Oxygen Isotope Equilibrium of the Shallow-Water Benthic Foraminifer Hanzawaia nipponica Asano in Tosa Bay, Southwest Japan

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Oxygen isotopic compositions (δ18O) of benthic foraminifer tests are widely used for reconstructing paleoceanographic changes, such as global ice volumes during glacial–interglacial cycles. Although deep-sea benthic foraminifers have been well characterized and are considered reliable indicators, little attention has been paid to the geochemistry of shallow-water benthic foraminifers. In this study we evaluated δ18O in the shallow-water benthic foraminifer Hanzawaia nipponica Asano, which lives in surface sediments on continental shelves and upper slopes under the influence of two warm currents, the Kuroshio and Tsushima currents, in the East China Sea, northwest Pacific, and southwestern Japan Sea. To evaluate oxygen isotope equilibrium, we analyzed δ18O of H. nipponica and ambient seawater on the continental shelf in Tosa Bay, southwest Japan. Seawater δ18O and salinity in Tosa Bay are similar to those of surface and subsurface waters in the Kuroshio region in the Okinawa Trough and the northwest Pacific. Vertical profiles of seawater δ18O show no variation with water depth (0–200 m) in Tosa Bay. However, tests of living H. nipponica (as determined by staining with Rose Bengal) and fossil (non-stained) H. nipponica, picked from samples of the top centimeter of seafloor sediment, yielded carbonate δ18O values that clearly increase with water depth, suggesting a temperature-dependent relationship. A comparison of carbonate δ18O values in living H. nipponica and those predicted on the basis of seawater δ18O and annual mean bottom temperature shows that H. nipponica tests are in oxygen isotopic equilibrium with ambient seawater. We determined the linear equations of δ18O–temperature relationship, and the slope of −5.26 (0.19‰°C−1) for living and −4.50 (0.22‰°C−1) for the fossil H. nipponica, respectively. The carbon isotopic compositions (δ13C) of H. nipponica also closely match seawater δ13C. Thus, we propose that the carbonate δ18O and δ13C of H. nipponica are useful proxies to reconstruct shallow-water paleoenvironmental changes in the northwest Pacific and its marginal seas.

Keywords: benthic foraminifer, Hanzawaia nipponica Asano, oxygen isotopic equilibrium, Tosa Bay, continental shelf, Kuroshio
INTRODUCTION

The oxygen isotopic composition (δ¹⁸O) of the carbonate tests of benthic foraminifers is widely used in studying the geologic history of the oceans, especially the deep ocean. For example, early researchers argued that the deep-sea benthic foraminifer *Uvigerina* spp. appears to record δ¹⁸O of calcite in isotopic equilibrium with seawater (Shackleton, 1974) and that *Cibicidoides wuellerstorfi* deviates from equilibrium by ~0.64‰ in the Pacific (Shackleton and Opdyke, 1973). Bemis et al. (1998) countered their argument by compiling published δ¹⁸O data for *Uvigerina* and *Cibicidoides* species from core tops in the Atlantic, Pacific, and Indian oceans and comparing them with predictions from the paleotemperature equation established by experimental results from planktic foraminifers, finding that *Cibicidoides* δ¹⁸O data were in excellent agreement with the equation whereas *Uvigerina* data were scattered. They concluded that the relative ¹⁸O enrichment of *Uvigerina over Cibicidoides* tests reflects the habitat differences of the genera: *Uvigerina* is infaunal and experiences low pH and decreased [CO₃²⁻] in pore waters, whereas *Cibicidoides* inhabits the sediment surface where bottom water pH and [CO₃²⁻] are higher (Bemis et al., 1998). As a result of these and other advances, much paleoceanographic research has made use of δ¹⁸O analyses of epifaunal deep-sea benthic foraminifers. In contrast, shallow-water benthic foraminifers have seen little application in paleoceanographic studies because it is assumed that δ¹⁸O in these species would be affected by freshwater input and larger temperature variations in the shallow-water environment. Although δ¹⁸O records from shallow-water settings are very important evidence of past environmental changes of the coastal ocean, there is presently no useful species of shallow-water benthic foraminifer to aid in reconstructing past δ¹⁸O changes.

