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

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Oxygen isotopic compositions ($\delta^{18}O$) 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 $\delta^{18}O$ 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 $\delta^{18}O$ of *H. nipponica* and ambient seawater on the continental shelf in Tosa Bay, southwest Japan. Seawater $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ values that clearly increase with water depth, suggesting a temperature-dependent relationship. A comparison of carbonate $\delta^{18}O$ values in living *H. nipponica* and those predicted on the basis of seawater $\delta^{18}O$ and annual mean bottom temperature shows that *H. nipponica* tests are in oxygen isotopic equilibrium with ambient seawater. We determined the linear equations of $\delta^{18}O$–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 ($\delta^{13}C$) of *H. nipponica* also closely match seawater $\delta^{13}C$. Thus, we propose that the carbonate $\delta^{18}O$ and $\delta^{13}C$ 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

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INTRODUCTION

The oxygen isotopic composition ($\delta^{18}O$) 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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* $\delta^{18}O$ data were in excellent agreement with the equation whereas *Uvigerina* data were scattered. They concluded that the relative ^{18}O enrichment of *Uvigerina* over *Cibicidoides* tests reflects the habitat differences of the genera: *Uvigerina* is infaunal and experiences low pH and decreased $[CO_3^{2-}]$ in pore waters, whereas *Cibicidoides* inhabits the sediment surface where bottom water pH and $[CO_3^{2-}]$ are higher (Bemis et al., 1998). As a result of these and other advances, much paleoceanographic research has made use of $\delta^{18}O$ 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 $\delta^{18}O$ in these species would be affected by freshwater input and larger temperature variations in the shallow-water environment. Although $\delta^{18}O$ 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 $\delta^{18}O$ 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 (Katto 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 the East China Sea (Inoue, 1989), off the San'in district in the southwest Japan Sea (Inoue, 1989), and in the Pacific Ocean near Japan off Kyushu Island (Akimoto and Torii, 1996), off Shikoku Island (Ishiwada, 1964; Inoue, 1989), off the Kii Peninsula (Uchio, 1968; Akimoto, 1990), in Suruga Bay (Akimoto, 1990), and off the Boso Peninsula (Kuwano, 1963). Living *H. nipponica* have been recorded at water depths ranging from 23 to 235 m (mainly at ~40 m) off the Pacific coast of western Japan (Aoshima, 1978). These records suggest that the main habitat of this species is the shallow continental shelf along southwestern Japan, where the seafloor is influenced by two major warm currents, the Kuroshio and Tsushima currents (Ishiwada, 1964; Matoba, 1976; Matoba and Honma, 1986; Inoue, 1989; Hasegawa, 1993).

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°35.25′E	100
St.26	32°15.0′N	133°38.25′E	200

Oxygen and carbon isotope compositions have been reported for fossil specimens of *H. nipponica* from one horizon of middle Pleistocene age in the lower Seogwipo Formation on Jeju Island (Li et al., 1999); however, there is no published evidence bearing on the oxygen isotope equilibrium of this species with seawater. In this study, we analyzed the $\delta^{18}O$ of ambient seawater 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 CO_2 was purified and analyzed for $\delta^{18}O$ in carbonate ($\delta^{18}O_c$) and carbon isotopic composition ($\delta^{13}C$) 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 $\delta^{18}O$ and $\delta^{13}C$ measurements.

