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Variation in stable carbon and oxygen isotopes of individual benthic foraminifera: tracers for quantifying the vital effect

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Abstract

Stable carbon and oxygen isotopic compositions ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of benthic foraminiferal carbonate shells have been used to reconstruct past bottom water environments. However, the details of factors controlling the isotopic disequilibrium between the shells and the surrounding bottom seawater (the vital effect) are still ambiguous. In this study, we analyzed the isotopic composition of individual benthic foraminifera of multiple species by using a customized high-precision analytical system, and found that the magnitude of the vital effect in different species is correlated with inter-individual variations. As a result, we can choose suitable species as bottom water proxies by using the inter-individual isotopic variations. In addition, by using the simplified interpretation of the vital effect established in this study, we can reconstruct the $\delta^{13}\text{C}$ values of dissolved inorganic carbon in bottom water by correcting foraminiferal isotopic compositions for the isotopic shift resulting from the vital effect. Our findings will allow the use of isotope data for all benthic foraminifera as more reliable proxies for reconstructing past bottom water conditions and evaluating global carbon cycling.

1 Introduction

Variations in the stable carbon and oxygen isotopic composition ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of foraminiferal carbonate shells have been used for over half a century to estimate paleoenvironmental parameters such as temperature, to quantify global changes in sea level and deep-sea circulation, and to document events such as large seafloor methane releases (Emiliani, 1955; Shackleton and Opdyke, 1973; Kennett et al., 2000; Zachos et al., 2001). In particular, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of benthic foraminiferal shells have been used as tracers to reconstruct past bottom water environments. However, there is still ambiguity concerning the factors controlling the isotopic disequilibrium between benthic foraminifera and the surrounding bottom seawater (the “vital effect”) (Grossman,

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1987; McCorkle et al., 1990; Spero et al., 1997; Zeebe et al., 1999; Bijma et al., 1999; Erez, 2003; Schmiedl et al., 2004).

Major isotopic variations in some species of benthic foraminifera are utilized as paleoindicators of bottom water conditions, but recently researchers have begun to quantify in detail the relationship between the isotopic composition of benthic foraminifera and environmental factors (Rathburn et al., 1996; McCorkle et al., 1997; Mackensen and Licari, 2004; Schmiedl et al., 2004; Fontanier et al., 2006; McCorkle et al., 2008). Precise calibration and validation of isotopic indicators in benthic foraminifera will broaden the range of their application as paleoenvironmental tracers. However two problems in using the isotopic evidence in foraminiferal shells have limited their range of application and the material available for use.

First, until recently it was not possible to analyze the stable isotopic compositions of carbonate samples smaller than about 20 μg (Revesz and Landwehr, 2002; Ishimura et al., 2004; de Groot, 2008; Velivetskaya et al., 2009) and obtain results with an acceptable error range; thus, each sample analyzed included multiple individuals, resulting in isotopic values averaged across individuals. The reported isotopic data of individual foraminiferal shells in previous studies are limited to the taxa that have large and thick CaCO_3 shells. Therefore, it was difficult to obtain data from sites with only foraminifera of small size or rare occurrence, for example, the deep sea or the high latitudes.

Second although the isotopic composition of biogenic carbonate is primarily determined by water temperature and ambient isotopes ($\delta^{18}\text{O}$ of water and $\delta^{13}\text{C}$ of dissolved inorganic carbon [DIC]), the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of deep-sea benthic foraminifera are known to deviate widely from equilibrium with seawater (Grossman, 1987; Rathburn et al., 1996; McCorkle et al., 1997; Fontanier et al., 2006; Mackensen and Licari, 2004), a variation generally known as the “vital effect”. Possible causes of the vital effect include respiration, ontogenetic effects, microhabitats, or carbonate ion concentrations, and many other factors have been suggested in previous studies (Rohling and Cooke, 1999; Mackensen, 2008). The complex interactions between these factors and the isotopic composition of biogenic calcite make it difficult to discuss

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them separately or to know the original values in calcite at equilibrium with bottom water. To reduce this “isotopic noise”, isotopic analyses in the past had to include several individual foraminifera. However, such average isotopic values do not always indicate the absolute isotopic values at equilibrium with ambient water (e.g., Grossman, 1987) and the details of the isotopic variations of whole benthic foraminifera are not well known. The stable isotopes in foraminifera could be more effectively used as environmental proxies, for example for modeling global carbon cycling, with a clearer understanding of the vital effect.

In this study, we analyzed the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of individual shells of deep-sea benthic foraminifera in core-top samples from four sites in marginal seas of the Northwestern Pacific Ocean to characterize the magnitude of inter-individual isotopic variations by using a custom made high-precision isotope analysis system (Ishimura et al., 2004, 2008). The quantity required by their system is less than 1/100 of that required by conventional analytical methods. Furthermore, the use of this technique allows interindividual and interspecies variability in recorded stable isotope signatures to be determined.

We expect the results to be useful for exploring which species are most appropriate to use as paleoindicators in paleoenvironmental studies. We also expect our findings of the characteristics of isotopic vital effect based on inter-species and inter-individual isotopic profiles will enhance the value of all of foraminifera as proxy to reconstruct the environmental changes.

2 Materials and methods

2.1 Foraminifer and water samples

Surface sediment samples were collected with multiple corers from two stations close to each other on the same continental slope in the Southwestern Sea of Okhotsk off Abashiri, Hokkaido Island, Japan. Samples were collected from a water depth of 870 m at $44^{\circ}10' \text{ N}$, $144^{\circ}45' \text{ E}$ during cruise HO76 of R/V Hokusei (Hokkaido University, Japan)

in September 1997 and from 1208 m at 44°31' N 145°00' E during cruise MR06-04 of R/V Mirai (Japan Agency for Marine-Earth Science and Technology [JAMSTEC]) in October 2006 (Fig. 1).

The top layer of the surface sediment (0–10 cm below the seafloor) was subsampled every centimeter and used to determine interindividual isotopic variation for each foraminiferal species selected for study. Prior to the isotopic analysis, the sediment was stained with 0.5 % Rose Bengal solution for at least one week to distinguish living foraminifera from dead. The samples were then washed in a 63- μ m-mesh sieve with 50 °C water. The sediment retained in the sieve was oven-dried at 40 °C, and individual foraminifera were picked out for isotopic analysis.