*Hanzawaia nipponica* is a species of benthic foraminifer that was first reported from Pliocene strata in Kawasaki, on the Pacific coast of Japan, by Asano (1944) and has been subsequently reported from Pliocene to Pleistocene sedimentary sequences around Japan, such as in Okinawa (LeRoy, 1964), Kochi (Katoh et al., 1953), and Shizuoka (Aoshima, 1978). Outside Japan, it has been recorded from upper Pliocene to lower Pleistocene shallow-marine deposits on Jeju Island in the Korea Strait (Li et al., 1999; Kang et al., 2010) and from a Holocene marine core in the Yellow Sea (Xiang et al., 2008). The living species is abundant in surface sediment on the continental shelf in Tosa Bay, off Shikoku Island, Japan, and contemporary *H. nipponica* tests from seafloor surface sediment in Tosa Bay, and we determined that the tests were in isotopic equilibrium with seawater. Our findings indicate that isotopic analyses of *H. nipponica*, a regionally abundant species recorded from the late Neogene to the present, can be valuable for paleoceanographic studies in shallow-marine environments.

METHODS

Sediment was collected with a Smith–McIntyre grab sampler from three sites (sites 5, 25, and 26) on the continental shelf of Tosa Bay (Table 1; Figure 1) by T/S Toyohata-maru and T/S Neptune operated by Kochi University. Sediment samples for this study were collected from the uppermost centimeter of the sediment in the grab sampler. These were stored in a refrigerator and stained with Rose Bengal to identify living individuals of *Hanzawaia nipponica* Asano. After 2 days, the stained sediments were washed with water through a 150-μm mesh sieve and the fractions remaining on the sieve were dried at 50°C in an oven. Stained tests larger than 150 μm, representing mature living foraminifers, were then picked for isotope analysis (Figure 2). These tests (7–10 specimens) were baked at 450°C in an electric oven to remove organic matter from the tests (e.g. Erez and Luz, 1983). Fossil individuals of *H. nipponica* (50 specimens) were also picked for isotope analysis. All tests were cleaned with methanol by ultrasonication, slightly crushed in a glass vial and weighed, and then cleaned carbonate fragments weighing approximately 100 μg were reacted with 100% phosphoric acid at 90°C in a vacuum. The released CO₂ was purified and analyzed for δ¹³C in carbonate (δ¹³C) and carbon isotopic composition (δ¹³C) using the isotope ratio mass spectrometer (IsoPrime, GV Instruments Ltd.), with its MultiPrep automated sample preparation module, at the Center for Advanced Marine Core Research, Kochi University. The results are expressed in relation to the Vienna Pee Dee Belemnite (VPDB) standard. The estimated analytical precisions were better than 0.1‰ for both δ¹⁸O and δ¹³C measurements.

Seawater samples were collected at depths representing the entire water column (Table 2) at sites 5, 25, and 26 using a

| TABLE 1 | Sampling sites in Tosa Bay, southwest Japan. |
| --- | --- |
| Site | Latitude | Longitude | Water depth (m) |
| St.5 | 32°25.133′N | 133°30.667′E | 40 |
| St.25 | 32°19.0′N | 133°36.25′E | 100 |
| St.26 | 32°15.0′N | 133°38.25′E | 200 |
conductivity–temperature–depth (CTD)/rosette multi-sampler system with Niskin bottles on November 20, 2009 during a cruise by T/S Toyohata-maru. These samples were placed in 6-ml glass vials without bubbles and stored in a refrigerator until isotopic measurements were made. Subsamples measuring 200 µL were transferred into 10-ml vials containing CO₂ gas (99.999%) and allowed to reach CO₂–H₂O exchange equilibrium at 25°C. The equilibrium CO₂ gas was purified and analyzed for seawater δ¹⁸O (δ¹⁸Osw) using the IsoPrime system at Kochi University. The results are expressed in relation to Vienna Standard Mean Ocean Water (VSMOW). The estimated analytical precision was better than 0.1‰.

