Response of benthic foraminifera to the organic carbon accumulation rates in the Okinawa Trough, East China Sea and in the Ryukyu fore Arc region, northwest Pacific

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1. Introduction

The biological and geochemical properties of benthic foraminifera preserved in the ocean sediments have been used extensively for paleoceanographic reconstruction. The faunal analyses of benthic foraminifera have been exploited either as tools to reconstruct the past changes in deep water conditions (Schnitker, 1979; Sen Gupta et al., 1982; Streeter and Lavery, 1982; Miao and Thunell, 1993) or as indicators of surface ocean productivity (Loubere and Banonis, 1987; Herguera and Berger, 1991; Herguera, 1992). The simple relationships between benthic faunas and environment may never been found because different parts of the fauna respond to different environmental variables (Streeter and Lavery, 1982) However, a close relationship between abundance of benthic foraminifera and flux of organic matter reached sediment surface has been reported from the world ocean, e.g. northeast Atlantic (Loubere and Banonis, 1987; Gooday, 1993), eastern equatorial Pacific (Pedersen et al., 1988), western equatorial Pacific (Herguera, 1992), South China and Sulu Seas (Miao and Thunell, 1993; Rathburn and Corliss, 1994), eastern South Atlantic Polar Front (Mackensen et al., 1993) and Adriatic Sea (Jorisen et al., 1992).

The stable isotopic composition of benthic foraminiferal tests are useful key for study of the ocean history. The stable carbon isotopic composition of benthic foraminiferal tests is an obvious tracer of the carbon cycle in deep ocean waters or as an indicator of surface productivity (Shackleton, 1977; Broecker, 1982; Zahn et al., 1986; Curry et al., 1988; Sarnthein et al., 1988; Mix et al., 1991; Vergnaud Grazzini and Pierre, 1992). Two benthic foraminifera, *Uvigerina peregrina* and *Cibicidoides wuellerstorfi*, have been widely used by paleoceanographer to reconstruct the past deep water or bottom water circulation (e.g. Duplessy et al., 1984; Zahn et al., 1987; Mix et al., 1991; Mackensen et al., 1993).

Because *C. wuellerstorfi* lives in nearly above the sediment surface (Rathburn and Corliss, 1994), this species secretes calcite with very close carbon isotopic composition to $\delta^{13}C_{\Sigma CO2}$ bottom water (Woodruff et al., 1980; Belanger et al., 1981; Graham et al., 1981; Zahn et al., 1986, 1987). In contrast, *U. peregrina* lives in the top of sediment, its $\delta^{13}C$ value is influenced by the $\delta^{13}C_{\Sigma CO2}$ of both pore water and overlying bottom water (Zahn et al., 1986; Vergnaud Grazzini and Pierre, 1992). Since ^{13}C-depleted CO_2 was released into the pore water by organic matter decomposition after its deposition, $\delta^{13}C$ of *U. peregrina* is strongly affected by changes of organic carbon flux from the surface ocean productivity (McCorkle *et al.*, 1985; Zahn *et al.*, 1986). Consequently, $\delta^{13}C$ departure between *U. peregrina* and *C. wuellerstorfi* may serve to document paleoproductivity changes of the ocean (Zahn et al., 1986).

In this study, the abundance fluctuations of *U. peregrina* and *C. wuellerstorfi* and their carbon isotopic compositions were analyzed to investigate the response of benthic foraminifera lived on the sea floor to the paleoproductivity changes in the surface ocean.

2. Materials and methods

Two marine sediment cores used for the present study, PN-3 and SST-4, were collected from the Okinawa Trough, East China Sea and from the Ryukyu Fore Arc region, northwest Pacific, respectively, during the MASFLEX 1994 cruise of the R/V *Bosei Maru* (Fig. 1). Core PN-3, 430 cm in length, was raised from 1058 m water depth at Lat. 28°05.98'N, Long. 127°20.55'E, and core SST-4, 260 cm in length, was taken from 2156 m water depth at Lat. 26°56.88'N, Long. 129°00.63'E.

Core PN-3 consists of homogeneous grayish olive to olive gray colored silt with brownish black part (15 cm thick of oxidized layer) at the core top (Fig. 2). The fine sand layers and molluscan shell fragments were found occasionally at 280 cm, 380 cm and 180 cm, 220 cm, 410 cm from core top, respectively. A volcanic ash layer is intercalated at 320 cm depth of the core. High magnetic susceptibility layer is found at the 40 cm from the core top. The SST-4 core consists of homogeneous grayish olive to olive gray colored silt from core top to 210 cm depth and turbidite sand layers between 210 cm and 250 cm (Fig. 2).

Oxygen and carbon isotope analyses were carried out on a planktonic foraminiferal species, *Globigerinoides sacculifer*, and two benthic foraminiferal species, *C. wuellerstorfi* and *U. peregrina*. We used 30-40 specimens of 355-425 μm diameter for *G. sacculifer*. For isotope analyses of *C. wuellerstorfi* and *U. peregrina*, we used 2-15 specimens larger than 250 μm. Isotopic measurement was carried out using a Finnigan MAT 251 mass spectrometer. The oxygen and carbon isotopic data are reported in δ notation relative to the PDB standard. Ten replicate measurements of Solnhofen Limestone sub-standard gave a precision of 0.03‰ for oxygen and 0.01‰ for carbon.

