nagao, M. Yamamoto, K. Suzuki, I. Kudo, S. Montani, A. Noda and M.  
611       Minagawa (2006): Distribution and sources of organic matter in surficial sediments  
612       on the shelf and slope off Tokachi, western North Pacific, inferred from C and N  
613       stable isotopes and C/N ratios. *Mar. Chem.*, **98**, 241–259.

614       Yamamoto, S. (2000): A basic investigation for high resolution analysis of  
615       paleo-climatic changes by the tetramethyl ammonium hydroxide (TMAH) method.  
616       *Bull. Faculty Education, Soka Univ.*, **49**, 61-78 (in Japanese).

617       Yamamoto, M., M. Yamamuro and R. Tada (2000): Late Quaternary records of organic  
618       carbon, calcium carbonate and biomarkers from Site 1016 off Point Conception,  
619       California margin. *Proc. ODP, Sci. Res.*, **167**, 183-194.

620       Yamamoto, M., H. Kayanne and M. Yamamuro (2001): Characteristics of organic  
621       matter in lagoonal sediments from the Great Barrier Reef. *Geochem. J.*, **35**,  
622       385-401.

623 Yamamoto, M. (2004): Data Report: Organic carbon, and alkenone sea-surface  
624 temperature from Sites 1175, 1176, and 1178, Nankai Trough. *Proc. ODP, Sci. Res.*,  
625 **190**, 196, 1-10.

626 Yamamoto, M., T. Oba, J. Shimamune and T. Ueshima (2004): Orbital-scale anti-phase  
627 variation of sea surface temperature in mid-latitude North Pacific margins during  
628 the last 145,000 years. *Geophys. Res. Lett.*, **31**, L16311,  
629 doi:10.1029/2004GL020138.

630 Yamamoto, M., Y. Ichikawa, Y. Igarashi and T. Oba (2005a): Late Quaternary variation  
631 of lignin composition in Core MD012421 off central Japan, NW Pacific.  
632 *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **229**, 179-186.

633 Yamamoto, M., R. Suemune and T. Oba (2005b): Equatorward shift of the subarctic  
634 boundary in the northwestern Pacific during the last deglaciation. *Geophys. Res.*  
635 *Lett.*, **32**, L05609, doi:10.1029/2004GL0201903.

636 Yamamoto, M., A. Shimamoto, T. Fukuhara, H. Naraoka, Y. Tanaka and A. Nishimura  
637 (2007): Seasonal and depth variations in molecular and isotopic alkenone  
638 composition of sinking particles from the western North Pacific. *Deep-Sea Res. I*,  
639 **54**, 1571-1592.

640 Yamamoto, M. (2009): Response of mid-latitude North Pacific surface temperatures to  
641 orbital forcing and linkage to the East Asian summer monsoon and tropical  
642 ocean-atmosphere interactions. *J. Quat. Sci.*, in press.

643

## Figure captions

Fig. 1. Map showing the locations of Core GH02-1030, previously studied core sites (PC-2 and PC4; Seki *et al.*, 2004, MD01-2412; Harada *et al.*, 2006a, PC-6; Minoshima *et al.*, 2007, MD01-2421; Yamamoto *et al.*, 2005b; PC-9; Ishiwatari *et al.*, 2001, MD01-2408; Fujine *et al.*, 2006) and sediment trap sites (JT-2; Sawada *et al.*, 1998, KNOT, 50N and 40N; Harada *et al.*, 2006b, WCT-2; Yamamoto *et al.*, 2007).

Fig. 2. Stratigraphic column of Core GH02-1030 (Ikehara *et al.*, 2006).

Fig. 3. Age-depth model of Core GH02-1030. Open circles indicate the samples that were not used for the age-depth model.