Profiles of water temperature and salinity were measured at 0.5-m depth intervals from the surface to the seafloor during the same cruise using a Compact-CTD system (Alec Electronics Ltd.). CTD profiles at these three sites were also measured.
each month from April 2009 to February 2010 by the research group of Usa Marine Biological Institute, Kochi University (Table 3). In this study, the nominal depths of the seafloor were 40 m at site 5, 100 m at site 25, and 200 m at site 26, although actual depths varied slightly from month to month. Accuracy of temperature and salinity measurements are ±0.02°C and ±0.03, respectively.

RESULTS AND DISCUSSION
Oceanic Structure and $\delta^{18}$O$_{sw}$ in Shallow Tosa Bay
Vertical profiles of monthly seawater temperature and salinity on the continental shelf in Tosa Bay show typical seasonal variations (Figure 3). Sea surface temperatures are about 28°C in summer and 17°C in winter at the three study sites (Figure 3). The surface water is thermally stratified during spring to summer, vertical mixing begins in October to November, and the temperature profile is almost uniform during January to March (Ichikawa and Hirota, 2004). The vertical temperature gradients on the day of sampling (November 20, 2009) were steeper than that of the annual mean temperature (Figure 3). The annual mean salinity in surface water was approximately 34.0 at site 5 and approximately 34.2 at sites 25 and 26 (Figure 3). Although the salinity of surface water in Tosa Bay decreased from July to September as a result of freshwater input from the Asian summer monsoon, the low-salinity layer was limited to the upper 80–90 m of the water column at sites 25 and 26. The sea surface salinity on the sampling day was slightly lower at site 5 (34.0) than at sites 25 (34.2) and 26 (34.2), but near the seafloor the salinity at site 5, the shallowest site (34.4), was similar to those at sites 25 (34.5) and 26 (34.6).

Although Tosa Bay is an open bay with a semicircular shelf–slope topography (Figure 1), the warm water of the Kuroshio does not flow directly through the bay. The most dominant current pattern is a counterclockwise circulation interacting with a cold eddy (Fujimoto, 1987; Kuroda et al., 2008). This circulation appears to be induced by the combined effect of changes in the position of the Kuroshio axis and the irregular topography of the continental margin (Awaji et al., 1991). The surface current, subsurface temperature, and vertical thermal structure on the continental slope in Tosa Bay are markedly influenced by the position of the Kuroshio axis, the counterclockwise circulation being enhanced as the Kuroshio axis moves near shore south of the Ashizuri and Muroto peninsulas (Kuroda et al., 2008). Therefore, the seafloor environment is affected by low-salinity coastal water only at depths shallower than 80–90 m in Tosa Bay, and the seafloor below 100 m is predominantly influenced by water originating from the Kuroshio.

TABLE 2 | Temperature, salinity, and oxygen isotopic composition in seawater ($\delta^{18}$O$_{sw}$) from three sites in Tosa Bay (November 20, 2009).