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

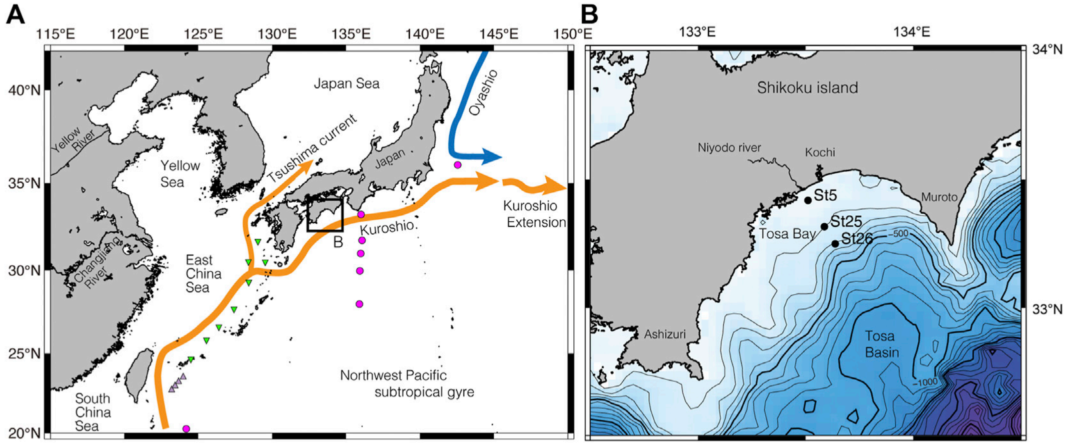

FIGURE 1 | Site location maps. **(A)** Index map with major surface currents in the northwest Pacific and marginal seas. The red circles indicate the location of the isotope data in Horibe and Ogura (1968), and light purple triangles show the location of the isotope data at Kuroshio sites in Horikawa et al. (2015). Green triangles show same at Okinawa Trough sites in Horikawa et al. (2015). **(B)** Bathymetric map showing site locations of surface sediment and seawater samples on the continental shelf in Tosa Bay; map location shown in **(A)**. Contour interval, 100 m.

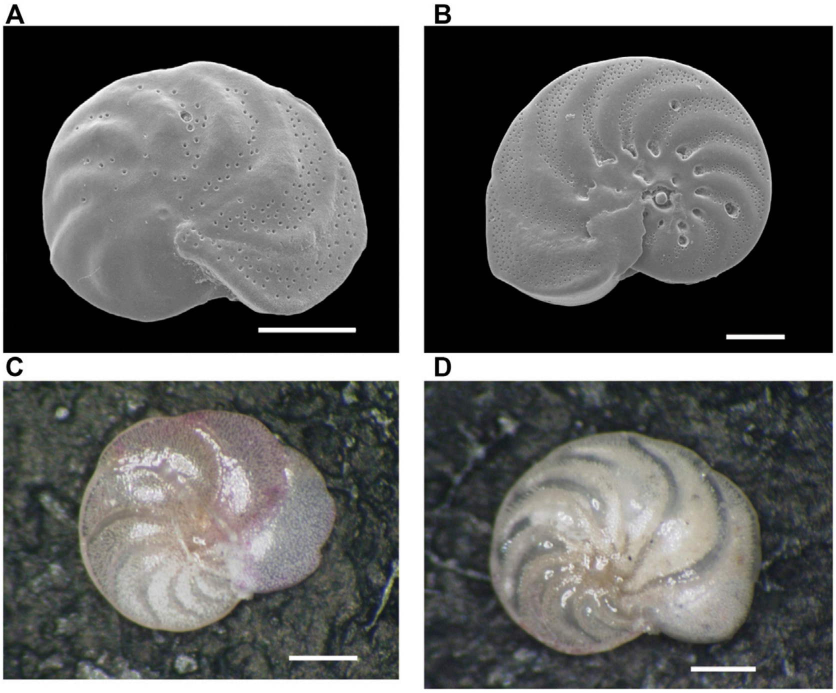

FIGURE 2 | Scanning Electron Microscope (SEM) and stereo microscopic images of the benthic foraminifer *Hanzawaia nipponica* (Asano) from surface sediment in Tosa Bay. **(A)** SEM image of living (stained) *H. nipponica* from site 25, **(B)** SEM image of living *H. nipponica* from site 5, **(C)** photomicrograph of living *H. nipponica* from site 5, **(D)** photomicrograph of fossil (non-stained) *H. nipponica* from site 25. Scale bars are 100 μm in **(A)** and **(B)** and 200 μm in **(C)** and **(D)**.

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 CO_2 gas (99.999%) and allowed to reach CO_2–H_2O exchange equilibrium at 25°C. The equilibrium CO_2 gas was purified and analyzed for seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) 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

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

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.