The dominant species in these samples were the hyaline calcareous benthic foraminifera of the *Cassidulina* group (*Cassidulina norvangi* *Islandiella norcrossi*, *Takayanagia delicata*), *Brizalina pacifica*, and *Stainforthia* sp. We analyzed the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of the non-symbiotic benthic foraminifera *C. norvangi*, *B. pacifica*, and *Stainforthia* sp. from the 870-m samples, and *Uvigerina akitaensis*, *I. norcrossi*, *T. delicata*, *Chilostomella ovoidea*, *Globobulimina auriculata* and *B. pacifica* from the 1208-m samples. All specimens used for isotopic measurements were examined under a stereomicroscope and confirmed to have transparent calcite shells with no authigenic carbonate (Fig. 2).

Water samples were also collected from the 1208-m water-depth site where foraminiferal samples were collected during cruise MR06-04 of the R/V Mirai in August 2006. Porewater samples were squeezed from sediments that had been collected with a 50-cm-long multiple corer, at depth intervals of 0, 1–3, 4–6, and 7–9 cm below the sea floor. Water column samples were collected using Niskin bottles mounted on a conductivity-temperature-depth (CTD) rosette sampler and used for isotopic analysis.

For comparison with our samples, we also determined the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of *Bulimina aculeata* shells in surface sediment from the Nankai Trough (33°42' N, 137°5' E; water depth 1881 m, Fig. 1) off Kumano, Japan, collected with a push corer by the submersible Shinkai6500 during cruise YK02-02 of R/V Yokosuka (JAMSTEC)

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in May 2002. This species has been used previously for the isotopic reconstruction of paleoenvironments (Oba, 1988; McCorkle et al., 1997; Mackensen and Licari, 2004). The sediment sample from 0 to 7 cm below the sea floor was used for porewater analysis and foraminiferal examination and then treated in the same manner as the samples from the Okhotsk Sea for analysis of the stable isotopes of individual shells. We also determined the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of *Globobulimina affinis*, *C. ovoidea*, and *Rutherfordoides* sp. in the upper 2 cm of sediment collected with a push corer from Sagami Bay (35°00' N, 139°14' E; water depth 1182 m) during cruise KT05-18 of R/V Tansei (JAMSTEC) in August 2005.

2.2 Stable carbon and oxygen isotope analysis

We used a continuous-flow isotope ratio mass spectrometry analytical system (Ishimura et al., 2004, 2008) to determine $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of individual foraminifera. This system allowed us to determine $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of as little as 0.2 μg CaCO_3 with a long-term external precision of better than $\pm 0.10\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.14\text{‰}$ for $\delta^{18}\text{O}$. This system can be used for high-precision stable isotope measurements of all foraminifera, including even the smallest species (Kimoto et al., 2009). Isotopic values are reported relative to the Vienna Pee Dee Belemnite (VPDB) standard. In addition to determining stable isotopes in both living and dead individual foraminifera, we also determined the stable isotopic compositions of samples composed of five individuals of *C. norvangi*, *B. pacifica*, or *Stainforthia* sp. for comparison. We also include here the analytical results from a previous study (Ishimura et al., 2004) for *C. norvangi* (reported as *Globocassidulina* sp.). The mass of calcite in foraminiferal shells was calculated from the volume of CO_2 gas evolved during their reaction with phosphoric acid (Ishimura et al., 2004).

The $\delta^{13}\text{C}$ values of dissolved inorganic carbon (DIC) in water were determined by the method presented in Miyajima et al. (1995). The $\delta^{18}\text{O}$ in water samples was analyzed by using a wavelength-scanned cavity ring-down spectroscopy isotopic water analyzer (L2120-i; Picarro Inc., Santa Clara, CA, USA) at Hokkaido University. Analytical errors

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of these methods are within $\pm 0.1\%$ for $\delta^{13}\text{C}$ and $\pm 0.2\%$ for $\delta^{18}\text{O}$. $\delta^{18}\text{O}$ values of water samples are reported relative to Vienna Standard Mean Ocean Water (VSMOW).

2.3 Calculation of isotopic differences between foraminiferal shells and bottom water ($\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$)

5 In this study the stable isotopic compositions of foraminiferal shells are discussed as $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$. $\Delta\delta^{13}\text{C}$ is the difference between the $\delta^{13}\text{C}$ of foraminiferal shell and the $\delta^{13}\text{C}_{\text{DIC}}$ of bottom water; $\Delta\delta^{18}\text{O}$ is the difference between the $\delta^{18}\text{O}$ of foraminiferal shell and calcite in equilibrium with bottom water conditions ($\delta^{18}\text{O}_{\text{e.c.}}$), as discussed in previous studies (McCorkle et al., 1990, 1997; Rathburn et al., 1996; Schmiedl et al., 10 2004; Fontanier et al., 2006; Basak et al., 2009). The $\delta^{18}\text{O}_{\text{e.c.}}$ values were calculated using equations proposed by Friedman and O'Neil (1977), which is the same procedure as in previous studies (Fontanier et al., 2006; Basak et al., 2009). The bottom water temperatures at the study sites were 2.3°C in the Sea of Okhotsk (Matsunaga and Tanaka, 2006), 1.9°C in the Nankai Trough (Hamamoto et al., 2005), and 2.9°C in 15 Sagami Bay.

2.4 Reliability of microscale isotopic analysis of carbonate

The reliability of isotope analysis for samples larger than $0.2\text{ }\mu\text{g CaCO}_3$ has already been demonstrated (Ishimura et al., 2004, 2008). The same analytical procedures can be used to analyze sub-microgram quantities to several hundred micrograms of carbonate. We did not observe any evidence of added errors from foraminiferal sampling 20 (e.g. addition of authentic carbonate, staining by Rose Bengal, etc.) or any systematic analytical errors (e.g. leakage of air, isotopic fractionation). The average single-shell isotopic values approximately corresponded to the average values from five shells analyzed together, confirming that interspecies differences in average isotopic values were 25 not due to the reduced sample size.

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3 Results and discussion

We obtained a dataset that included (1) $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of foraminifera and water samples, (2) weights of individual shells, (3) isotopic distributions within species (inter-individual isotopic variations), and (4) weighted average isotope values for each species (inter-species isotopic variations). The isotopic values of bottom water are shown in Table 1. All analytical results from foraminiferal shells are shown in Table 2. No systematic difference was observed in isotopic values between living and dead individuals, and isotopic differences among shells collected from different depths were within the range of inter-individual isotopic deviations for each species. The analyzed individuals show various interspecies differences in $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$, together with species-specific interindividual variations.