| Site | Water depth (m) | Temperature (°C) | Salinity | $\delta^{18}$O$_{sw}$ (‰, VSMOW) | Std.dev (‰) |
|------|----------------|------------------|---------|---------------------------------|-------------|
| St.5 | 0              | 22.24            | 34.01   | 0.180                           | 0.02        |
|      | 10             | 22.43            | 34.05   | 0.154                           | 0.03        |
|      | 25             | 22.37            | 34.18   | 0.173                           | 0.03        |
|      | 40             | 22.14            | 34.41   | 0.236                           | 0.06        |
| St.25| 0              | 22.67            | 34.25   | 0.321                           | 0.02        |
|      | 10             | 22.71            | 34.25   | 0.169                           | 0.03        |
|      | 25             | 22.71            | 34.26   | 0.286                           | 0.04        |
|      | 50             | 22.71            | 34.27   | 0.292                           | 0.03        |
|      | 75             | 22.71            | 34.27   | 0.167                           | 0.01        |
|      | 100            | 20.87            | 34.52   | 0.244                           | 0.02        |
| St.26| 0              | 22.86            | 34.23   | 0.259                           | 0.04        |
|      | 10             | 22.87            | 34.28   | 0.295                           | 0.03        |
|      | 25             | 22.87            | 34.28   | 0.233                           | 0.04        |
|      | 50             | 22.83            | 34.29   | 0.295                           | 0.06        |
|      | 75             | 22.62            | 34.27   | 0.271                           | 0.03        |
|      | 100            | 21.25            | 34.54   | 0.263                           | 0.02        |
|      | 150            | 18.31            | 34.60   | 0.274                           | 0.02        |
|      | 200            | 16.22            | 34.61   | 0.209                           | 0.03        |

Analytical error: ±0.02 ±0.03 <0.1

TABLE 3 | Seasonal maximum, minimum, and annual mean value of bottom water temperature and salinity from three sites in Tosa Bay.

| Site | Water depth (m) | Bottom water temperature (°C) | Bottom water salinity |
|------|----------------|-------------------------------|----------------------|
|      |                | max | min | annual mean | max | min | annual mean |
| St.5 | 40             | 27.5 | 16.1 | 20.8        | 34.6 | 33.8 | 34.4        |
| St.25| 100            | 21.8 | 13.8 | 17.9        | 34.6 | 34.3 | 34.5        |
| St.26| 200            | 16.2 | 9.4  | 12.5        | 34.6 | 34.3 | 34.5        |
On the date of sampling, the three sites in Tosa Bay had $\delta^{18}O_{sw}$ ranging from 0.15 to 0.32‰ (Table 2; Figure 4). Although not all of the Tosa Bay data lie on the regression lines of surface water from the East China Sea to the Kuroshio region (Oba, 1990; Horikawa et al., 2015) and their $\delta^{18}O_{sw}$ values appear relatively high (Figure 4), the $\delta^{18}O_{sw}$–salinity data appear to be consistent with previously published results. These $\delta^{18}O_{sw}$ values and salinity values in Tosa Bay are very close to those of Kuroshio surface water from east of Taiwan (salinity = 34.2–34.4 and $\delta^{18}O_{sw} = 0.1–0.2$‰) and Kuroshio subsurface water (40–100 m) in the Okinawa Trough (salinity = 34.4–34.7 and $\delta^{18}O_{sw} = 0.15–0.35$‰) (Horikawa et al., 2015). The $\delta^{18}O_{sw}$ values in Tosa Bay are also consistent with those in surface and subsurface waters (0.25‰–0.4‰; 0–200 m) from the Kuroshio Extension and subtropical gyre (Oba and Yasuda, 1992). There is little available $\delta^{18}O_{sw}$–salinity data of typical Kuroshio waters, but data from the Kuroshio region south of Japanese Islands show that Kuroshio water has higher salinity and $\delta^{18}O$ there than in the localities just described (Horibe and Ogura, 1968) (Figure 4). The $\delta^{18}O$ data from Horibe and Ogura (1968) were converted from

![FIGURE 3](image-url) Measured temperature and salinity profiles at three sites in Tosa Bay. (A) temperature and (B) salinity at site 5, (C) temperature and (D) salinity at site 25, (E) temperature and (F) salinity at site 26. Thin colored lines are monthly values, heavy dashed lines are annual mean values (April 2009 to February 2010).
δD data via the formula $\delta^{18}O = \delta D/8.03$. Slope 8.03 is derived from the relationship between $\delta^{18}O$ and $\delta D$ of observed global data (Mathieu et al., 2002).