About 350-400 specimens of *G. sacculifer* of 300-500 μm diameter were used for the AMS ^{14}C measurement. Sample preparation and graphite target preparation were conducted at our laboratory using a batch preparation method (Kitagawa *et al.*, 1993) and the AMS^{14}C measurement was carried out at the Dating and Materials Research Center, Nagoya University. After corrected for reservoir age (Bard, 1988), all AMS^{14}C ages were calibrated into the calendar year age, using the calibration curve of Stuiver and Pearson (1993) for ^{14}C age younger than 8 kyr and the calibration equation of Bard *et al.* (1993) and Bard, 1996 (pers. com.) for ^{14}C ages older than 8 kyr (Table 1). The calibrated ^{14}C ages are consistent with the $\delta^{18}O$ stratigraphy (Wahyudi, 1997). We estimate that cores PN-3 and SST-4 record continuous deposition during the past 40 kyr and 30 kyr, respectively. Age of each sample is estimated from interpolating and extrapolating between six age control points (Table 1).

For the organic matter analyses, 750 mg of the powdered sediments were decalcified with 1 N HCl solution for several hours, centrifuged and washed with distilled water. The carbonate free sediments were freeze-dried and crushed into powder. Then, these were used for quantitative analysis of organic carbon content using a sealed tube

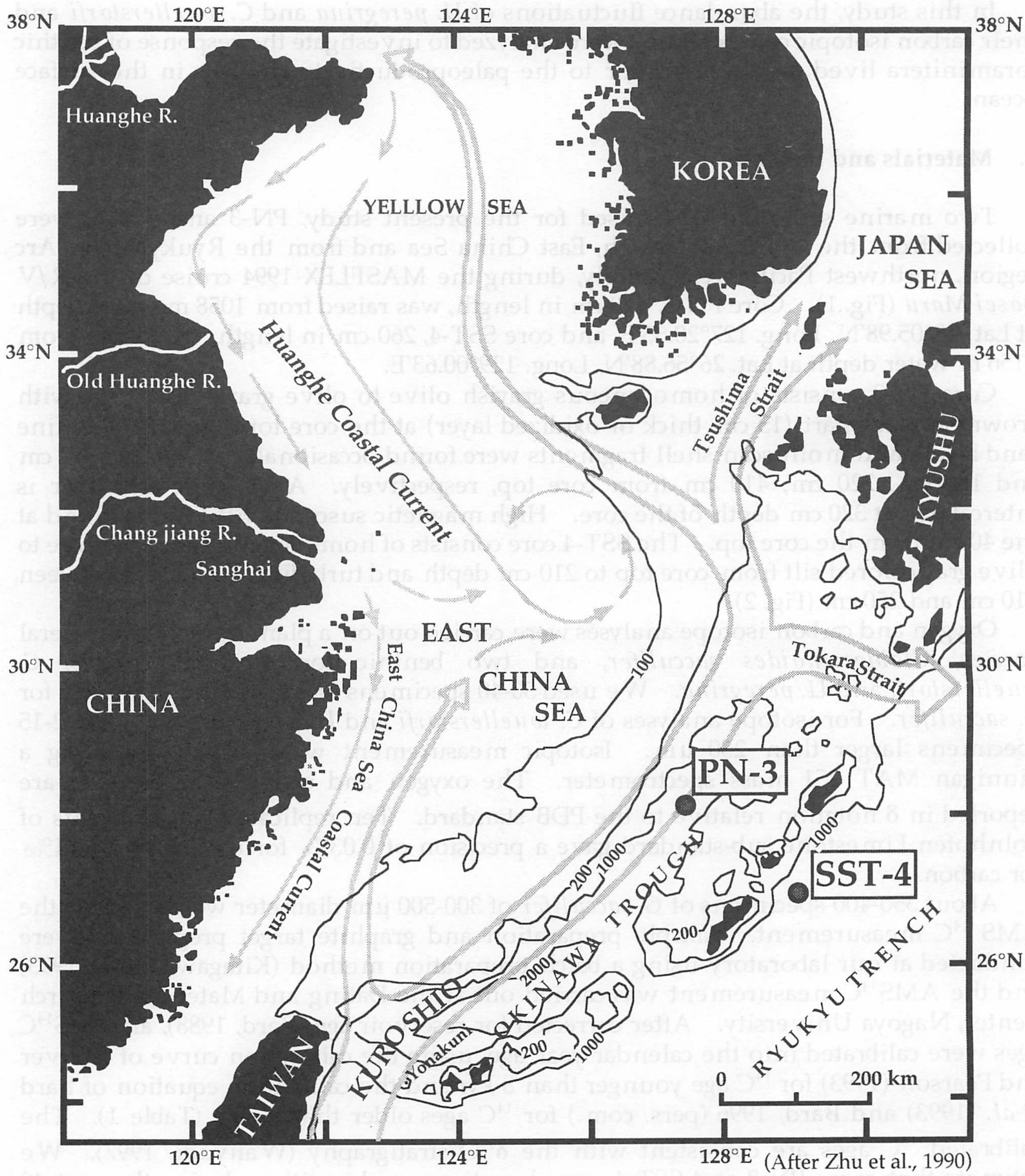

Figure 1. Location of cores PN-3 and SST-4.