3.1 Characteristics of isotopic disequilibrium in benthic foraminifera: choosing more reliable species as bottom water indicator

We calculated the difference between $\delta^{13}\text{C}$ values of foraminifera and DIC in bottom water ($\Delta\delta^{13}\text{C}$) and between $\delta^{18}\text{O}$ values of foraminifera and calcite in equilibrium with bottom water ($\Delta\delta^{18}\text{O}$). The individual foraminifera showed interspecies differences in $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$, as well as variation among individuals of a species (Fig. 3 and Table 2). The magnitude of isotopic variation of individual shells of *Bulimina aculeata* was identical within the analytical precision, and their isotopic values were almost the same as the $\delta^{13}\text{C}$ of DIC in bottom water ($\delta^{13}\text{C}_{\text{DIC}}$) and $\delta^{18}\text{O}$ of calcite in equilibrium with bottom water ($\delta^{18}\text{O}_{\text{e.c.}}$). Although *Uvigerina akitaensis* and the *Cassidulina* group (*Islandiella norcrossi*, *Cassidulina norvangi*, and *Takayanagia delicata*) showed slightly negative average $\Delta\delta^{13}\text{C}$ values, their $\delta^{18}\text{O}$ values were close to $\delta^{18}\text{O}_{\text{e.c.}}$ values with smaller deviations (SD < 0.4‰, Fig. 3). These small inter-individual variations in isotopic composition and mean $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values close to seawater demonstrate the usefulness of these species for estimating the past isotopic composition of deep-sea water from even a limited number of individuals. Other species exhibited

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interindividual variations substantially greater than the analytical precision. Moreover, $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$ values in *Brizalina pacifica* and *Stainforthia* sp. were extremely negative compared with previously reported values for benthic foraminifera (Grossman, 1987; Rathburn et al., 1996; McCorkle et al., 1997; Mackensen and Licari, 2004; Fontanier et al., 2006)

All species tended to show ^{13}C - and ^{18}O -enriched $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$ values in proportion to individual weight (Fig. 4a). Also, the $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$ values were inversely proportional to shell weight, and larger (heavier) individuals tended to have isotopic values closer to $\delta^{13}\text{C}_{\text{DIC}}$ and $\delta^{18}\text{O}_{\text{e.c.}}$ (Fig. 4b, Supplementary Fig. 1). The isotopic shift associated with growth stage has been reported as the “ontogenetic isotope effect” for some larger species (Schmiedl et al., 2004; Fontanier et al., 2006; Schumacher et al., 2010). We found that this trend is not limited to certain species but is common among species. Our initial findings show that species with low inter-individual deviations in isotopic composition are more suitable as direct proxies of the bottom water environment. Moreover, the magnitude of the inter-species and inter-individual vital effect can be simplified to its correlation with the mass of the individual calcite shell.

3.2 Application of inter-individual isotopic variations to estimate more reliable isotopic values of bottom water in the past

Although we found that the species with smaller isotopic deviations are more suitable as environmental proxies, some of those species (*U. akitaensis* and the *Cassidulina* group) had carbon isotopic values that were slightly negative relative to ambient values ($\Delta\delta^{13}\text{C} \approx -2\text{‰}$). Therefore, we could not correctly estimate the original $\delta^{13}\text{C}_{\text{DIC}}$ values of water by using isotopic evidence from these species. However, Fig. 3 displays a trend of proportionally more negative average $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$ values of species with increasing inter-individual variations. We determined the relationship between average $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values and inter-individual distributions (SD within species) at the two sites in the Sea of Okhotsk (Fig. 5a and b). The regression lines all have high correlation coefficients ($r^2 > 0.8$), indicating that the coefficients of variation are almost

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constant. Moreover, the intercepts of the regression lines (at $SD = 0$) for $\delta^{13}C$ are almost identical to the $\delta^{13}C_{DIC}$ (Table 3). In foraminiferal samples collected from Sagami Bay, we found the same trend in the $\delta^{13}C$ profile (Fig. 5c, $r^2 = 0.998$), and the intercept of the regression line also corresponded to the $\delta^{13}C_{DIC}$ values in the bay. The differences between the intercept values and the actual $\delta^{13}C_{DIC}$ at these three sites are within 0.3‰, substantially closer to $\delta^{13}C_{DIC}$ than the $\Delta\delta^{13}C$ values of all species.

We conclude that we can more reliably estimate $\delta^{13}C_{DIC}$ values of bottom water by accounting for the vital effect in foraminifera. This technique promises to yield $\delta^{13}C$ data for bottom water where water samples are not available. On the other hand, there is still uncertainty in $\delta^{18}O_{e.c.}$ values owing to changes of bottom water temperature and analytical errors in measuring $\delta^{18}O$ of water. In addition, the choice of equation for calculating $\delta^{18}O_{e.c.}$ affects the results; for example there is a 0.7‰ difference in $\delta^{18}O_{e.c.}$ values at our study sites as calculated by the equations of Friedman and O'Neil (1977) and Kim and O'Neil (1997). We propose applying the isotopic vital effect using the inter-individual isotopic distributions of species as an index of the reliability of bottom water isotope values. Also the $\delta^{13}C_{DIC}$ can be reconstructed from foraminiferal isotopes without water samples by correcting for the vital effect. This permits the utilization of stored sediment samples from throughout the world, even those with no associated isotopic data for bottom water. In addition, we can estimate the absolute $\delta^{13}C$ changes in the ocean bottom by comparing the calibrated isotope values to the relative $\delta^{13}C$ curves previously reported, and thereby better understand worldwide environmental changes.

3.3 Possible causes of inter-species and inter-individual isotopic variations

In contrast, even considering the isotopic variation in sediments owing to the decomposition of organic matter and the presence of a geothermal gradient, we cannot account for the extremely negative isotopic values and the large interindividual variation in $\delta^{13}C$ and $\delta^{18}O$, especially observed in *B. pacifica* and *Stainforthia* sp. The $\delta^{13}C$ values of most individuals were much lower than $\delta^{13}C_{DIC}$ values of pore water at the sediment

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depth of which they had been taken (Tables 1 and 2). Furthermore, the $\delta^{18}\text{O}$ variation of 6‰ among species (Fig. 3) corresponds to a temperature difference of $\pm 24^\circ\text{C}$ which is greater than the geothermal gradient. The isotopic variation may instead be related to the carbonate ion concentration ($[\text{CO}_3^{2-}]$) effect that is hypothesized as controlling $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in calcifying organisms (Spero et al., 1997). $\delta^{18}\text{O}$ in planktonic foraminifera reportedly decreases with increasing $[\text{CO}_3^{2-}]$ and pH (Spero et al., 1997). We observed a similar trend in the isotopic shift among benthic species (Fig. 6). This similarity between laboratory experiments with planktonic foraminifera and our natural samples of benthic foraminifera suggests that the inter-individual and inter-species isotopic variations are strongly affected by the $[\text{CO}_3^{2-}]$ effect. However, infaunal species, such as *B. pacifica* and *Stainforthia* sp. in particular, should have positive isotopic values because of the low pH and decreased $[\text{CO}_3^{2-}]$ of ambient water in sediment resulting from decomposition of organic matter (Bemis et al., 1998). Our results show the opposite trend.