The $\delta^{18}O_{sw}$ values averaged over the water column are 0.19‰ at site 5, 0.25‰ at site 25, and 0.26‰ at site 26. These results suggest that site 5 might be affected by freshwater with lower $\delta^{18}O$ values from the Niyodo River. The $\delta^{18}O$ values of surface water (river, stream, and spring water) in southern Shikoku are ranging from $-5.9$‰ to $-7.9$‰ (calculated average value $-6.6$‰) (Mizota and Kusakabe, 1994), indicating that the freshwater $\delta^{18}O$ from Shikoku is almost consistent with the intercept of regression line a (Figure 4), which was derived from surface water in East China Sea and Kuroshio region in south of Japanese Islands (Oba, 1990). However, the discrepancy at site 5 is much smaller in water near the seafloor (Table 2), which suggests that freshwater influences only the surface mixed layer near the mouth of the Niyodo River. We lack data to assess the impact of seasonal changes, but because the seasonal salinity variation in bottom-water is small (Figure 3), we assume that the seasonal variation of $\delta^{18}O_{sw}$ in bottom water is negligible.

**Oxygen Isotope Equilibrium of *H. nipponica***

The $\delta^{18}O$ values of living and fossil *H. nipponica* increase with water depth in Tosa Bay, even though the vertical profile of $\delta^{18}O_{sw}$ is almost constant (Table 4; Figure 5). The differences in $\delta^{18}O$ with depth may depend on water temperature, given that $\delta^{18}O_{sw}$ varies so little with depth (Figure 5A). However, $\delta^{18}O_c$ in many foraminifer species differs from the equilibrium state (e.g., Shackleton, 1973; Bemis et al., 1998), and a specific offset value should be calculated to assess the temperature dependence of $\delta^{18}O$ in *H. nipponica*. Although the biology of *H. nipponica* is not documented in detail, the life span of shallow-water benthic foraminifers is typically from several months to a year (Murray, 1991). For example, the life cycle of Planoglabratella opercularis, a benthic inhabitant of rocky shore environments, is completed in 40–65 days (Tsuchiya et al., 2014). We assumed that the life span of *H. nipponica* is more than 3 months, and on that basis we estimated the effect on calcification in the shallow ambient environment in Tosa Bay. Predicted $\delta^{18}O_c$ values were calculated, assuming oxygen isotopic equilibrium in foraminiferal calcite, from...
This equation was determined from culturing experiments with a symbiont-bearing planktic foraminifer, *Orbulina universa*, grown under low-light conditions (Bemis et al., 1998). The adjustment of −0.27‰ to the seawater term compensates for the δ¹⁸O difference between the VSMOW and PDB standards. We calculated δ¹⁸Oc from the δ¹⁸Osw values at each of our three study sites and various bottom-water temperatures for each site: monthly values, the annual mean value, and average values for the 3-month period September to November, based on measurements from April 2009 to February 2010.