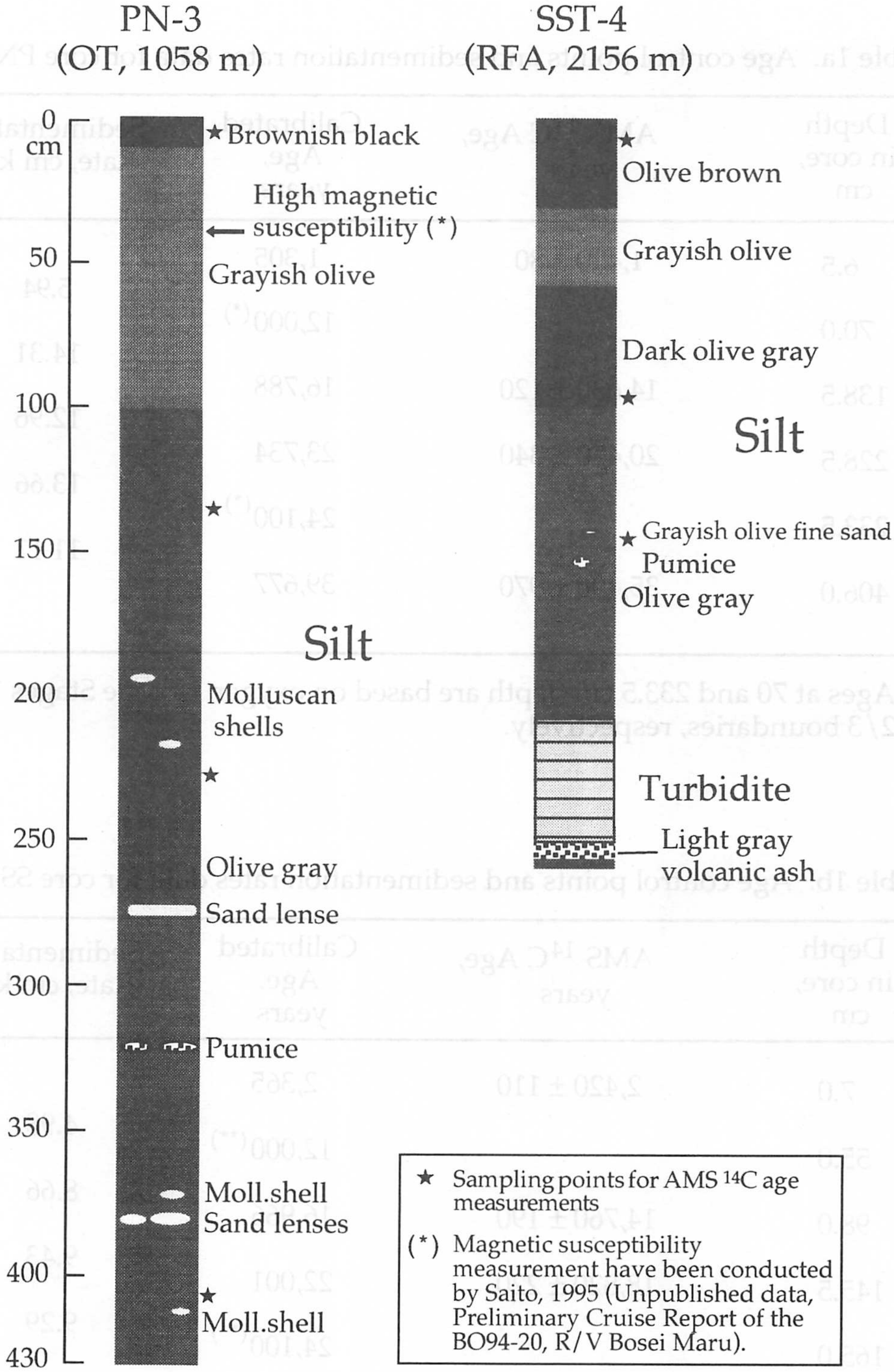

Figure 2. Lithology of cores PN-3 from Okinawa Trough (OT) and SST-4 from Ryukyu Fore Arc region (RFA), showing the sampling points for AMS ^{14}C age measurements.

Table 1a. Age control points and sedimentation rates data for core PN-3.

Depth in core, cm	AMS ^{14}C Age, years	Calibrated Age, years	Sedimentation Rate, cm kyr^{-1}
6.5	1,420 ± 80	1,305	
			5.94
70.0		12,000(*)	
			14.31
138.5	14,630 ± 120	16,788	
			12.96
228.5	20,470 ± 340	23,734	
			13.66
233.5		24,100(*)	
			11.11
406.0	35,400 ± 970	39,677	

(*) Ages at 70 and 233.5 cm depth are based on oxygen isotope Stages 1/2 and 2/3 boundaries, respectively.

Table 1b. Age control points and sedimentation rates data for core SST-4.