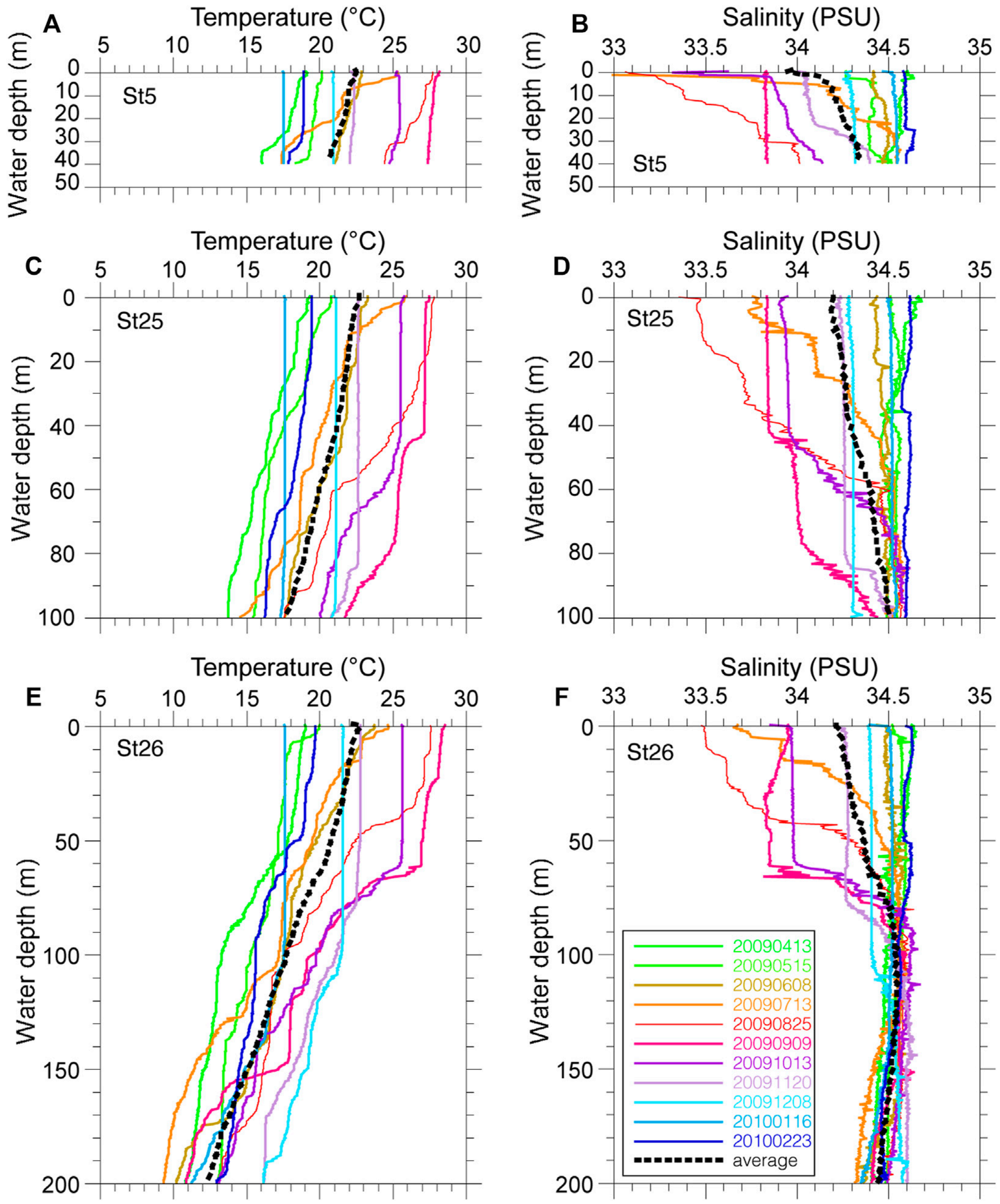

FIGURE 3 | Measured temperature and salinity profiles at three sites in Tosa Bay. **(A)** temperature and **(B)** salinity at site 5, **(C)** temperature and **(D)** salinity at site 25, **(E)** temperature and **(F)** salinity at site 26. Thin colored lines are monthly values, heavy dashed lines are annual mean values (April 2009 to February 2010).