Fig. 4. Changes in (A) total organic carbon (TOC), (B)  $C_{37:2}$  and  $C_{37:3}$  alkenone concentrations, (C)  $U_{37}^K$ -derived temperature, (D) the concentrations of short-chain  $n$ - $C_{14}$ - $C_{18}$  fatty acids (SCFAs) and (E) long-chain  $n$ - $C_{26}$ - $C_{30}$  fatty acids (LCFAs), (F) the ratio of LCFAs to SCFAs (LCFA/SCFA), (G) long-chain  $C_{27}$ ,  $C_{29}$ , and  $C_{31}$   $n$ -alkane concentration and (H) the carbon preference index of  $n$ -alkanes ( $C_{24}$ - $C_{34}$ ;  $CPI_{NA}$ ), in (I)  $\Sigma 8$ , (J)  $\Delta$ , (K) S/V, (L) C/V, (M) Ad/Al (solid circle = Ad/Al<sub>v</sub>; open circle = Ad/Al<sub>s</sub>), (N) vegetation pattern reconstructed based on pollen assemblages (Yaeko Igarashi, unpublished data), and (O) reconstructed sea level (Lambeck *et al.*, 2002) in Core GH02-1030 during the last 23,000 years. YD = Younger Dryas period, BA = Bølling-Allerød period, OD = Oldest Dryas period, and LGM = Last Glacial Maximum.

Fig. 5. (A) Alkenone temperature records from Core GH02-1030 during the last 23,000

years and those off northeastern Japan (PC-6; Minoshima *et al.*, 2007) and off central Japan (MD01-2421; Yamamoto *et al.*, 2005b; Isono *et al.*, 2009). (B) Alkenone temperature records from the Sea of Okhotsk (PC-2 and PC4; Seki *et al.*, 2004, MD01-2412; Harada *et al.*, 2006a) and those in the Sea of Japan (PC-9; Ishiwatari *et al.*, 2001, MD01-2408; Fujine *et al.*, 2006) during the last 23,000 years. The temperatures were calculated using an equation obtained by a culture-based calibration (Prah *et al.*, 1988).

Fig. 6. Changes in sinking flux of alkenones (kinked line),  $U_{37}^K$ -based temperature (open circle) in 1998 at 39°N, 147°E (Yamamoto *et al.*, 2007), and the flux-weighted annual average  $U_{37}^K$ -based temperatures (closed circles) calculated if we assume that the onset of alkenone production is delayed month by month.

Fig. 7. Schematic diagrams showing the development of an alluvial fan and changes in the erosion and transportation of terrestrial soil and organic debris to study site in response to marine transgression since the last glacial maximum. Arrow thickness indicates the amount of transportation.