Recent findings suggest a novel explanation for the extremely negative and heterogeneous interindividual isotopic compositions of some benthic foraminifera. One study of intracellular calcification found that a widespread strategy among benthic foraminifera is to elevate the pH at the site of calcification to promote calcite precipitation, and described a mechanism that produces a ^{13}C -depleted foraminiferal shell (de Nooijer et al., 2009). This mechanism would explain the negative shift of $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$. Heterogeneity of pH in foraminiferal cells may thus be one cause of the interindividual differences in isotopic compositions observed in this study.

Another study reported that some benthic foraminifera accumulate intracellular nitrate stores that are respired through denitrification (Risgaard-Petersen et al., 2006) and nitrate pooling is reported as common in foraminifera, including species closely related to *B. pacifica* and *Stainforthia* sp., from very diverse benthic marine environments (Pina-Ochoa et al., 2010). Evidence for isotopic fractionation of $\delta^{18}\text{O}$ through denitrification has been reported previously (Sigman et al., 2005) indicating that ^{18}O -depleted nitrate is respired during denitrification. Although details of the isotopic fractionation

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through respiration and calcification in foraminiferal cells are not well known, high concentrations of nitrate in such species and its respiration through intracellular denitrification is expected to alter the isotopic composition and the magnitude of isotopic variation. Moreover, both intracellular calcification and denitrification occur at the individual level and any associated isotopic fractionation would affect individuals and not the entire population, thus potentially leading to larger interindividual isotopic differences. On the other hand, vital effects were originally thought to result from the incorporation of isotopically depleted carbon and oxygen compounds derived from the metabolic CO₂ pool within an organism into its shell (Grossman, 1987; Erez, 2003). It appears that these metabolic vital effects, some other vital effects (Rohling and Cooke, 1999; Mackensen, 2008), and microenvironmental heterogeneity (Mackensen et al., 1993) play roles in the observed inter-individual differences in isotopic signatures, and their intensity is reflected in the magnitude of inter-individual isotopic variations. Further *in situ* biological observations and culture experiments such as those in previous studies (Spero et al., 1997; Hintz et al., 2004; Nomaki et al., 2005; Risgaard-Petersen et al., 2006; McCorkle et al., 2008; de Nooijer et al., 2009; Pina-Ochoa et al., 2010) should help to clarify the mechanisms responsible for large interindividual isotopic variations in foraminifera.

4 Conclusions

In this study, we show a simplified analysis of the vital effect in benthic foraminifera based on inter-individual isotopic variations, and its application to estimating bottom water conditions precisely. We analyzed isotopes in individual foraminifera of multiple benthic species from the same environments and found that the magnitude of the vital effect in each species was correlated with the inter-individual variation. Therefore, we can choose suitable species as bottom water proxies by using inter-individual isotopic variations. Furthermore, by using the simplified interpretation of the vital effect established in this study, we can reconstruct $\delta^{13}\text{C}$ values of dissolved inorganic carbon in

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bottom water from foraminiferal isotopic compositions where water samples are not available, by correcting for the isotopic shift (vital effect).

Benthic foraminifera have been distributed widely in the ocean from the Cambrian period to the present. Our method on the basis of clarifying the inter-individual isotopic variations of foraminifera can be used to evaluate the suitability of benthic foraminiferal taxa as stable isotope indicators of paleoceanographic conditions, and to detect potential errors associated with their use. Our findings enable us to use the isotope data from all benthic foraminifera as more reliable proxies for reconstructing past bottom water conditions.

Supplementary material related to this article is available online at:
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Table 1. $\delta^{13}\text{C}$ of dissolved inorganic carbon, $\delta^{18}\text{O}$ of water samples, and water temperature in the study area.

Site	Sea of Okhotsk (MR06-4 St.4) (44°31' N, 145°00' E)		
Water depth	1208 m		
Water depth (m)	$10^3 \times \delta^{13}\text{C}$ (VPDB)	$10^3 \times \delta^{18}\text{O}$ (VSMOW)	Temperature (°C)
30	+0.9	-0.7	-
50	+1.0	-0.6	-
75	+0.8	-0.6	-
100	+0.9	-0.6	-
200	+0.9	-0.6	-
300	+0.6	-0.6	-
500	-0.5	-0.5	-
700	-0.3	-0.4	2.2
1000	-0.3	-0.4	2.3
1158	-0.4	-0.4	2.3
Site	Sea of Okhotsk (MR06-4 St.4) (44° 31' N, 145° 00' E)		
Water depth	1208 m		
Depth in sediment (cm)	$10^3 \times \delta^{13}\text{C}$ (VPDB)	$10^3 \times \delta^{18}\text{O}$ (VSMOW)	Temperature (°C)
Bottom water	-0.4	-0.3	2.3
2	-0.2	-0.4	-
4	-0.3	-0.6	-
7	-0.6	-0.5	-
60	-	-0.4	-
Site	Nankai Trough (33°40' N, 136° 37' E)		
Water depth	2040 m		
Depth in sediment (cm)	$10^3 \times \delta^{13}\text{C}$ (VPDB)	$10^3 \times \delta^{18}\text{O}$ (VSMOW)	Temperature (°C)
Bottom Water	-1.0	-0.1	1.9
1	-1.2	-0.1	-
2	-1.3	-0.2	-
3	-2.6	-0.2	-
5	-2.9	0.0	-
7	-2.7	-0.2	-
9	-2.6	-0.3	-
Site	Sagami Bay (35°00' N, 139°14' E)		
Water depth	1182 m		
Depth in sediment (cm)	$10^3 \times \delta^{13}\text{C}$ (VPDB)	$10^3 \times \delta^{18}\text{O}$ (VSMOW)	Temperature (°C)
Bottom water	0.0	-0.2	2.9

The isotopic data from the Nankai Trough are from Toki (2004).

