Radiocarbon age differences between benthic–planktonic foraminifera in sediment cores from the Shatsky Rise, central North Pacific

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Benthic–planktonic foraminiferal radiocarbon age differences in deep-sea sediments are a useful paleo-proxy to estimate deep-water ventilation age from the last glacial maximum to the Holocene. However, it is very difficult to collect reasonable sediment cores for ventilation age reconstruction in the carbonate-corrosive Pacific Ocean. The Shatsky Rise, which is located in the central part of the North Pacific, is a peculiar spot in that carbonate sediments can be collected from abyssal depths. We analyzed benthic–planktonic foraminiferal radiocarbon age differences in two gravity core samples (Core NGC102 and Core NGC108) collected from the Shatsky Rise. The two cores consisted mostly of bioturbated calcareous ooze. Sedimentation rates were 1.4–5.3 cm/ka in Core NGC102 (2,612 m water depth) and 2.3–6.6 cm/ka in Core NGC108 (3,390 m water depth). Benthic–planktonic foraminiferal age differences showed large variances, from 7,010±90 to 180±130 years in Core NGC102 and from 2,730±80 to 580±110 years in Core NGC108. In Core NGC102, the age differences (6,440 years on average) in the mixed layer were approximately 4,700 years older than the modern North Pacific deep-water age, reflecting the upward mixing of old benthic foraminifera and low sedimentation rates. On the other hand, the age difference (2,470 years) at 14–16 cm depth may be approximately similar to the past deep-water age at that time. The age differences (180±130 to 280±140 years) at 22–28 cm depths (16–17 ka, corresponding to Heinrich stadial event 1) were remarkably smaller than the modern deep-water age. In Core NGC108, the benthic–planktonic age difference (990±200 years) at 15,700 cal BP was estimated to be 760 years younger than the modern deep-water age. This small age difference suggests an active ventilation event of Pacific deep waters during Heinrich stadial event 1; however, causes such as atmospheric 14C decrease and/or sediment mixing (e.g., bioturbation) cannot be excluded.

Key words: bioturbation, deep-water, foraminifera, North Pacific, radiocarbon

Introduction

The time series record of air bubbles in the Antarctic Vostok ice core suggests that atmospheric concentrations of CO2 during the last glacial maximum were approximately 90 ppm lower than during the Holocene (Petit et al., 1999). The glacial potential sink of CO2 lost from the atmosphere is thought to be the deep ocean, which is the largest carbon reservoir; e.g., the Pacific and Southern Oceans (Broecker et al., 2004). The deglacial increase of atmospheric CO2 and decrease in radiocarbon suggest the active release of 14C-depleted CO2 from old carbon reservoirs during the Heinrich stadial 1 episode. However, the source and process of the 14C-depleted CO2 are still unclear (Broecker and Barker, 2007; Broecker et al., 2008). In paleoceanographic studies, radiocarbon age differences between benthic and planktonic foraminifera (hereinafter B–P foraminiferal age differences) from the same horizon have been used to determine the ventilation age of deep water (Broecker et al., 1984, 1999, 2004, 2008; Shackleton et al., 1988; Duplessy et al., 1989; Adkins and Boyle, 1997; Ahagon et al, 2003). Recently, many studies of B–P foraminiferal age differences from the North Pacific have been reported (Galbraith et al., 2007; Okazaki et al., 2010; Lund, 2013; Davies-Walczak et al., 2014; Rae et al., 2014; Cook and Keigwin, 2015; Keigwin et al., 2004).
and Lehman, 2015). However, there are no data on B–P foraminiferal age differences for deep-sea sediments in the central North Pacific, because it is very difficult to collect reasonable sediment cores for ventilation age reconstruction in the carbonate-corrosive Pacific Ocean.

We analyzed B–P foraminiferal age differences in two gravity core samples collected from abyssal depths in the Shatsky Rise. Paleoceanographic data from the middle-latitude central North Pacific are lacking due to poor carbonate preservation on the abyssal plain. The Shatsky Rise, which is located in the central part of the North Pacific (Fig. 1) and has thick carbonate sediments, is an especially important area for understanding the Quaternary climate record (Kawahata et al., 1999; Ohkushi et al., 2000, 2003; Maeda et al., 2002).