The results (Figure 6) show that the δ¹⁸Oc values of living *H. nipponica* lie well within the seasonal variation of predicted δ¹⁸Oc at every site and are nearly equal to the predicted δ¹⁸Oc values based on the annual mean bottom temperature. They also suggest that the δ¹⁸Oc values of living *H. nipponica* are heavier than the predicted δ¹⁸Oc values from the 3-months average. Because we assumed a life span of 3 months for this species, the discrepancy indicates that *H. nipponica* has a much longer life cycle. This finding is also supported by the fact that δ¹⁸Oc values of living and fossil *H. nipponica* are very close to each other (Figure 5B). From these results, we conclude that the carbonate tests of *H. nipponica* are in oxygen isotopic equilibrium with the ambient seawater. Although there are only three sites in this study, it is possible to evaluate the relationship between δ¹⁸Oc of benthic foraminifer and bottom water temperature. Figure 7 shows the relationship δ¹⁸Oc of living and fossil *H. nipponica* and annual mean bottom water temperature in Tosa Bay. It is clear that the relationship is linear in both cases. The slope of the linear function is −5.26 (0.19‰ °C⁻¹) for the living and −4.50 (0.22‰ °C⁻¹) for the fossil *H. nipponica*, respectively (Figure 7).
Although we applied the $\delta^{18}O$–temperature equation of Bemis et al. (1998) to our data, there are other $\delta^{18}O$–temperature relationships that yield various estimates for calcification of benthic foraminifers. For instance, Shackleton (1974) used core-top data to calibrate a $\delta^{18}O$–temperature relationship for the benthic foraminifer *Uvigerina* spp., and Zahn and Mix (1991) proposed that $\delta^{18}O$ in *Uvigerina peregrina* at water depths greater than 2 km could be described best by the equation of Erez and Luz (1983), derived from culture experiments with the planktic foraminifer *Globigerinoides sacculifer*. Both of these studies assumed that *Uvigerina* precipitates its test in oxygen isotope equilibrium with ambient seawater. Bemis et al. (1998) compared Eq. 1 to an analysis of a compilation of published $\delta^{18}O$ data for the benthic foraminifers *Uvigerina* and *Cibicidoides* from core tops in the Atlantic, Pacific and Indian oceans, the Arabian Sea, and the Gulf of Mexico. They found that the $\delta^{18}O$ data for *Cibicidoides* were in excellent agreement with Eq. 1, which was based on culture experiments in low-light conditions with the planktic foraminifer *Orbulina universa*. Our data for *H. nipponica* show that the relationship between $\delta^{18}O$ and ambient temperature closely fits Eq. 1 (Figure 8). The $\delta^{18}O$ data also show a similar trend with temperature in equations based on benthic foraminifers (Shackleton, 1974) and inorganic calcite (Kim and O’Neil, 1997). We conclude that the shallow-water benthic foraminifer *H. nipponica* precipitates its test close to oxygen isotopic equilibrium with seawater, as does the deep-sea benthic foraminifer *Cibicidoides*. The equation of Bemis et al. (1998) appears to be widely applicable to foraminifers, including benthic foraminifers in shallow and deep-sea environments. Although *H. nipponica* is restricted to continental shelves and upper slopes, this species may be very useful for elucidating paleoenvironmental changes in shallow-water settings affected by the Kuroshio and Tsushima current in the northwest Pacific and adjoining seas. Planktic foraminifer, which have been used in many isotope studies, have relatively large depth habitat (e.g. Schiebel and Hemleben, 2017), in contrast, benthic foraminifer have the advantage of being able to extract information on limited water depths, thus our new result is very important to advance paleoceanographic research in shallow water of past ocean.

**Carbon Isotopes of H. nipponica**

Our determinations showed that $\delta^{13}C$ of living *H. nipponica* ranged from 0.03 to 0.99‰, and those of fossil *H. nipponica* ranged from 0.63 to 0.94‰ (Table 4; Figure 5C). The differences between living and fossil specimens were small at site 25 (0.05‰) and site 26 (0.17‰) and much greater (0.74‰) at site 5, the shallowest site, where living specimens exhibited relatively depleted values (Figure 5C). Although $\delta^{13}C$ values of seawater in Tosa Bay have not been reported, values in the Kuroshio off the Boso Peninsula have been reported as a gradation from ~1.2‰ in surface water to ~0.8‰ in subsurface water at ~200 m depth (Figure 5C; Oba et al., 2006). Similarly, Kroopnick (1985) reported $\delta^{13}C$ values of 1.2‰ in surface water in the Kuroshio region off central Japan (station 224; 34°25′N, 142°00′E). Our results show that the $\delta^{13}C$ of *H. nipponica* is very close to these values in bottom water at site 25 (100 m) and site 26 (200 m) (Figure 5C), suggesting that $\delta^{13}C$ in *H. nipponica* reflects the $\delta^{13}C$ of ambient seawater. The depleted $\delta^{13}C$ values of *H. nipponica* at site 5 suggest that the $\delta^{13}C$ of benthic foraminifers in the surface mixed layer are greatly influenced