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Table 2a. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of individual foraminiferal shells collected from the surface sediment at study sites, as well as the averages of multiple specimens analyzed together. $\Delta\delta^{13}\text{C}$, isotopic difference between the $\delta^{13}\text{C}$ of analyzed foraminiferal shell and the $\delta^{13}\text{C}$ of DIC ($\delta^{13}\text{C}_{\text{DIC}}$) in bottom water; $\Delta\delta^{18}\text{O}$, isotopic difference between the $\delta^{18}\text{O}$ of analyzed foraminifera and the $\delta^{18}\text{O}$ of calcite in equilibrium with bottom water ($\delta^{18}\text{O}_{\text{e.c.}}$).

Species	Depth (cmbsf)	Number of specimens analyzed	Individual weight (μg)	$10^3 \times \delta^{13}\text{C}$ Relative to VPDB	$10^3 \times \delta^{18}\text{O}$	$10^3 \times \Delta\delta^{13}\text{C}$	$10^3 \times \Delta\delta^{18}\text{O}$
<i>Bulimina aculeata</i> (Nankai Trough, water depth 2040 m)							
<i>Bulimina aculeata</i>	0–7	1	23.12	–1.56	+3.12	–0.56	–0.24
<i>Bulimina aculeata</i>	0–7	1	21.30	–1.10	+3.13	–0.10	–0.23
<i>Bulimina aculeata</i>	0–7	1	10.93	–0.84	+2.99	+0.16	–0.37
<i>Bulimina aculeata</i>	0–7	1	12.53	–1.49	+3.14	–0.49	–0.23
<i>Bulimina aculeata</i>	0–7	1	48.33	–1.13	+3.32	–0.13	–0.04
<i>Bulimina aculeata</i>	0–7	1	20.56	–1.32	+3.21	–0.32	–0.15
<i>Bulimina aculeata</i>	0–7	1	17.57	–1.25	+3.27	–0.25	–0.10
<i>Bulimina aculeata</i>	0–7	1	5.50	–1.49	+3.20	–0.49	–0.16
Average, 1σ	0–7	8	19.98	-1.27 ± 0.24	$+3.17 \pm 0.10$	–0.27	–0.19
<i>Cassidulina norvangi</i> (Sea of Okhotsk, water depth 870 m)							
<i>Cassidulina norvangi</i>	0–1	1	3.33	–1.91	+2.21	–1.51	–0.76
<i>Cassidulina norvangi</i>	0–1	1	3.66	–1.70	+2.86	–1.30	–0.11
<i>Cassidulina norvangi</i>	0–1	1	3.96	–1.42	+2.77	–1.02	–0.20
<i>Cassidulina norvangi</i>	0–1	1	4.46	–1.59	+2.53	–1.19	–0.44
<i>Cassidulina norvangi</i>	0–1	1	5.71	–1.50	+3.19	–1.10	+0.22
<i>Cassidulina norvangi</i>	0–1	1	2.80	–1.90	+2.86	–1.50	–0.11
<i>Cassidulina norvangi</i>	0–1	1	4.90	–1.18	+3.08	–0.78	+0.11
<i>Cassidulina norvangi</i>	0–1	5	4.84 (avg.)	–1.57	+3.15	–1.17	+0.18
<i>Cassidulina norvangi</i> (living)	0–1	1	3.73	–1.79	+3.17	–1.39	+0.20
<i>Cassidulina norvangi</i> (living)	0–1	1	4.31	–1.51	+3.07	–1.11	+0.10
<i>Cassidulina norvangi</i> (living)	0–1	5	4.45 (avg.)	–1.66	+3.03	–1.26	+0.06
<i>Cassidulina norvangi</i> (living)	5–6	1	4.29	–1.85	+3.03	–1.45	+0.06
<i>Cassidulina norvangi</i> (living)	5–6	1	2.58	–1.92	+3.13	–1.52	+0.16
<i>Cassidulina norvangi</i> (living)	5–6	1	1.59	–1.86	+2.85	–1.46	–0.11
<i>Cassidulina norvangi</i> (living)	5–6	1	4.17	–1.12	+1.70	–0.72	–1.26
<i>Cassidulina norvangi</i> (living)	5–6	1	1.72	–1.91	+2.60	–1.51	–0.37
<i>Cassidulina norvangi</i> (living)	7–8	1	5.03	–1.58	+2.84	–1.18	–0.12
<i>Cassidulina norvangi</i> (living)	7–8	1	2.94	–2.18	+2.96	–1.78	–0.01
<i>Cassidulina norvangi</i> (living)	7–8	1	4.66	–1.79	+3.11	–1.39	+0.14
<i>Cassidulina norvangi</i> (living)	7–8	1	2.33	–2.82	+3.19	–2.42	+0.22
Average, 1σ	0–1	19	4.39	-1.61 ± 0.21	$+2.90 \pm 0.30$	–1.21	–0.07
Average, 1σ	5–6	5	2.87	-1.69 ± 0.34	$+2.80 \pm 0.57$	–1.29	–0.17
Average, 1σ	7–8	4	3.74	-2.09 ± 0.55	$+3.02 \pm 0.15$	–1.69	+0.06
Total average, 1σ	0–8	28	4.02	-1.74 ± 0.36	$+2.87 \pm 0.37$	–1.34	–0.10
<i>Brizalina pacifica</i> (Sea of Okhotsk, water depth 870 m)							
<i>Brizalina pacifica</i>	0–1	1	1.06	–5.03	+0.63	–4.63	–2.34
<i>Brizalina pacifica</i>	0–1	1	0.99	–5.25	+0.68	–4.85	–2.29
<i>Brizalina pacifica</i>	0–1	1	0.92	–4.44	+1.37	–4.04	–1.60
<i>Brizalina pacifica</i>	0–1	1	0.74	–5.57	+1.84	–5.17	–1.13
<i>Brizalina pacifica</i>	0–1	1	0.35	–4.33	+1.46	–3.93	–1.51
<i>Brizalina pacifica</i> (living)	0–1	1	0.92	–6.08	+1.67	–5.68	–1.29
<i>Brizalina pacifica</i> (living)	0–1	5	0.68 (avg.)	–4.45	+2.15	–4.05	–0.82
<i>Brizalina pacifica</i> (living)	0–1	1	1.17	–5.65	+2.28	–5.25	–0.69
<i>Brizalina pacifica</i> (living)	0–1	1	1.02	–4.15	+1.00	–3.75	–1.97
<i>Brizalina pacifica</i> (living)	0–1	1	0.82	–4.74	+1.19	–4.34	–1.78
<i>Brizalina pacifica</i> (living)	0–1	1	0.88	–6.87	+1.81	–6.47	–1.16
<i>Brizalina pacifica</i> (living)	0–1	1	0.56	–5.75	+0.70	–5.35	–2.27

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Table 2b. Continued.