In previous studies, the B–P foraminiferal age differences in the northwestern Pacific indicated a transient response of intermediate water ventilation during the last deglaciation (Ahagon et al., 2003). Kienast et al. (2006) documented a close relation between Eastern Pacific cooling and Atlantic overturning circulation during the last deglaciation (Heinrich stadial 1 episode). Thermohaline circulation change in the terminus of global deep-water circulation as the main cause of millennial scale climate changes needs to be evaluated. Thus, in this study we preliminarily report the B–P foraminiferal age differences in the Shatsky Rise and evaluate the influence of post-depositional processes. Additionally, we discuss the possibility of northern Pacific deep-water ventilation changes during the Heinrich stadial 1 episode.

Samples and methods

Two gravity cores Core NGC102 (32°19.84’N, 157°51.00’E; water depth 2,612 m) and Core NGC108 (36°36.85’N, 158°20.90’E; water depth 3,390 m) were taken from the Shatsky Rise in the central North Pacific Ocean during cruise NH95-2 Cruise of the R/V Hakurei-maru (Fig. 1). Core NGC102 consists mostly of homogeneous, yellowish-brown, calcareous oozes. Core NGC108 is mainly composed of homogeneous, gray to olive gray, silica-rich calcareous oozes.

A single planktonic foraminifera species, *Globorotalia inflata* from both cores, and a single benthic species consisting of *Uvigerina peregrina* from Core NGC102 and mixed benthic species from Core NGC108, were used for accelerator mass spectrometer (AMS) dating. In Core NGC 102, *U. peregrina* was abundant as a single species and sufficient for the 14C analysis. However, in Core NGC108, the abundance of any one benthic species was not enough for radiocarbon analysis, so we used mixed species consisting of several species of benthic foraminifera. The radiocarbon ages in Core NGC108 reflect averaged results with respect to abundance patterns of the benthic species selected for analysis. Most benthic species would have a shallow infaunal life style in these sites, because the food supply from the water column is not high at this abyssal condition. Thus, we think that radiocarbon ages of the benthic species reflect past deep-water radiocarbon concentration. Each sample consisted of approximately 400 planktonic and 200–400 benthic tests. These specimens were cleaned ultrasonically in H2O2 (30%). Each sample was reacted with 100% phosphoric acid within evacuated glass vessels at 25°C. Graphitization of the samples was performed following the procedure described in Uchida et al. (2004). Radiocarbon analysis was conducted at the AMS facility at the National Institute for Environmental Studies (NIES-TERRA) (Tanaka et al., 2000). We used a reservoir age of 400 years, and the radiocarbon ages of the planktonics were calibrated against INTCAL04 (Reimer et al., 2004) using the CALIB program for dating (Stuiver et al., 2005). For additional data to evaluate sediment mixing, δ18O and δ13C values from a single specimen of *U. peregrina* from the surface sediments above 30 cm depth of Core NGC102 were measured at Woods Hole Oceanographic Institution.

Results

The foraminiferal radiocarbon ages analyzed in this study
are shown in Table 1 and Fig. 2, in which the vertical profiles of the $\delta^{18}$O values for $G.\ inflata$ are included. In Core NGC102, planktonic foraminiferal ages for the top 28 cm of the core ranged from 2,260±50 to 14,730±100 BP, and benthic ages from 8,500±70 BP to 15010±100 BP.

Radiocarbon ages for the top 3 samples of the core were similar, which indicates a mixed layer above 12 cm depth (Fig. 2a, Table 1). The $\delta^{18}$O values for $G.\ inflata$ indicate a marine isotope stage (MIS) boundary (14 ka) between MIS1 and MIS2 around 18 cm depth (Fig. 2b). In Core NGC108,
planktonic foraminiferal ages for the top 50 cm of the core ranged from 1,280 ± 50 to 15,290 ± 80 BP and benthic ages from 4,010 ± 60 BP to 15,870 ± 80 BP (Fig. 2). Additional radiocarbon ages in the mixed layer were obtained from the multiple core NMC20, which was collected from the coring site of Core NGC108 (Nishimura, 1997). The results indicate a mixed layer thickness of about 10 cm (Fig. 2). δ¹⁸O values from *G. inflata* in NGC108 indicate a MIS boundary between MIS1 and MIS2 around 36 cm depth.