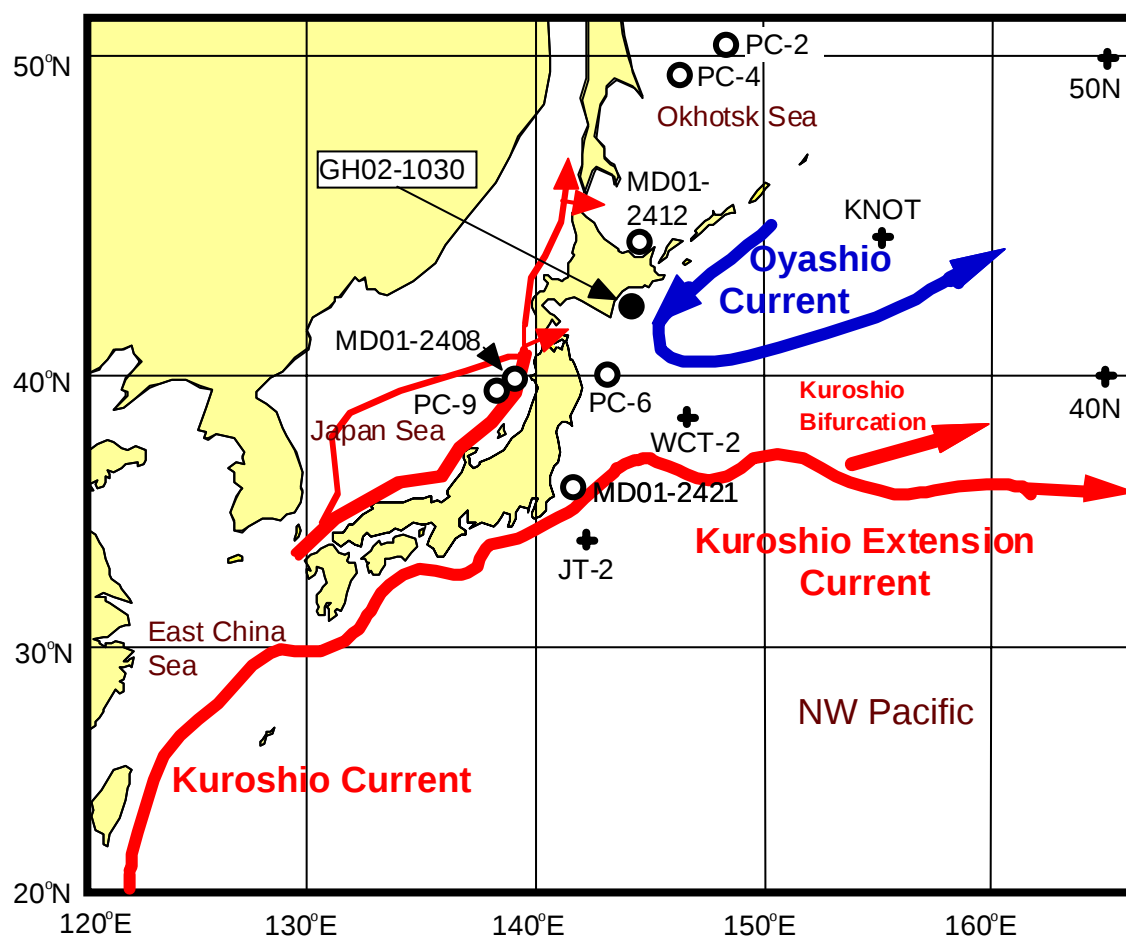


Fig. 1