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

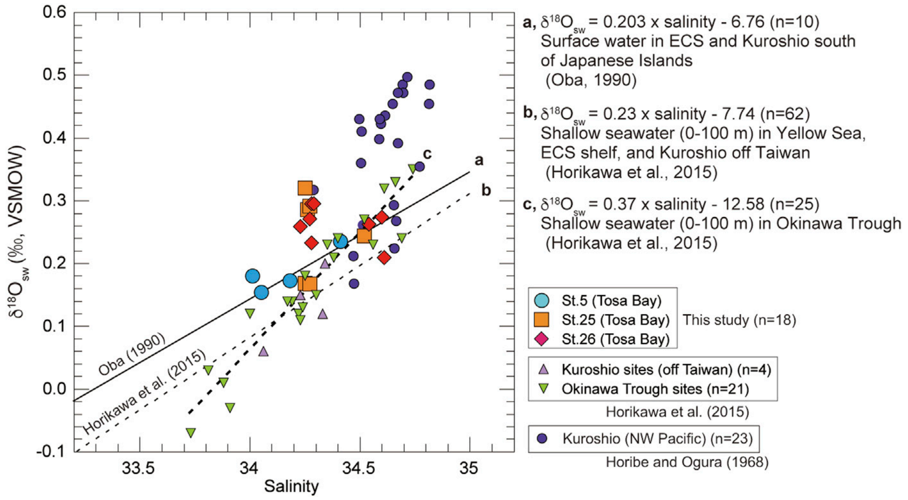

FIGURE 4 | Plot of seawater $\delta^{18}O_{sw}$ against salinity (0–200 m) in Tosa Bay during November and published data from other northwest Pacific and East China Sea sites. Regression line **(A)** is derived from surface-water data in the East China Sea and the Kuroshio south of the Japanese Islands (Oba 1990). Regression line **(B)** is from shallow water (0–100 m) data in the Yellow Sea, East China Sea, and the Kuroshio off Taiwan (Horikawa et al., 2015). Regression line **(C)** is derived from shallow water (0–100 m) data in the Okinawa Trough (Horikawa et al., 2015). Equations from the literature are also shown. Equation of regression line c is calculated from data in the Okinawa Trough sites in Horikawa et al. (2015). End-member data for the Kuroshio are from northwest Pacific (Horibe and Ogura 1968).

TABLE 4 | Oxygen and carbon isotopic compositions of living (stained) and fossil (non-stained) *H. nipponica* from three sites in Tosa Bay.

Site	**Water depth (m)**	**living *Hanzawaia nipponica***			**fossil *Hanzawaia nipponica***		
		Specimens	**$\delta^{18}O$ (‰, VPDB)**	**$\delta^{18}C$ (‰, VPDB)**	**Specimens**	**$\delta^{18}O$ (‰, VPDB)**	**$\delta^{13}C$ (‰, VPDB)**
St.5	40	10	−0.89	0.03	50	−1.00	0.77
St.25	100	9	−0.35	0.99	50	−0.38	0.94
St.26	200	7	0.68	0.80	50	0.83	0.63

Analytical error: <0.1‰

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 δD 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 $\delta^{18}O_c$ 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 $\delta^{18}O_c$ 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 $\delta^{18}O_c$ 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

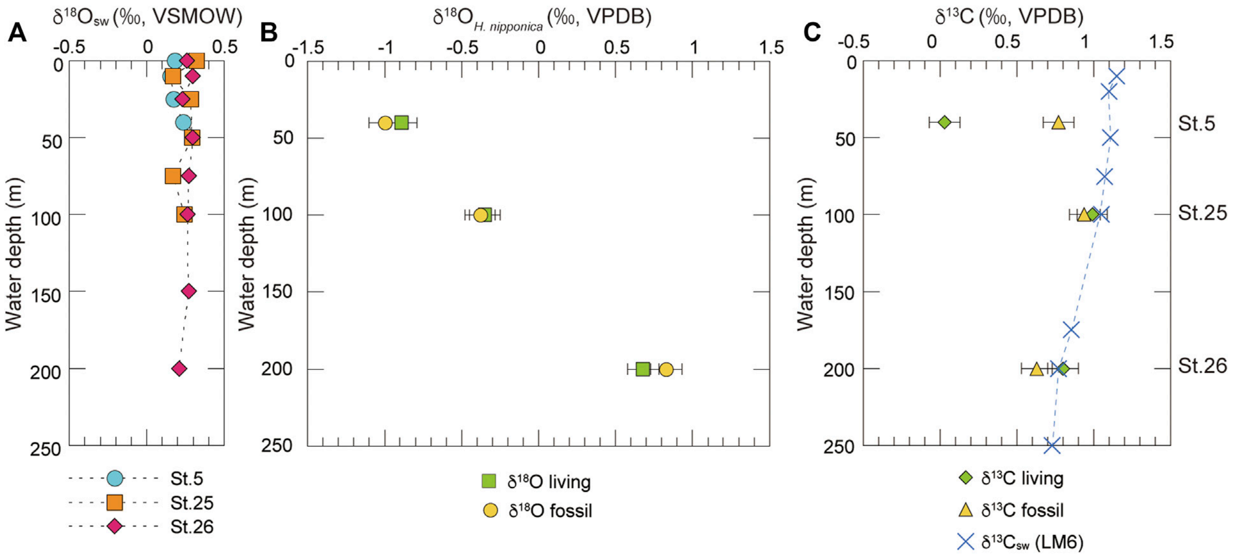

FIGURE 5 | Oxygen and carbon isotopic compositions of seawater and *H. nipponica* at three sites in Tosa Bay. **(A)** Vertical profiles of oxygen isotopic compositions of seawater. **(B)** Oxygen and **(C)** carbon isotopic compositions of living and fossil *H. nipponica* specimens. Horizontal bars represent analytical error of 0.1‰. The $\delta^{13}C$ values of seawater at station LM6 (34°67'N, 142°05'E) in the Kuroshio region off the Boso Peninsula (Oba et al., 2006) are also plotted in **(C)**.