The δ¹⁸O and δ¹³C values of a single specimen and changes in abundance of the benthic foraminifer *U. peregrina* in Core NGC102 are shown in Table 2 and Fig. 3. The δ¹⁸O values were high (4.28–5.11‰) at 28–30 cm and low with a large variance from 3.19‰ to 5.04‰ in the mixed layer. The δ¹³C values were low (−0.82 to −1.17‰) at 28–30 cm and had a large variance from −0.16‰ to −0.92‰ in the mixed layer. Fig. 3 also shows the vertical changes in abundance of foraminifers in Core NGC102. The *U. peregrina* abundances rapidly increased from 23 cm to 15 cm depth, with a peak (550 specimens/g) at 15 cm depth; there were 300–400 specimens/g in the mixed layer. Peak abundances of both benthic and planktonic foraminifera occurred at 15 cm (Fig. 3c). Fig. 4 shows the vertical changes in abundance of foraminifers in Core NGC108. Benthic foraminiferal abundance peaks were observed at 1 and 42 cm (Fig. 4). *G. inflata* abundance ranged from 200 to 600 specimens/g (de Silva, 1999). The abundances in the lower layer were higher than those in the upper layer. Overall, the abundance patterns between planktonic and benthic foraminifera were similar.

The vertical profile of the linear sedimentation rate (LSR) is shown in Fig. 5. The LSR was calculated from the planktonic foraminiferal radiocarbon ages listed in Table 1. In Core NGC102, the LSR rapidly increased from 1.4 to 5.3 cm/ka with increasing depth. In Core NGC108, the LSR was 2.3–6.6 cm/ka.

The changes of the B–P foraminiferal age differences in this study are shown in Fig. 6. In Core NGC102, the B–P foraminiferal age differences in the mixed layer ranged from 6,090 ± 90 to 7,010 ± 90 years (Fig. 6). The age differences decreased remarkably with increasing depth and were very small (180 ± 130 and 280 ± 140 years) in the deglacial horizons (22–24 and 26–28 cm). In Core NGC108, the age differences gradually decreased with increasing depth from 2,730 ± 80 at 2–4 cm depth to 580 ± 110 years at 48–50 cm depth.

**Discussion**

The B–P foraminiferal age differences in differences are
good indicators of ventilation rates, their values might be biased through sedimentary processes. Here, we describe our data and several problems associated with our data.

Sedimentary process and B–P foraminiferal age differences

In Core NGC102, the B–P foraminiferal age differences (6,440 years on average) in the mixed layer are approximately 4,700 years older than the modern North Pacific
deep-water age (1,750 years) reported by Broecker et al. (1988). Thus, the age differences in the mixed layer do not directly indicate accurate deep-water radiocarbon ages. Sediment particles, such as foraminiferal tests, were vertically mixed due to bioturbation. In the mixed layer, old and young foraminiferal specimens were strongly mixed by bioturbation. Bioturbation promotes a time-averaging effect on the paleoenvironmental record in the sediments. A simple model of the sediment-mixing process is as follows: 1) The burrowing activity of benthic organisms largely homogenizes the sediments in the mixed layer, which lies just below the seafloor; 2) Most sediment particles come to rest once they become incorporated into the historical layer below the mixed layer; and 3) Conversely, older particles remaining in the mixed layer are successively distributed with decreasing abundance into overlying sediments as sediment mixing continues during sedimentation. According to a simple mixed layer model suggested by Berger and Heath (1968), it is possible that sediment particles can be transported upward a distance equal to three times the thickness of the mixed layer. Since the mixed layer in Core NGC102 is approximately 12 cm, foraminiferal tests could have possibly been transported up to ca. 30 cm. Thus, the B–P foraminiferal age differences in the core sequences reflect not only deep-water ages, but also the time-averaging effect that results from the vertical mixing of foraminiferal tests with sediment particles. The time-averaging effect is theoretically the same for both benthic and planktonic foraminifera.