Species	Depth (cmbst)	Number of specimens analyzed	Individual weight (μg)	$10^3 \times \delta^{13}\text{C}$ Relative to VPDB	$10^3 \times \delta^{18}\text{O}$	$10^3 \times \Delta\delta^{13}\text{C}$	$10^3 \times \Delta\delta^{18}\text{O}$
<i>Brizalina pacifica</i> (living)	5–6	1	1.13	–1.93	+2.38	–1.53	–0.59
<i>Brizalina pacifica</i> (living)	5–6	1	0.81	–3.96	+2.44	–3.56	–0.52
<i>Brizalina pacifica</i> (living)	5–6	1	0.83	–3.38	+2.42	–2.98	–0.54
<i>Brizalina pacifica</i> (living)	5–6	1	0.59	–3.30	+2.05	–2.90	–0.91
<i>Brizalina pacifica</i> (living)	5–6	1	0.64	–4.16	+1.51	–3.76	–4.48
<i>Brizalina pacifica</i> (living)	7–8	1	0.67	–2.90	+1.17	–2.50	–1.80
Average, 1 σ	0–1	16	0.92	–5.19 $\pm$ 0.82	+1.40 $\pm$ 0.57	–4.79	–1.57
Average, 1 σ	5–6	5	0.80	–3.35 $\pm$ 0.87	+1.56 $\pm$ 1.72	–2.95	–1.41
Total average, 1 σ	0–8	22	0.80	–4.55 $\pm$ 1.22	+1.43 $\pm$ 0.96	–4.15	–1.54
<i>Stainforthia</i> sp. (Sea of Okhotsk, water depth 870 m)							
<i>Stainforthia</i> sp.	0–1	5	0.23 (avg.)	–4.26	+2.54	–3.86	–0.43
<i>Stainforthia</i> sp.	0–1	1	0.42	–6.65	+2.67	–6.25	–0.30
<i>Stainforthia</i> sp.	0–1	1	0.46	–4.15	+2.81	–3.75	–0.15
<i>Stainforthia</i> sp.	0–1	1	0.26	–5.19	+2.00	–4.79	–0.97
<i>Stainforthia</i> sp.	0–1	1	0.36	–4.16	+2.78	–3.76	–0.19
<i>Stainforthia</i> sp.	0–1	1	0.20	–8.24	+1.76	–7.84	–1.21
<i>Stainforthia</i> sp.	5–6	1	0.49	–3.53	+2.59	–3.13	–0.38
<i>Stainforthia</i> sp. (living)	5–6	1	0.25	–4.00	+2.41	–3.60	–0.56
<i>Stainforthia</i> sp. (living)	5–6	1	0.26	–5.51	–0.20	–5.11	–3.17
<i>Stainforthia</i> sp. (living)	5–6	1	0.41	–3.83	+2.54	–3.43	–0.43
Average, 1 σ	0–1	10	0.28	–5.44 $\pm$ 1.68	+2.43 $\pm$ 0.44	–5.04	–0.54
Average, 1 σ	5–6	4	0.35	–4.22 $\pm$ 0.88	+1.83 $\pm$ 1.36	–3.82	–1.13
Total average, 1 σ	0–6	14	0.30	–4.95 $\pm$ 1.49	+2.19 $\pm$ 0.90	–4.55	–0.78
<i>Brizalina pacifica</i> (Sea of Okhotsk, water depth 1208 m)							
<i>Brizalina pacifica</i>	0–1	1	0.44	–6.80	+0.05	–6.40	–2.92
<i>Brizalina pacifica</i>	1–2	1	0.61	–4.70	+1.49	–4.30	–1.48
<i>Brizalina pacifica</i>	1–2	1	0.39	–11.00	–1.59	–10.60	–4.56
<i>Brizalina pacifica</i>	1–2	1	0.76	–4.45	+1.28	–4.05	–1.69
<i>Brizalina pacifica</i>	7–8	1	0.31	–7.12	–0.77	–6.72	–3.74
Average, 1 σ	0–8	5	0.50	–6.81 $\pm$ 2.63	+0.09 $\pm$ 1.32	–6.41	–2.88
<i>Uvigerina akitaensis</i> (Sea of Okhotsk, water depth 1208 m)							
<i>Uvigerina akitaensis</i>	0–1	1	9.32	–1.59	+2.87	–1.19	–0.09
<i>Uvigerina akitaensis</i>	0–1	1	4.41	–1.90	+2.94	–1.50	–0.02
<i>Uvigerina akitaensis</i>	0–1	1	3.19	–1.62	+3.35	–1.22	+0.39
<i>Uvigerina akitaensis</i>	1–2	1	22.56	–0.99	+3.33	–0.59	+0.37
<i>Uvigerina akitaensis</i> (living)	5–6	1	16.55	–1.19	+3.61	–0.79	+0.64
Average, 1 σ	0–6	5	11.21	–1.46 $\pm$ 0.36	+3.22 $\pm$ 0.30	–1.06	+0.25
<i>Chilostomella ovoidea</i> (Sea of Okhotsk, water depth 1208 m)							
<i>Chilostomella ovoidea</i> (living)	0–1	1	3.19	–2.71	+2.63	–2.31	–0.34
<i>Chilostomella ovoidea</i>	1–2	1	6.99	–3.19	+3.58	–2.79	+0.61
<i>Chilostomella ovoidea</i> (living)	1–2	1	11.16	–2.43	+3.48	–2.03	+0.51
<i>Chilostomella ovoidea</i> (living)	1–2	1	13.98	–2.10	+3.07	–1.70	+0.10
<i>Chilostomella ovoidea</i> (living)	5–6	1	1.75	–3.56	+2.58	–3.16	–0.38
Average, 1 σ	0–6	5	7.41	–2.80 $\pm$ 0.59	+3.07 $\pm$ 0.46	–2.40	+0.10
<i>Islandiella norcrossi</i> (Sea of Okhotsk, water depth 1208 m)							
<i>Islandiella norcrossi</i> (living)	0–1	1	5.03	–0.93	+3.38	–0.53	+0.41
<i>Islandiella norcrossi</i> (living)	0–1	1	2.82	–1.31	+2.88	–0.91	–0.08
<i>Islandiella norcrossi</i> (living)	0–1	1	1.18	–1.76	+2.82	–1.36	–0.15
<i>Islandiella norcrossi</i> (living)	1–2	1	1.84	–1.52	+2.88	–1.12	–0.08
<i>Islandiella norcrossi</i> (living)	7–8	1	4.17	–0.88	+3.18	–0.48	+0.21
Average, 1 σ	0–8	5	3.01	–1.28 $\pm$ 0.39	+3.03 $\pm$ 0.24	–0.88	+0.06
<i>Globobulimina auriculata</i> (Sea of Okhotsk, water depth 1208 m)							
<i>Globobulimina auriculata</i> (living)	0–1	1	1.43	–2.07	+3.32	–1.67	+0.36
<i>Globobulimina cf. auriculata</i> (living)	0–1	1	168.73	–0.69	+3.73	–0.29	+0.77
<i>Globobulimina auriculata</i> (living)	1–2	1	0.72	–3.51	+2.45	–3.11	–0.52
<i>Globobulimina auriculata</i> (living)	5–6	1	1.37	–2.09	+3.43	–1.69	+0.46