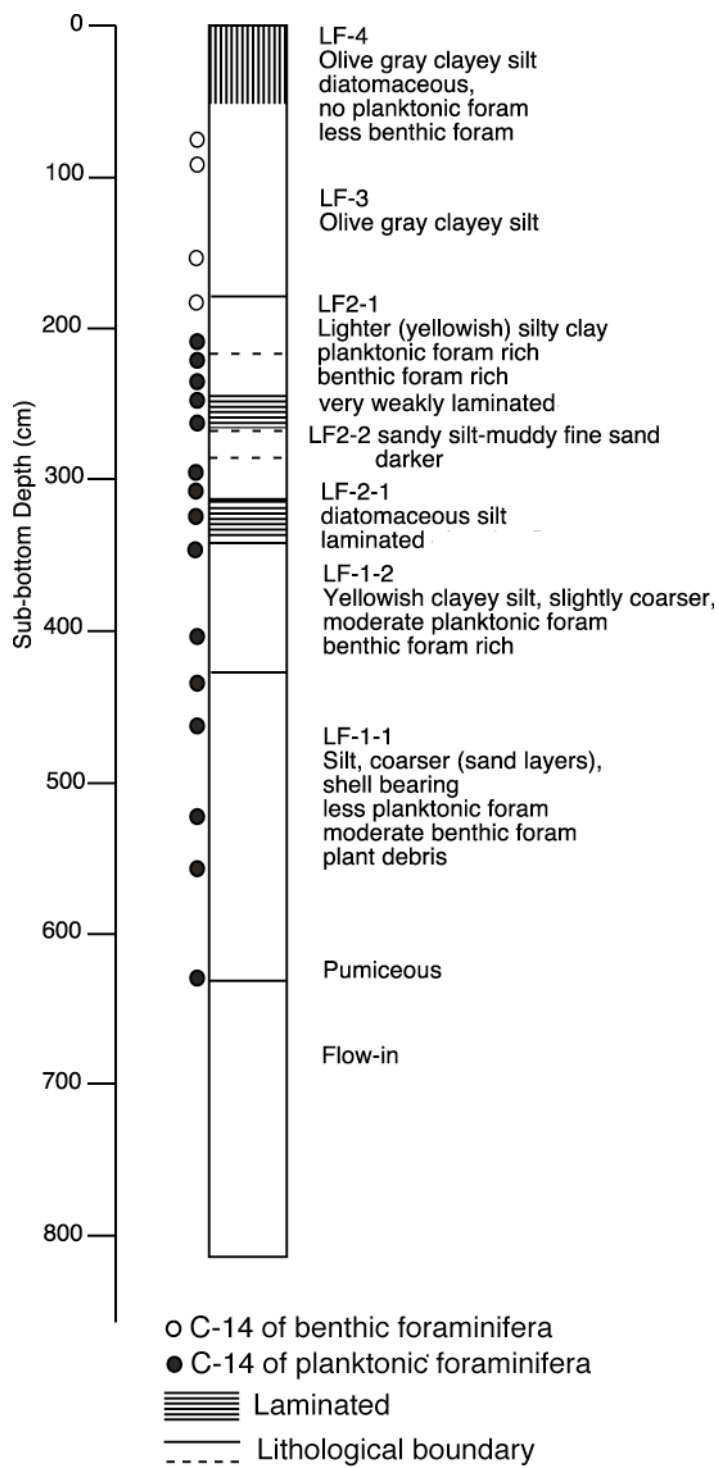
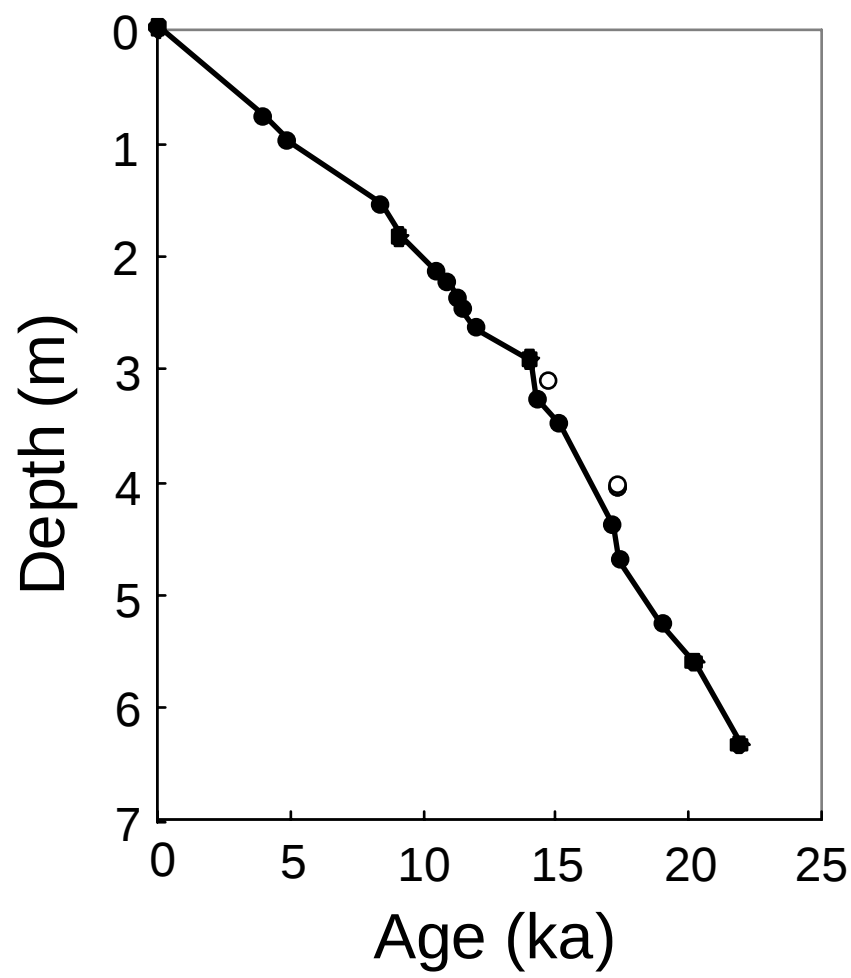