Broecker et al. (1999) demonstrated the importance of the joint effects of bioturbation and the variable rain abundance (accumulation rate) of foraminifera on the radiocarbon age of a single foraminiferal species. Thus, in Core NGC102, different time-series patterns of accumulation rates between benthic and planktonic foraminiferal tests are possibly associated with the large age differences in the mixed layer.

The plots of single-specimen $\delta^{18}$O values of U. peregrina vs. core depth indicate upward mixing of three glacial specimens (ca. 4.6–5.0‰) and two deglacial specimens (ca. 3.7–4.0‰) with heavier $\delta^{18}$O values into the Holocene mixed layer (Fig. 3a). Based on vertical comparison of the $\delta^{18}$O values, these glacial specimens would have been transported from 15–30 cm depths. The upward transportation of glacial specimens into the mixed layers is also indicated in the plots of the $\delta^{13}$C values of U. peregrina (Fig. 3b). Thus, benthic foraminiferal ages (8,500–9,270 BP) in the mixed layer are estimated to be older than when there is no contribution of glacial specimens.

On the other hand, planktonic foraminifera have peak abundances at 14–16 cm depth, similar to those of benthic foraminifera (Fig. 3c). Thus, relatively old planktonic foraminifera are anticipated in the mixed layer, due to the upward mixing of glacial specimens. However, in contrast to the age trend of benthic foraminifera, planktonic foraminiferal ages (2,260–2,600 BP) in the mixed layer are estimated to be at least 2,000 years younger than in the case of no abundance changes, based on the low LSR (1.4 cm/ka) and mixed layer thickness (12 cm). The results imply high relative abundances of the latest Holocene specimens of G. inflata relative to early Holocene specimens in the mixed layer.

The other potential source for the relatively young or old ages in the mixed layer may be the effect of carbonate
dissolution. Most deep-sea sites below the lysocline depth (>4 km depth) in the equatorial Pacific have core top $^14$C ages of more than 4 ka, and this has been attributed to chemical erosion of Holocene carbonate sediments (Oxburgh and Broecker, 1993). Holocene sediments in the Pacific overlie calcite-rich glacial sediments so that chemical erosion provides a relatively large flux of old calcite into the mixed layer. The chemical erosion effect in the deep-sea sites below the lysocline is consistent with old benthic ages in the mixed layer in Core NGC102, but contradicts with the young planktonic ages. Core NGC102 site is slightly shallower than the lysocline depth. Thus, there is no evidence of chemical erosion due to strong dissolution, although carbonates in the mixed layer can have been partially dissolved through weak dissolution.

Holocene carbonate sediments at Core NGC108 site, which is located under the lysocline depth, have been moderately dissolved, and the carbonate content is about 30–50 wt.% (Maeda et al., 2002). Thus, core top foraminiferal ages in Core NGC108 may become relatively older by chemical erosion. This range of the carbonate content in Core NGC108 is clearly lower than that (50–70 wt.%) in Core NGC102 (Kawahata et al., 1999). However, carbonate accumulation rates were higher in Core NGC108 than in Core NGC102 (Maeda et al., 2002). The Core NGC108 site near the subarctic front is characterized by higher biological productivity than the Core NGC102 site. Thus, the younger benthic age in the mixed layer of Core NGC108 reflects a higher accumulation rate than that at Core NGC102. Likewise, the planktonic age in the mixed layer of Core NGC108 is younger than that of Core NGC102, although the difference between both sites is larger in benthics than in planktonics. These results indicate a slightly higher accumulation/dissolution ratio for G. inflata in Core NGC108.

The main cause of the large difference in benthic ages in mixed layer between both sites is because of abnormal old benthic ages in Core NGC102. The abnormal old benthic ages in Core NGC102 would be attributed to the combination of the temporal variance in abundance patterns and low sedimentation rates.