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Table 2c. Continued.

Species	Depth (cmbstf)	Number of specimens analyzed	Individual weight (µg)	$10^3 \times \delta^{13}\text{C}$ Relative to VPDB	$10^3 \times \delta^{18}\text{O}$	$10^3 \times \Delta\delta^{13}\text{C}$	$10^3 \times \Delta\delta^{18}\text{O}$
<i>Globobulimina auriculata</i> (living)	5–6	1	0.51	–3.80	+1.93	–3.40	–1.04
Average, 1σ	0–6	5	34.55	–2.43 ± 1.26	+2.97 ± 0.76	–2.03	+0.01
Average, 1σ (small individual)	0–6	4	1.01	–2.87 ± 0.92	+2.78 ± 0.72	–2.47	–0.19
<i>Takayanagia delicata</i> (Sea of Okhotsk, water depth 1208 m)							
<i>Takayanagia delicata</i> (living)	0–1	1	3.43	–1.58	+3.24	–1.18	+0.27
<i>Takayanagia delicata</i> (living)	0–1	1	2.09	–2.15	+3.01	–1.75	+0.04
<i>Takayanagia delicata</i> (living)	1–2	1	2.37	–2.38	+2.61	–1.98	–0.36
<i>Takayanagia delicata</i> (living)	5–6	1	1.70	–2.52	+2.90	–2.12	–0.06
<i>Takayanagia delicata</i> (living)	7–8	1	3.07	–2.10	+2.88	–1.70	–0.08
Average, 1σ	0–8	5	2.53	–2.14 ± 0.36	+2.93 ± 0.23	–1.74	–0.04
Others (Sea of Okhotsk, water depth 1208 m)							
<i>Nonionella globosa</i>	1–2	1	1.90	–3.00	+3.14	–2.60	+0.17
<i>Nonionella globosa</i>	1–2	1	1.89	–2.82	+2.96	–2.42	–0.00
<i>Nonionella labradorica</i>	1–2	1	5.76	–1.14	+3.48	–0.74	+0.51
<i>Nonionella labradorica</i>	1–2	1	5.64	–0.96	+3.21	–0.56	+0.24
<i>Globobulimina affinis</i> (Sagami Bay, water depth 1182 m)							
<i>Globobulimina affinis</i> (living)	0–2	1	31.9	–3.43	+2.92	–3.41	–0.05
<i>Globobulimina affinis</i> (living)	0–2	1	43.4	–3.65	+3.32	–3.63	+0.35
<i>Globobulimina affinis</i> (living)	0–2	1	49.8	–1.58	+2.22	–1.56	–0.75
<i>Globobulimina affinis</i> (living)	0–2	1	7.4	–3.25	+2.78	–3.23	–0.18
<i>Globobulimina affinis</i> (living)	0–2	1	44.4	–2.43	+3.29	–2.41	+0.32
<i>Globobulimina affinis</i> (living)	0–2	1	5.9	–1.81	+3.03	–1.79	+0.06
Average, 1σ		6	30.5	–2.69 ± 0.88	+2.93 ± 0.41	–2.67	–0.04
<i>Chilostomella ovoidea</i> (Sagami Bay, water depth 1182 m)							
<i>Chilostomella ovoidea</i> (living)	0–2	1	4.7	–2.95	+2.89	–2.93	–0.08
<i>Chilostomella ovoidea</i> (living)	0–2	1	2.5	–5.25	+1.61	–5.23	–1.36
<i>Chilostomella ovoidea</i> (living)	0–2	1	6.5	–4.34	+2.94	–4.32	–0.03
<i>Chilostomella ovoidea</i> (living)	0–2	1	5.8	–2.49	+1.57	–2.47	–1.40
<i>Chilostomella ovoidea</i> (living)	0–2	1	5.9	–3.27	+2.73	–3.25	–0.24
<i>Chilostomella ovoidea</i> (living)	0–2	1	4.9	–4.94	+3.02	–4.92	+0.05
Average, 1σ		6	5.0	–3.87 ± 1.13	+2.46 ± 0.68	–3.85	–0.51
<i>Rutherfordoides</i> sp. (Sagami Bay, water depth 1182 m)							
<i>Rutherfordoides</i> sp. (living)	0–2	1	4.5	–1.18	+0.55	–1.16	–2.42
<i>Rutherfordoides</i> sp. (living)	0–2	1	6.5	–0.88	+2.92	–0.86	–0.05
<i>Rutherfordoides</i> sp. (living)	0–2	1	3.9	–1.56	+2.47	–1.54	–0.50
<i>Rutherfordoides</i> sp. (living)	0–2	1	7.5	–0.96	+3.07	–0.94	+0.10
<i>Rutherfordoides</i> sp. (living)	0–2	1	5.3	–1.13	+2.58	–1.11	–0.39
<i>Rutherfordoides</i> sp. (living)	0–2	1	3.9	–0.95	+2.61	–0.93	–0.36
Average, 1σ		6	5.3	–1.11 ± 0.25	+2.37 ± 0.92	–1.09	–0.60

Results of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analysis for *Cassidulina norvangi* reported in a previous study (Ishimura et al., 2004) are denoted by an asterisk.

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Table 3. Comparison of predicted isotopic values of calcite in equilibrium with bottom water at the study sites (intercepts of regression lines in Fig. 5) and the actual isotopic values of calcite in equilibrium with bottom water.