Depth in core, cm	AMS ^{14}C Age, years	Calibrated Age, years	Sedimentation Rate, cm kyr^{-1}
7.0	2,420 ± 110	2,365	
			4.98
55.0		12,000(**)	
			8.66
98.0	14,760 ± 190	16,966	
			9.43
145.5	18,820 ± 220	22,001	
			9.29
165.0		24,100(**)	

(**) Ages at 55.0 and 165.0 cm depth are based on oxygen isotope Stages 1/2 and 2/3 boundaries, respectively.

combustion method described by Minagawa *at al.* (1984). Organic carbon mass accumulation rate (MAR) was determined using the following equation (e.g. Pedersen *et al.*, 1991; Thunell *et al.*, 1992):

$$C_{org}\ \mathrm{MAR}\ (\mathrm{g\ cm^{-2}\ kyr^{-1}}) = \rho \quad \nu \quad (C_{org})$$

where ν is sedimentation rate (in cm per kyr), ρ is sediment dry bulk density (in grams per cubic centimeter).

3. Response of benthic foraminiferal abundance to surface productivity

Both *C. wuellerstorfi* and *U. peregrina* show high abundance during the stages 2 and 3 (Fig. 3). Generally, the abundance of the infaunal species, *U. peregrina,* is higher and is more fluctuated compared with epifaunal *C. wuellerstorfi* throughout the core. In core PN-3, the individual number of *U. peregrina* larger than 180 μm in stage 1 is fewer than 50 per gram of sediment and increases to more than 50 (up to ~ 350) in the stages 2 and 3, while that of *C. wuellerstorfi* increases from fewer than 10 in the stage 1 to more than 50 at the stages 2 and 3 (Fig. 3). In core SST-4, *U. peregrina* increases from fewer than 20 in stage 1 to more than 100 (up to ~200) in stages 2 and 3, while *C. wuellerstorfi* increases from fewer than 10 in the stage 1 to more than 50 at the stages 2 and 3 (Fig. 3).

Higher abundance of *U. peregrina* and *C. wuellerstorfi* during the stages 2 and 3 than in stage 1 corresponds to the fluctuation of organic carbon accumulation rates (Fig. 4). The same trend has been found in somewhere else (e.g. the northeast United States continental shelf (Miller and Lohmann, 1982); the eastern equatorial Pacific (Pedersen et al., 1988); California continental margin (Quinterno and Gardner, 1987)). Gooday (1988) reported that some deep sea benthic species including *C. wuellerstorfi* (his *Planulina wuellerstorfi*) from the northeast Atlantic, are phytodetritus-feeder and that their abundance increase when the phytodetritus flux increases.

Although the complex factors such as difference in water mass and other sediment properties control the abundance of the benthic foraminifera, generally the most important factor controlling the high production of benthic foraminifera is a high concentration of organic matter derived from the high productivity in the surface water (Pedersen et al., 1988; Herguera, 1992; Herguera and Berger, 1992; Jorissen et al., 1992; Mackensen et al., 1993; Miao and Thunell, 1993; Rathburn and Corliss, 1994).

Since the high concentration and accumulation rates of organic carbon in both cores PN-3 and SST-4 is due to a high productivity during the glacial (Wahyudi, 1997), we suggest that abundance of *C. wuellerstorfi* and *U. peregrina* are controlled by the fluctuation of surface productivity.

4. $\delta^{13}C$ departure between *Uvigerina peregrina* and *Cibicidoides wuellerstorfi*: implication for variations of surface productivity

The carbon isotope records of *U. peregrina* shows low values during the stages 2 and 3 and high values in stage 1 (Figs. 5). The magnitude of glacial to Holocene

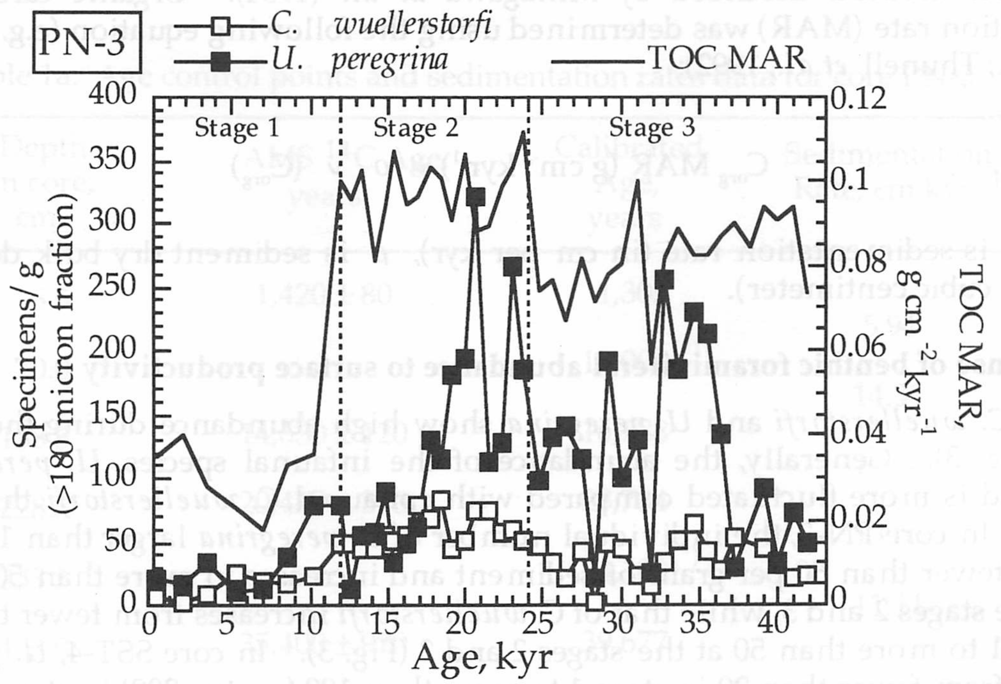

Figure 3a. Benthic foraminiferal abundances and organic carbon mass accumulation rates (TOC MAR) profiles as a function of age in core PN-3.