$$T\,(^{\circ}C) = 16.5 - 4.8\left(\delta^{18}O_C - \left(\delta^{18}O_{SW} - 0.27\right)\right) \qquad (1)$$

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 $\delta^{18}O$ difference between the VSMOW and PDB standards. We calculated $\delta^{18}O_c$ from the $\delta^{18}O_{sw}$ 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 $\delta^{18}O_c$ values of living *H. nipponica* lie well within the seasonal variation of predicted $\delta^{18}O_c$ at every site and are nearly equal to the predicted $\delta^{18}O_c$ values based on the annual mean bottom temperature. They also suggest that the $\delta^{18}O_c$ values of living *H. nipponica* are heavier than the predicted $\delta^{18}O_c$ 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 $\delta^{18}O_c$ 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 $\delta^{18}O_c$ of benthic foraminifer and bottom water temperature. **Figure 7** shows the relationship $\delta^{18}O_c$ 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**).

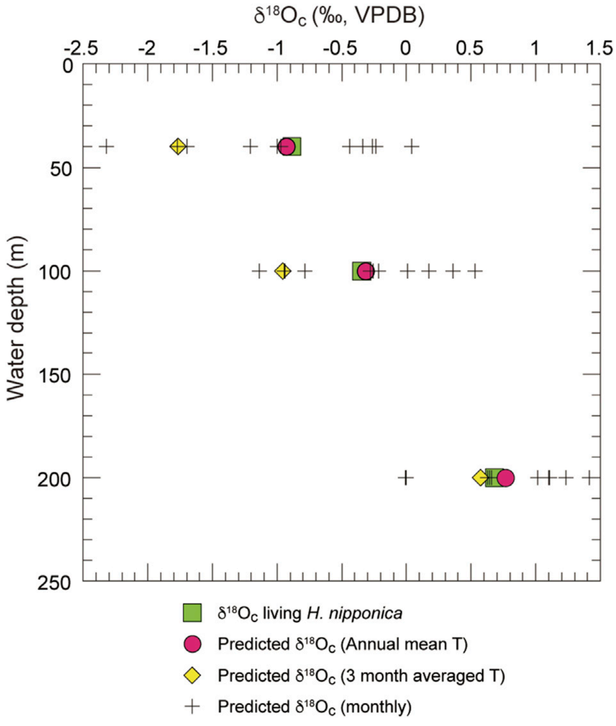

FIGURE 6 | Predicted and measured $\delta^{18}O_c$ of living *H. nipponica* plotted against water depth. Plus symbols show the monthly predicted $\delta^{18}O_c$ values at sites 5 (40 m), 25 (100 m), and 26 (200 m). Red filled circles and yellow filled diamond symbols show the predicted $\delta^{18}O_c$ values for annual mean temperatures and 3-months average temperature (September to November), respectively. The predicted $\delta^{18}O_c$ values are calculated from water temperature and $\delta^{18}O_{sw}$ in Tosa Bay using a calcite equilibrium equation (Bemis et al., 1998).