**B–P foraminiferal age differences in the core sequences of the Shatsky Rise**

The changes of the B–P foraminiferal age differences in two cores are shown with those reported in the northern Pacific areas in Fig. 6. In Core NGC102, the B–P foraminiferal age differences (6,440 years on average) in the mixed layer are approximately 4,700 years older than the modern North Pacific deep-water age (1,750 years) reported by Broecker et al. (1988). Peak abundances of benthic and planktonic foraminifera occur at 14–16 cm depth (Fig. 3c). Carbonate sediments are well preserved at this deglacial horizon (12.4–12.7 ka). A line of evidence suggests that the time-averaging effect is almost the same for both the benthic and planktonic foraminifera. Thus, the B–P foraminiferal age difference (2,470 years) may approximately indicate similar to the past deep-water age at that time. On the other hand, the B–P foraminiferal age differences (180 ± 130 to 280 ± 140 years) at 22–28 cm depths (16–17 ka, corresponding to Heinrich stadial event 1) were remarkably smaller than the modern deep-water age. Changing patterns in U. peregrina and G. inflata abundances were roughly similar from 15 to 30 cm depth, although the time resolution of the data is poor. These two species have peak abundances at 14–16 cm depth and decrease to 30 cm depth. Thus, the mixing rate between old and young specimens would have approximately the same effect on both planktonic and benthic foraminifera. The small B–P foraminiferal age difference may reflect the past deep-water age at that time, although the high contribution of mixing of relatively young benthic specimens from the deglacial horizon cannot be excluded.

In Core NGC108, the B–P foraminiferal age difference (2,730 years) in the mixed layer is approximately 1,000 years older than the modern North Pacific deep-water age (1,750 years) reported by Broecker et al. (1988). By contrast, the age B–P foraminiferal difference (1,350 years) at 24–26 cm depth, where the calibrated age (12,750 cal BP) corresponds to the Younger Dryas cold event, is approximately 400 years younger than the modern deep-water age. The B–P foraminiferal age differences below the 24–26 cm depth decrease with increasing depth. The B–P foraminiferal age difference (990 ± 200 years) at 40–42 cm depth, where the calibrated age (15,730 ± 290 cal BP) corresponds to Heinrich stadial event 1, is estimated to be 760 years less than the modern deep-water age. The 40–42 cm horizon is characterized by a higher sedimentation rate (5–7 cm/ka) and peak abundances of both benthic and planktonic foraminifera. Thus, the B–P foraminiferal age difference in this horizon may indicate the past deep-water age. The B–P foraminiferal age difference (580 ± 200 years) at the 48–50 cm depth, where the calibrated age (18,100 ± 18,400 cal BP) corresponds to the end of the last glacial maximum, is approximately 1,200 years less than the modern deep-water age. The temporal changes of the B–P foraminiferal age differences in this study are shown in Fig. 7 with those reported from the several areas in the northern Pacific.

At both the Core NGC102 and Core NGC108 sites, the B–P foraminiferal age differences are distinctly small during Heinrich stadial 1 episode, although the age differences during the Holocene were more or less larger than the
modern deep-water ages. The small age differences may reflect the active ventilation of North Pacific deep waters during the Heinrich stadial 1 episode. This interpretation is consistent with previous results from two shallower sites (978 m and 1,366 m) off the northern Japan (Duplessy et al. 1989; Ohkushi et al., 2004) and an deep-water site (3,210 m) in the east Equatorial Pacific (Shackleton et al., 1988) (Fig. 7). The B–P foraminiferal age differences at the one site (Core CH84-14; 978 m) are estimated to be approximately 1,000 years younger than the modern value. Cooling in the North Pacific potentially modified the formation of the North Pacific Intermediate Water (NPIW). The origin of the modern NPIW is formed in the Sea of Okhotsk (Yasuda, 1997). The Okhotsk intermediate water is produced by brine rejection during the formation of sea ice on the continental shelf in winter and is ventilated the subpolar gyre of the open Pacific. Keigwin (1998) documented the existence of better ventilation at depths shallower than 2 km in the glacial Sea of Okhotsk. A stronger process than that of modern NPIW formation, which occurred in the Subarctic Pacific at times of extreme cooling of surface waters, e.g., during Heinrich events, may have contributed to the deep-water formation in the North Pacific.