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**FIGURE 7** | Relationship between $\delta^{18}O_c$ of living and fossil *H. nipponica* and annual mean bottom water temperature at three sites in Tosa Bay. Green squares show data from living *H. nipponica* and orange triangles indicate data from fossil *H. nipponica*.

**FIGURE 8** | Predicted $\delta^{18}O$ values for living *H. nipponica* from surface sediments on the continental shelf in Tosa Bay. Published relations between temperature and $\delta^{18}O$ are also plotted (Shackleton 1974; Kim and O’Neil 1997; Bemis et al., 1998). The *H. nipponica* data show a good fit to the equation of Bemis et al. (1998).
by factors such as photosynthetic processes, local river input, and contributions of depleted δ13C from terrestrial organic materials.

In general, the distribution of δ13C in the ocean is controlled by the interaction of biological uptake at the sea surface, air–sea gas exchange, and decomposition in deeper water masses. Photosynthesis in shallow waters preferentially extracts 12C from the carbon-bearing ions in seawater, enriching the ΣCO2 of surface water in 13C. The δ13C value in seawater after primary producers have removed all nutrients, then, is controlled by the mean δ13C and the mean nutrient concentration of the ocean (Broecker, 1982). Because the carbon taken up by phytoplankton has a δ13C value of approximately −20‰, the surface reservoir is enriched by 2.0‰ relative to the mean δ13C of deep water (Curry et al., 1988). Therefore, δ13C data of fossil benthic foraminifers can be used to reconstruct past properties of deep water and infer past changes in ocean ventilation (e.g., Curry and Oppo, 2005; Ullerman et al., 2016).

Although further research will be necessary to better specify the dominant factors of δ13C in H. nipponica, the δ13C of this species is nearly identical to that of seawater. This similarity means that δ13C of H. nipponica can be used to reconstruct the history of carbon circulation in subsurface to intermediate waters in the northwest Pacific and its marginal seas.

## CONCLUSION

The main findings of this study are as follows:

1) The oxygen isotopic composition (δ18Osw) and salinity of seawater samples from Tosa Bay generally overlap with those of the Kuroshio, which flows from the Okinawa Trough past Tosa Bay to the northwest Pacific. Although the surface and subsurface waters at site 5, the shallowest site, are influenced by freshwater input, the bottom water at all sites (40–200 m) is minimally influenced by less saline coastal water.

2) The δ18O values increased with water depth in living and fossil specimens of the benthic foraminifer Hanzawaia nipponica, whereas δ18Osw did not vary with water depth in Tosa Bay. The δ18O values of living H. nipponica were predicted well by the calcite equilibrium equation of Bemis et al. (1998) using the annual mean bottom-water temperature, indicating that the carbonate tests of H. nipponica form in oxygen isotopic equilibrium with ambient seawater. This result reinforces the utility of the equation of Bemis et al. (1998) for calculating δ18Osw and temperature for foraminifers, including benthic foraminifers in shallow and deep marine environments.

3) Tests of H. nipponica faithfully record the δ13C of ambient seawater, although the δ13C of this species in the surface mixed layer is difficult to interpret owing to the influence of various factors.

4) Data on δ18O and δ13C of H. nipponica are useful proxies to reconstruct paleoenvironmental changes in the shallow waters of the northwest Pacific and its marginal seas.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

MI proposed the topic and conceived and designed the study. SKi carried out the sampling and the experimental study. SKa collaborated with the corresponding author in the identification of benthic foraminifers. MI and SKi analyzed the data and helped in their interpretation. All authors read and approved the final manuscript.

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