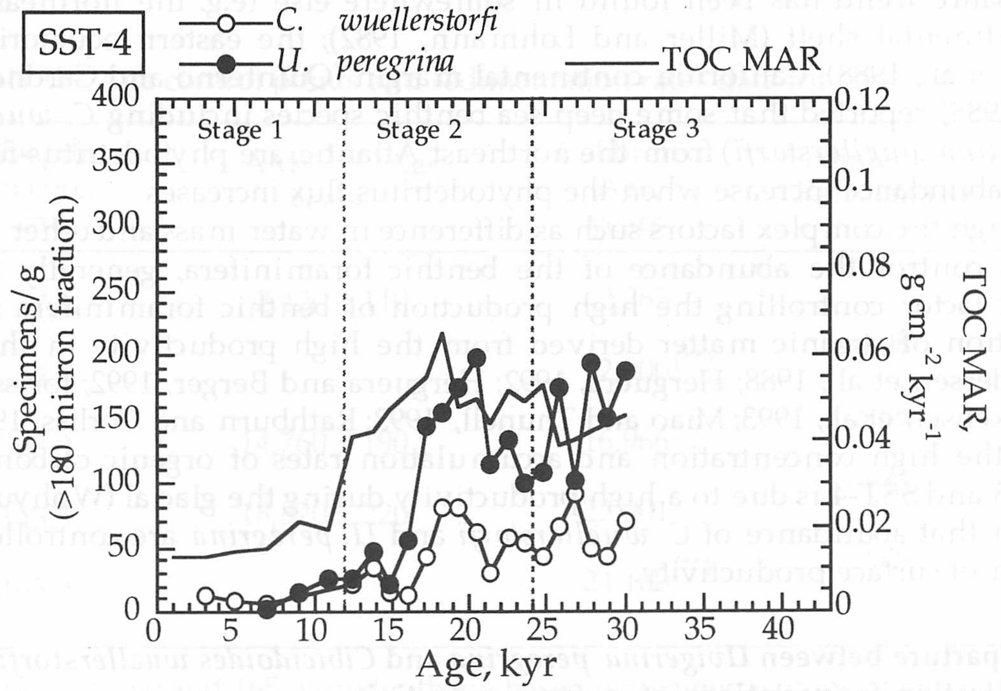

Figure 3b. Benthic foraminiferal abundance and organic carbon mass accumulation rates (TOC MAR) profiles as a function of age in core SST-4.

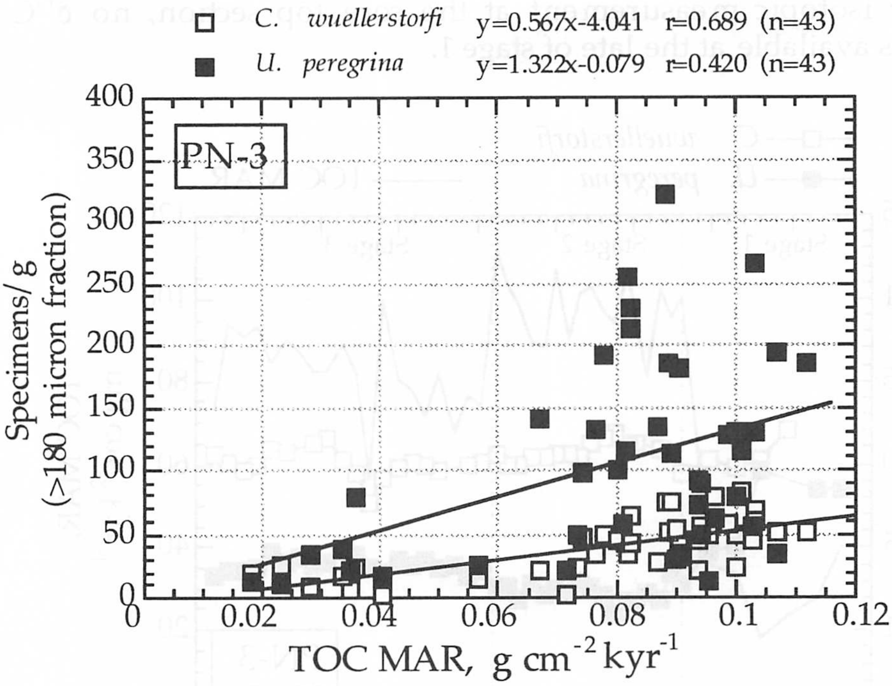

Figure 4a. Plots of benthic foraminiferal abundances and organic carbon mass accumulation rates (TOC MAR) in core PN-3.