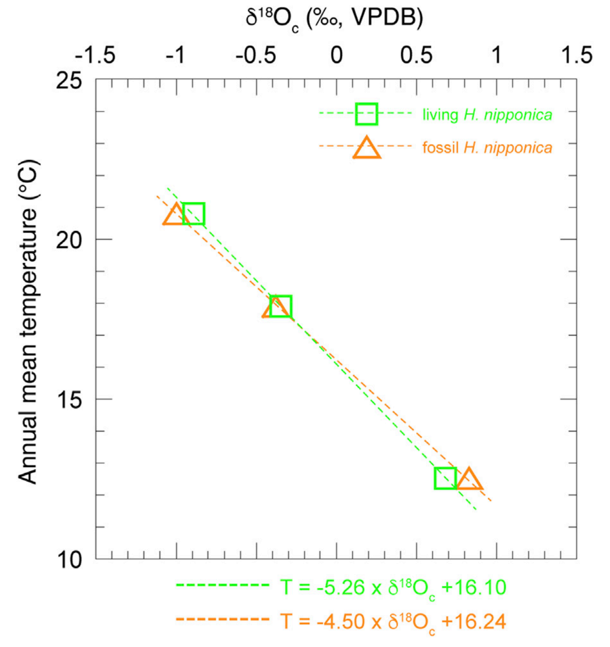

FIGURE 7 | Relationship between $\delta^{18}O_c$ of living and fossil *H. nipponica* and annual mean bottom water temperature at three sites in Tosa Bay. Green squares show data from living *H. nipponica* and orange triangles indicate data from fossil *H. nipponica*.

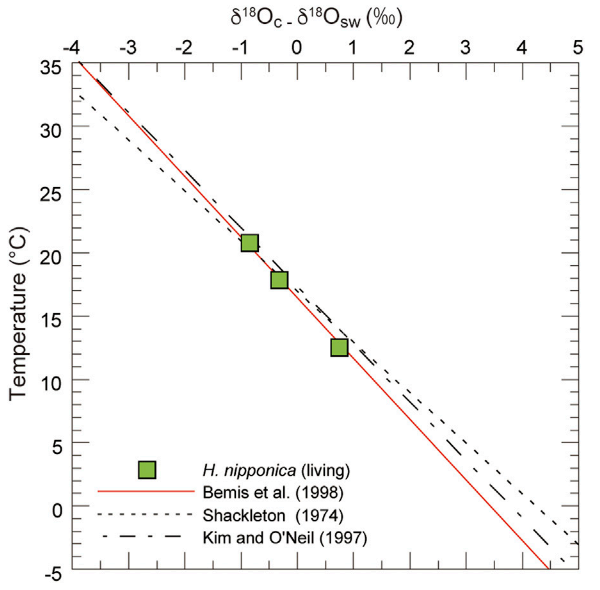

FIGURE 8 | Predicted $\delta^{18}O$ values for living *H. nipponica* from surface sediments on the continental shelf in Tosa Bay. Published relations between temperature and $\delta^{18}O$ are also plotted (Shackleton 1974; Kim and O'Neil 1997; Bemis et al., 1998). The *H. nipponica* data show a good fit to the equation of Bemis et al. (1998).

Although we applied the $\delta^{18}O_c$–temperature equation of Bemis et al. (1998) to our data, there are other $\delta^{18}O_c$–temperature relationships that yield various estimates for calcification of benthic foraminifers. For instance, Shackleton (1974) used core-top data to calibrate a $\delta^{18}O_c$–temperature relationship for the benthic foraminifer *Uvigerina* spp., and Zahn and Mix (1991) proposed that $\delta^{18}O_c$ 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 $\delta^{18}O_c$ 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 by factors such as photosynthetic processes, local river input, and contributions of depleted $\delta^{13}C$ from terrestrial organic materials.

In general, the distribution of $\delta^{13}C$ 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 ^{12}C from the carbon-bearing ions in seawater, enriching the ΣCO_2 of surface water in ^{13}C. The $\delta^{13}C$ value in seawater after primary producers have removed all nutrients, then, is controlled by the mean $\delta^{13}C$ and the mean nutrient concentration of the ocean (Broecker, 1982). Because the carbon taken up by phytoplankton has a $\delta^{13}C$ value of approximately −20‰, the surface reservoir is enriched by 2.0‰ relative to the mean $\delta^{13}C$ of deep water (Curry et al., 1988). Therefore, $\delta^{13}C$ 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 $\delta^{13}C$ in *H. nipponica*, the $\delta^{13}C$ of this species is nearly identical to that of seawater. This similarity means that $\delta^{13}C$ 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 ($\delta^{18}O_{sw}$) 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 $\delta^{18}O_c$ values increased with water depth in living and fossil specimens of the benthic foraminifer *Hanzawaia nipponica*, whereas $\delta^{18}O_{sw}$ did not vary with water depth in Tosa Bay. The $\delta^{18}O_c$ 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 $\delta^{18}O_{sw}$ and temperature for foraminifers, including benthic foraminifers in shallow and deep marine environments.
3) Tests of *H. nipponica* faithfully record the $\delta^{13}C$ of ambient seawater, although the $\delta^{13}C$ of this species in the surface mixed layer is difficult to interpret owing to the influence of various factors.
4) Data on $\delta^{18}O_c$ and $\delta^{13}C$ 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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