Alternative explanations for the small B–P foraminiferal age differences, such as sediment mixing (e.g., bioturbation) or deglacial atmospheric 14C decrease, cannot be ruled out (Adkins and Boyle, 1997; Broecker and Barker, 2007). Moreover, Galbaith et al. (2007) and other studies documented the foraminiferal radiocarbon evidence of a poorly ventilated water mass in the deep subarctic Pacific during

Fig. 7 Variation of the ventilation age of the Pacific deep waters (Core TR163-31B, 33° 7′ S, 83° 58′ W, 3,210 m, Core NGC108, and Core NGC102) and of the Pacific intermediate waters (cores Core CH84-14, 41° 44′ N, 142° 33′ E, 978 m, and Core MR01-K03 PC4, 41° 07′ N, 142° 42′ E, 1,366 m). Vertical bar indicates 1σ error range.
the last glacial maximum. Thus, the verification of this dip will require further measurements from the Shatsky Rise. As suggested by Broecker et al. (2004), many more measurements in higher sedimentation cores collected from the abyssal Pacific are needed to create an adequate radiocarbon inventory since the last glacial.

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北太平洋中央部シャツキーライズから採取されたコア堆積物の底生・浮遊性有孔虫の放射性炭素年代差

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深海堆積物の同一層準における浮遊性有孔虫と底生有孔虫の放射性炭素年代差は最終氷期から完新世にかけての海洋循環速度を示す深層水の年齢を推定するための有効な古環境指標となる。しかし、炭酸塩の保存性が悪い太平洋の深海底では、深層水の年齢復元に適する海底堆積物コアを得ることは非常に難しい。北太平洋の中央部に位置するシャツキーライズは、有孔虫殻からなる炭酸塩物質を多く含む深海堆積物が堆積する数少ない場所である。本研究ではシャツキーライズから得られた2本の海底コア試料（コア NGC102 とコア NGC108）の底生・浮遊性有孔虫の放射性炭素年代差を分析した。本コアは生物攪拌を受けた石灰質軟泥である。堆積速度は、コア NGC102（水深 2612 m）で 1.4 ～ 5.3 cm/k yr であり、コア NGC108（水深 3390 m）で 2.3 ～ 6.6 cm/k yr であった。底生・浮遊性年代差は、コア NGC102 で 7010 年 ～ 180 年、コア NGC108 で 2730 年 ～ 580 年を示した。コア NGC102 において、海底面下の堆積物混合層で得られた大きな底生・浮遊性年代差（平均で 6440 年）は報告されている現代の北太平洋深海水の年齢よりもおよそ 4700 年大きい。この底生・浮遊性年代差が実際の深層水の年齢から大きくずれたのではなく、堆積速度が遅いため生物による堆積物の鉛直混合（生物攪拌）の影響を受けて、古い層準の底生有孔虫個体が上方移動したことが底生・浮遊性年代差に反映された結果と考察した。一方、14 ～ 16 cm では年代差 2470 年とおよそ現代の深層水の年齢に近くなるが、22 ～ 28 cm では 180 ～ 220 年と小さすぎる年代差である。コア NGC108 は、コア NGC102 より堆積速度が速く、底生有孔虫・浮遊性有孔虫の産出個体数変動パターンが類似しており、底生・浮遊性年代差への生物攪拌の影響が比較的小さいと考えられる。15700 年前の底生・浮遊性年代差の値（990 ± 200 年）は、現代の深層水の年齢より 760 年小さい。この小さい年代差は、ハインリヒ寒冷イベント1の間に北太平洋で深層水が形成され、その影響下にコア NGC108 地点があった可能性を示す。しかし生物攪拌や大気放射性炭素濃度の減少による見かけ上の効果を反映するかの検討が今後の課題である。