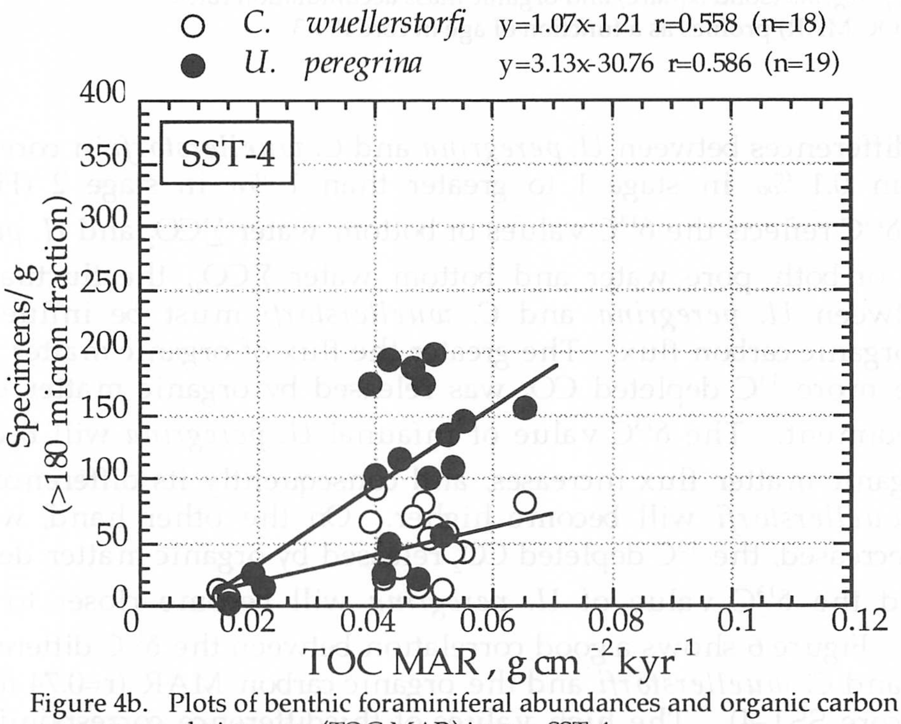

Figure 4b. Plots of benthic foraminiferal abundances and organic carbon mass accumulation rates (TOC MAR) in core SST-4.

change in $\delta^{13}C$ is about 0.8 ‰. Because there is not enough number of large specimens for isotopic measurement at the core top section, no $\delta^{13}C$ record of *C. wuellerstorfi* is available at the late of stage 1.

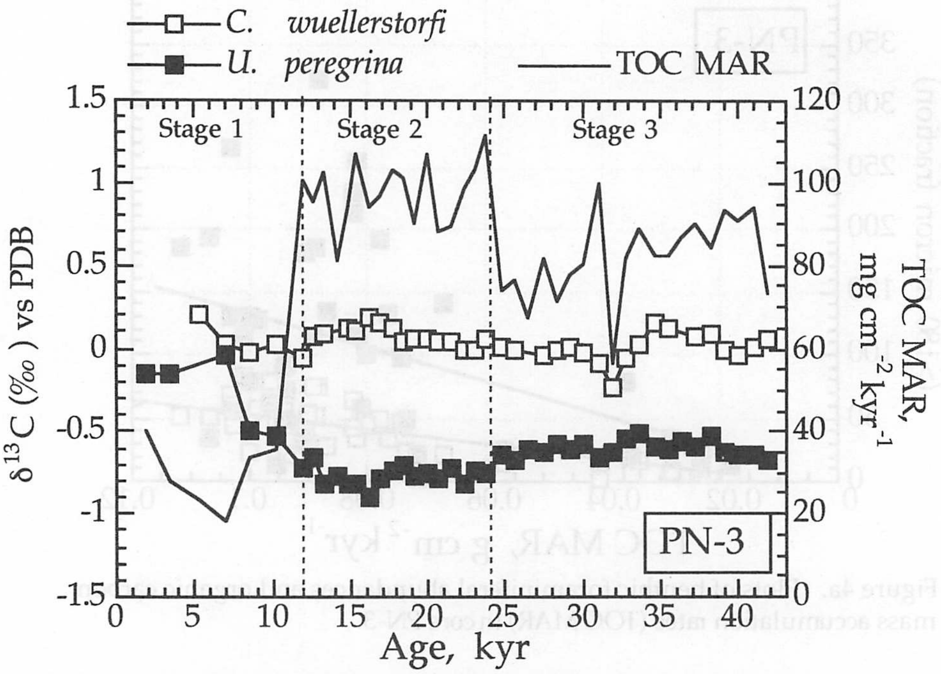

Figure 5a. Carbon isotope ratio of *C. wuellerstorfi* (open square), *U. peregrina* (solid square) and organic mass accumulation rates (TOC MAR) profiles as a function of age in core PN-3.