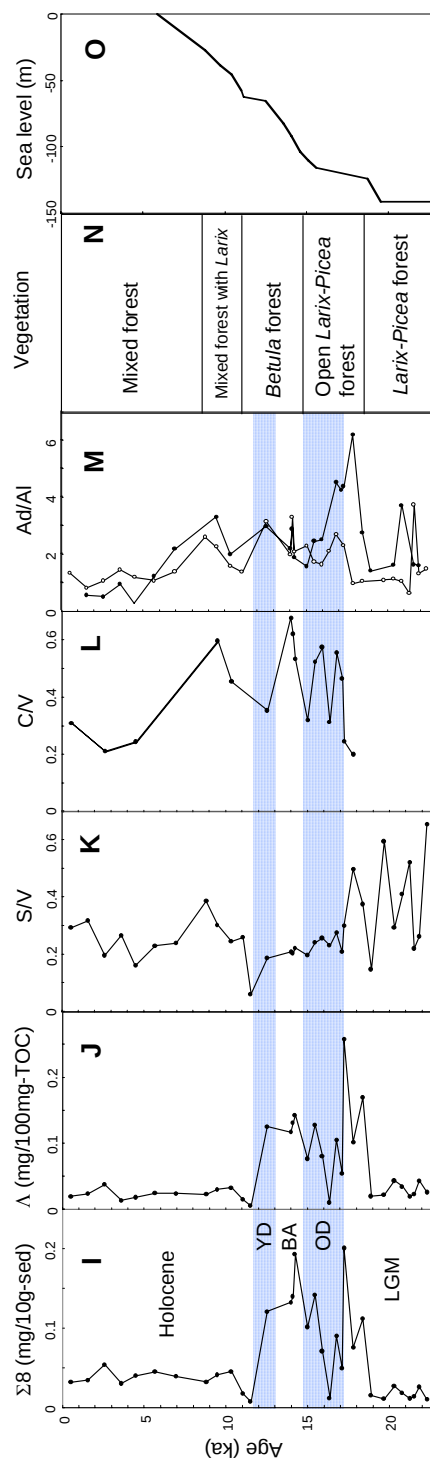
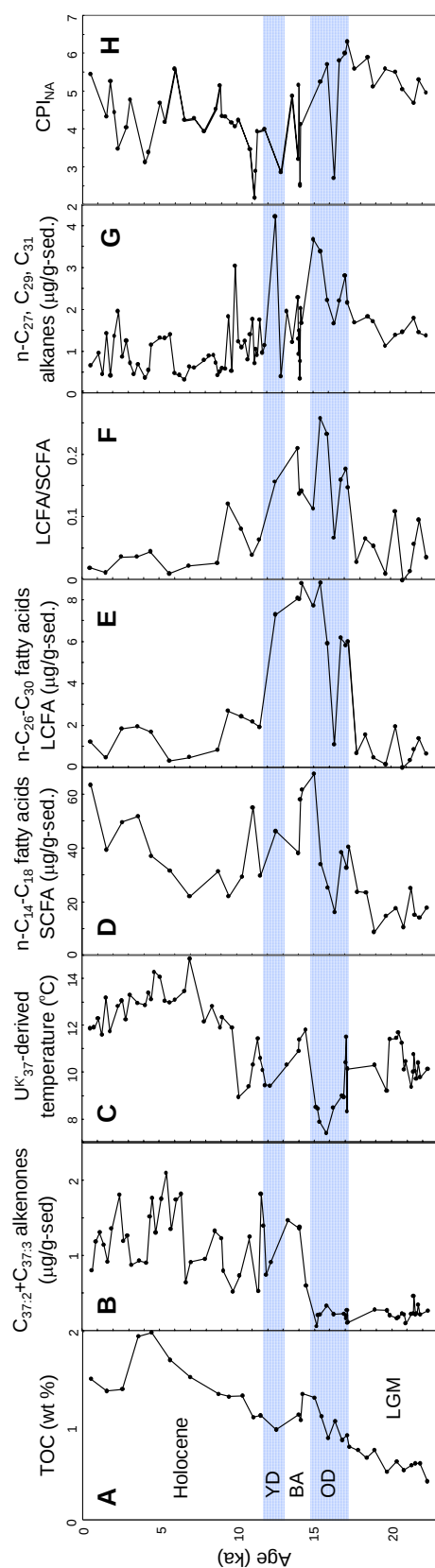
Fig. 2