The $\delta^{13}C$ differences between *U. peregrina* and *C. wuellerstorfi* in core PN-3 varies from less than 0.1 ‰ in stage 1 to greater than 1 ‰ in stage 2 (Fig. 5). If *C. wuellerstorfi* $\delta^{13}C$ reflects the $\delta^{13}C$ values of bottom water $\sum CO_2$ and *U. peregrina* $\delta^{13}C$ reflects those of both pore water and bottom water $\sum CO_2$, the fluctuation in $\delta^{13}C$ difference between *U. peregrina* and *C. wuellerstorfi* must be influenced by the variation of organic carbon flux. The greater the flux of organic matter reaching the sediment, the more ^{13}C depleted CO_2 was released by organic matter decomposing within the sediment. The $\delta^{13}C$ value of infaunal *U. peregrina* will become lighter when the organic matter flux increases, and consequently its difference to the $\delta^{13}C$ value of *C. wuellerstorfi* will become higher. On the other hand, when organic matter flux decreased, the ^{13}C depleted CO_2 released by organic matter decomposition decreased, and the $\delta^{13}C$ value of *U. peregrina* will become closer to those of *C. wuellerstorfi*. Figure 6 shows a good correlation between the $\delta^{13}C$ difference between *U. peregrina* and *C. wuellerstorfi* and the organic carbon MAR (r=0.74 for core PN-3 and r=54 for core SST-4). The high values of thisdifference correspond to the high flux of organic carbon. Because the organic carbon MAR in cores PN-3 and SST-4 reflect the variability of the surface water productivity, we suggest that the $\delta^{13}C$

difference between *U. peregrina* and *C. wuellerstorfi* reflects the variation of surface water productivity in the Okinawa Trough and the Ryukyu Fore Arc region.

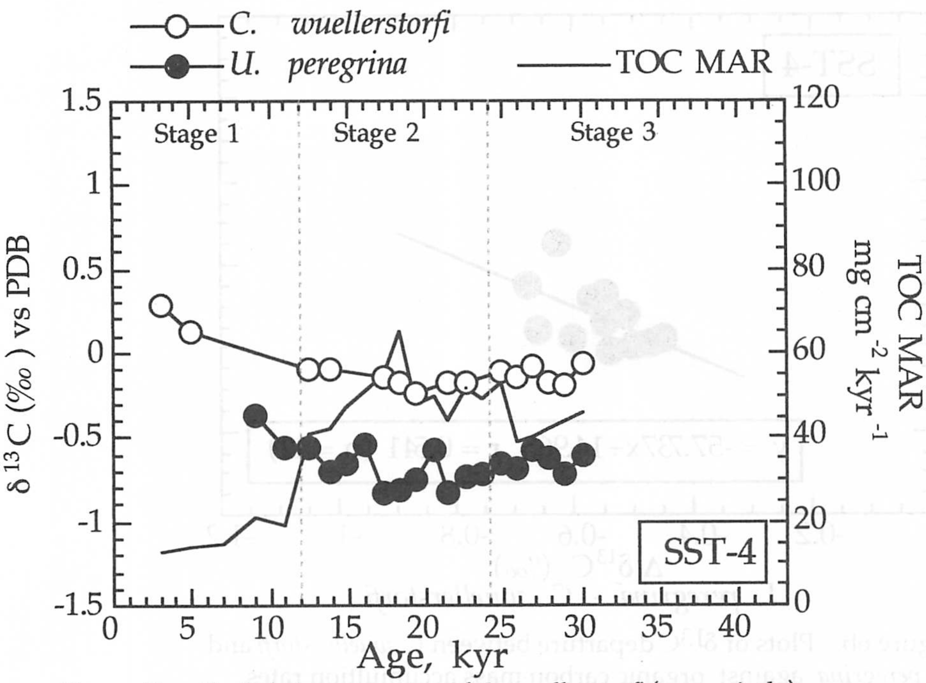

Figure 5b. Carbon isotope ratio of *C. wuellerstorfi* (open circle), *U. peregrina* (solidcircle) and organic carbon mass accumulation rates (TOC MAR) profiles as a function of age in core SST-4.

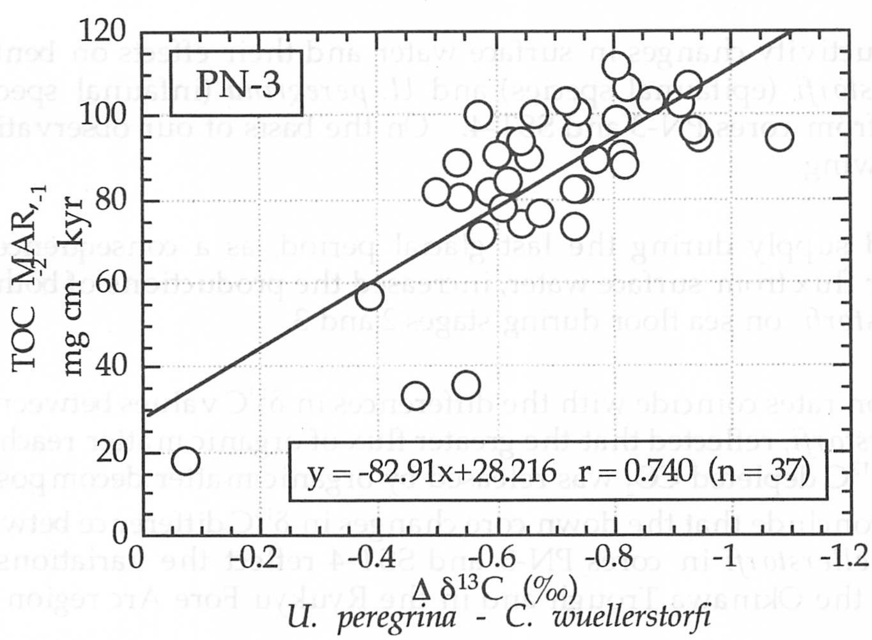

Figure 6a. Plots of $\delta^{13}C$ departure between *C. wuellerstorfi* and *U. peregrina* against organic carbon mass accumultion rates (TOC MAR) in core PN-3.