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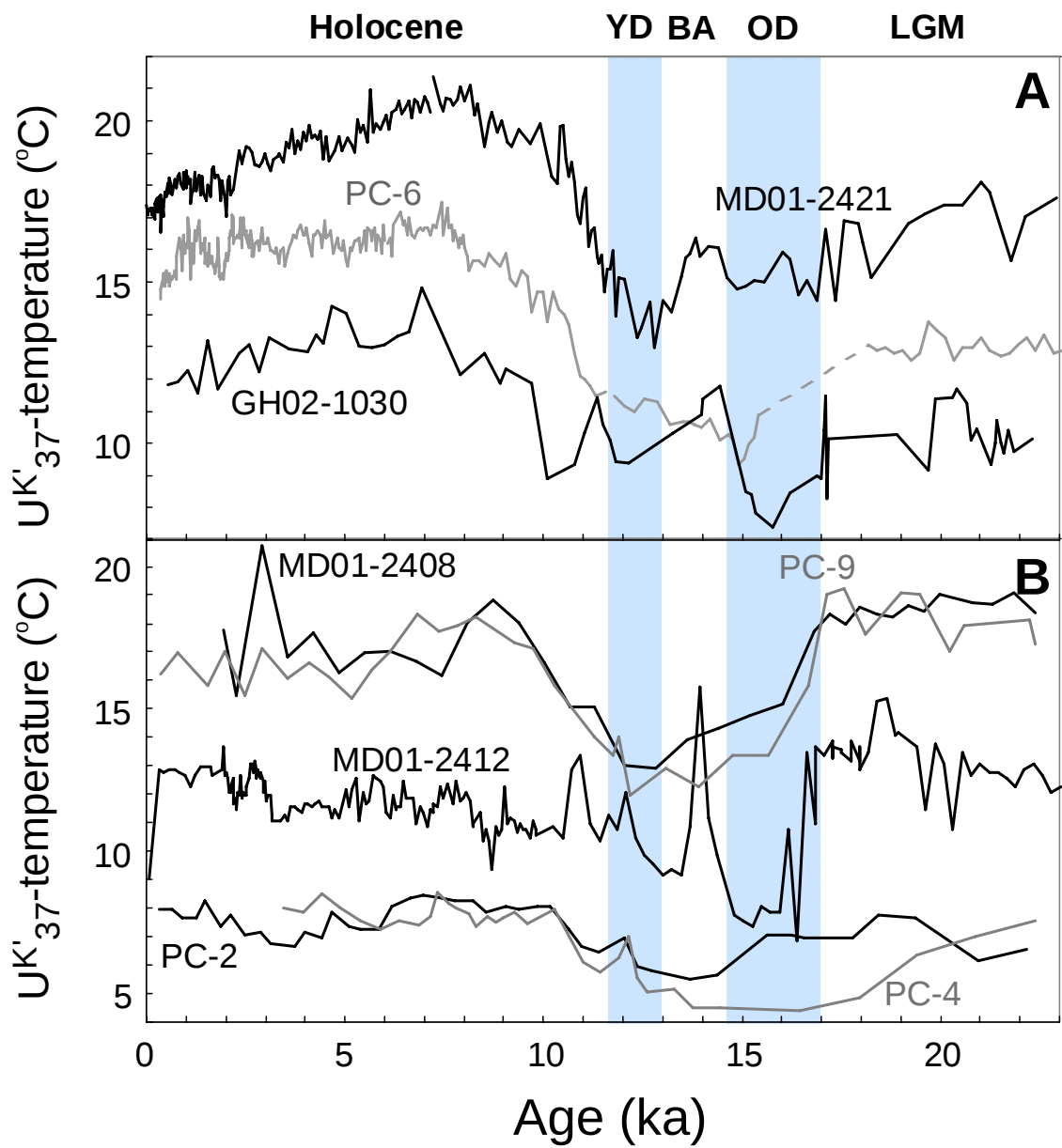
693 Fig. 3

694



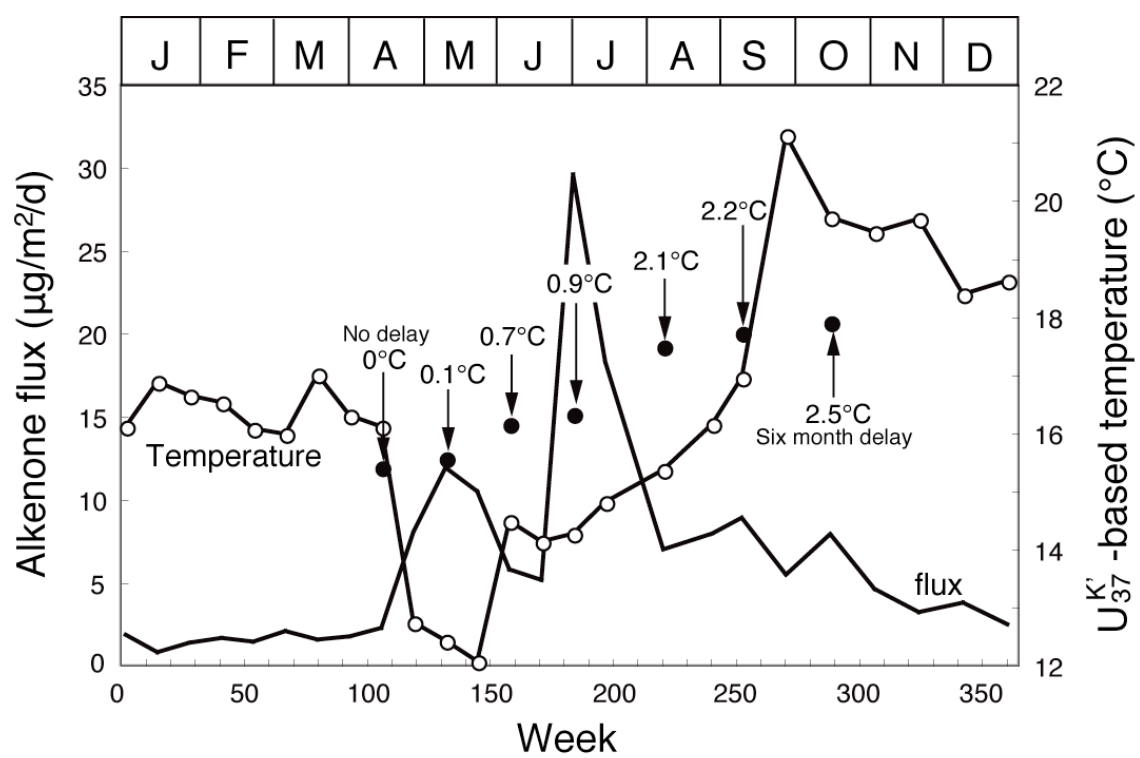
695

696 Fig. 4



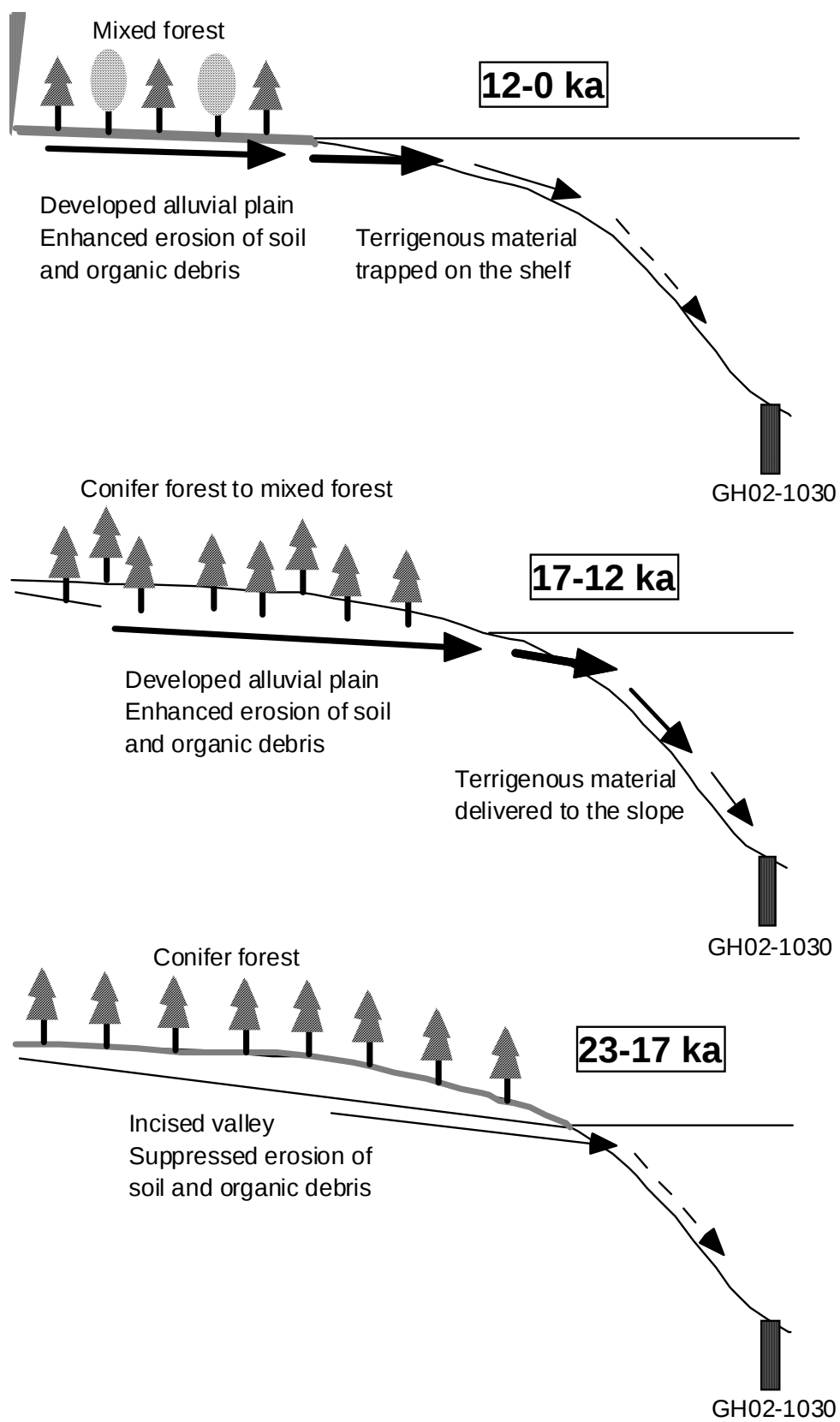
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698 Fig.5



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700 Fig 6



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702 Fig. 7