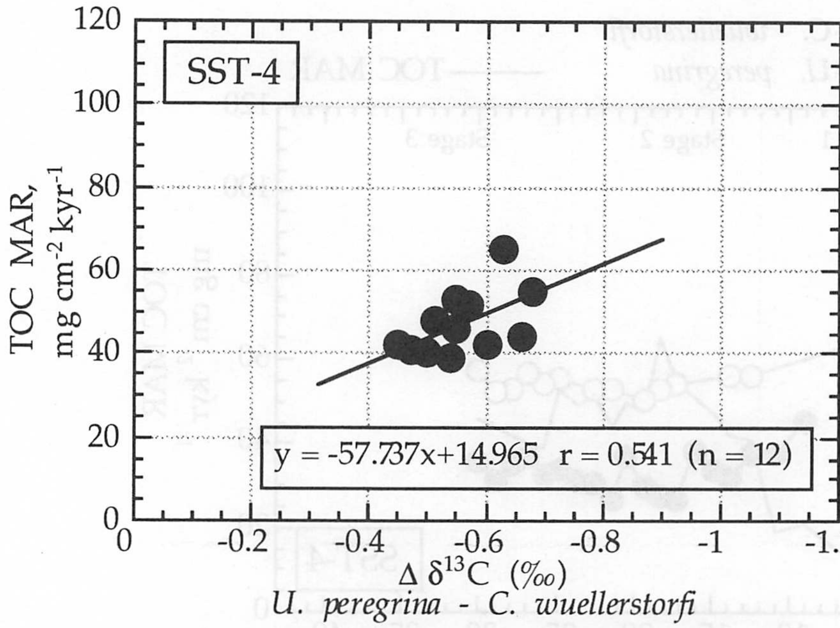

Figure 6b. Plots of $\delta^{13}C$ departure between *C. wuellerstorfi* and *U. peregrina* against organic carbon mass accumulation rates (TOC MAR) in core SST-4.

5. Summary

The last 42 kyr productivity changes in surface water and their effects on benthic foraminifera *C. wuellerstorfi* (epifaunal species) and *U. peregrina* (infaunal species) have been investigated from cores PN-3 and SST-4. On the basis of our observation, we conclude as the following.

1. The greater food supply during the last glacial period, as a consequence of enhanced organic matter flux from surface water, increased the productions of both *U. peregrina* and *C. wuellerstorfi* on sea floor during stages 2 and 3.

2. TOC accumulation rates coincide with the differences in $\delta^{13}C$ values between *U. peregrina* and *C. wuellerstorfi*, reflected that the greater flux of organic matter reaching the sediment, the more ^{13}C depleted CO_2 was released by organic matter decomposing within sediment. We conclude that the down core changes in $\delta^{13}C$ difference between *U. peregrina* and *C. wuellerstorfi* in cores PN-3 and SST-4 reflect the variations in organic matter fluxes in the Okinawa Trough and in the Ryukyu Fore Arc region for the last 42 kyr.

3. The productivity in surface water (as a food supplier) controlled the abundance

of organism lived on the sea floor. Decomposition of organic matter also play a role for controlling carbon isotopic composition of not only sea water $\sum CO_2$ in the water column but also the pore water $\sum CO_2$ in the sediment. It is a possibility that this $\delta^{13}C$ difference can be utilized as an indicator of the past changes in surface water productivity. These results provide new evidence for paleoceanographic history of the Okinawa Trough and the Ryukyu Fore Arc region.

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沖縄トラフ及び琉球前弧海域における有機炭素沈積量と底生有孔虫の応答

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浮遊性有孔虫 *Globigerinoides sacculifer* 殻の AMS ^{14}C 年代測定結果及び $\delta^{18}O$ カーブから PN-3 コア(沖縄トラフ)の最下部は約 4 万年、SST-4 コア(琉球前弧海域)の最下部は約 3 万年まで達していると判断される。PN-3 及び SST-4 コアの有機炭素沈積量の測定結果から、沖縄トラフ及び琉球前弧海域において最終氷期には後氷期に比べ生物生産が高かったと考えられる。海底表面に生息している底生有孔虫 *Cibicidoides wuellerstorfi* (epifauna)と堆積物の表層付近に生息している *Uvigerina peregrina* (infauna)の産出量及び両者の殻から測定された $\delta^{13}C$ 値の差は有機炭素沈積量と相関しており、このことは、海洋表層の生物生産量を直接反映していると考えられる。

以上の結果から、*C.wuellerstorfi* と *U. peregrina* の $\delta^{13}C$ 値の差は、海洋表層における生物生産の変動を示すインディケーターとして用いることができると示唆された。

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