Isotopic values of calcite in equilibrium with bottom water				
Site	Estimated values (intercepts of regression lines in Fig. 5)		Actual values	
	$10^3 \times \delta^{13}\text{C}_{\text{DIC}}$ Relative to VPDB	$10^3 \times \delta^{18}\text{O}_{\text{e.c.}}$ Relative to VPDB	$10^3 \times \delta^{13}\text{C}_{\text{DIC}}$ Relative to VPDB	$10^3 \times \delta^{18}\text{O}_{\text{e.c.}}$ Relative to VPDB
Sea of Okhotsk (water depth 1208 m)	−0.6	+4.0	−0.4	+3.0
Sea of Okhotsk (water depth 870 m)	−0.7	+3.6	−0.4	+3.0
Sagami Bay (water depth 1182 m)	−0.3	+3.3	−0.0	+3.0

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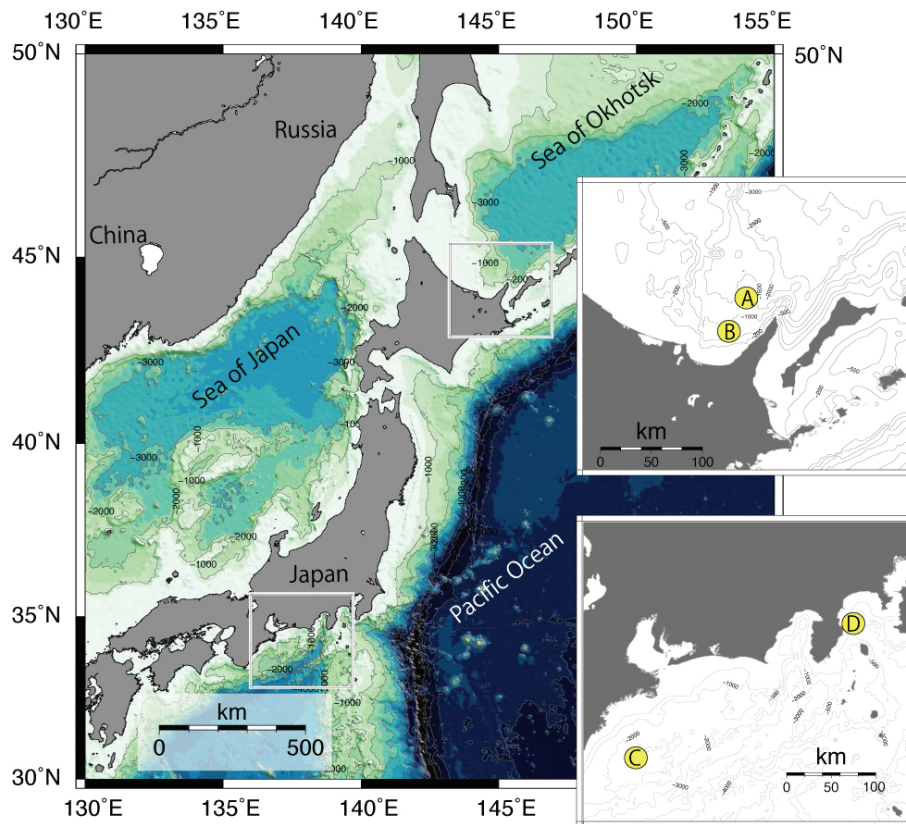



Fig. 1. Map of the study area and sampling sites. Site A (44°10' N, 144°45' E; water depth 870 m) and site B (44°31' N, 145°00' E; water depth 1208 m), Sea of Okhotsk off Abashiri; site C (33°42' N, 137°5' E; water depth 1881 m), Nankai Trough off Kumano; site D (35°00' N, 139°14' E; water depth 1182 m), Sagami Bay.

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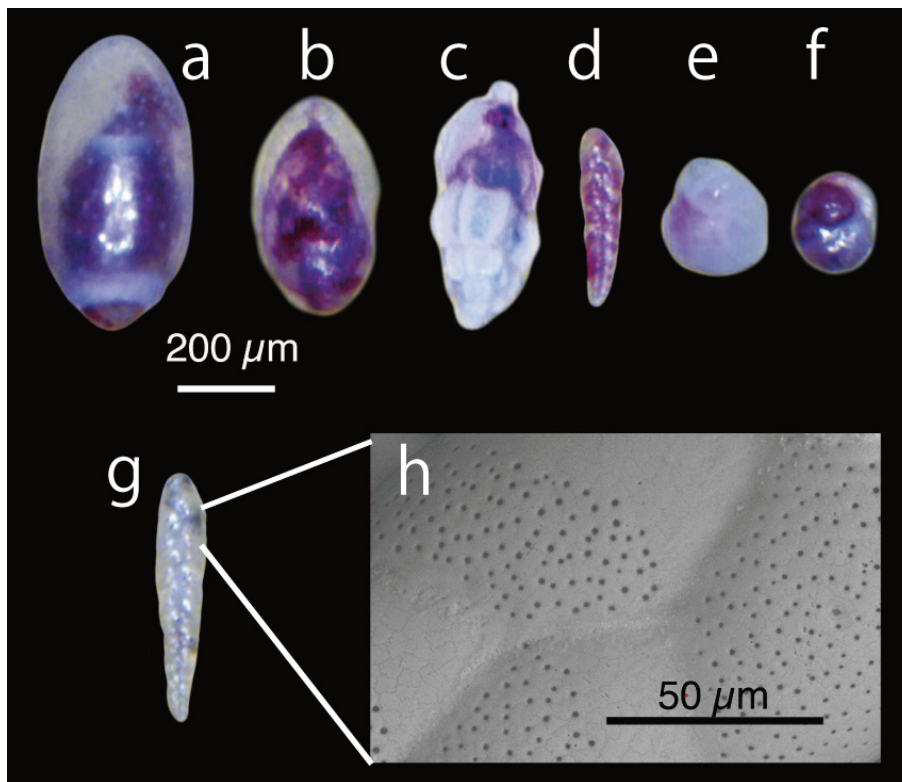


Fig. 2. Photomicrographs of Rose Bengal-stained specimens of analyzed foraminifera (a–g). (a) *Chilostomella ovoidea* (b) *Globobulimina auriculata*, (c) *Uvigerina akitaensis*, (d) *Brizalina pacifica*, (e) *Islandiella norcrossi*, (f) *Takayanagia delicata* (g) dead *B. pacifica* (h) Scanning electron micrograph of *B. pacifica*.

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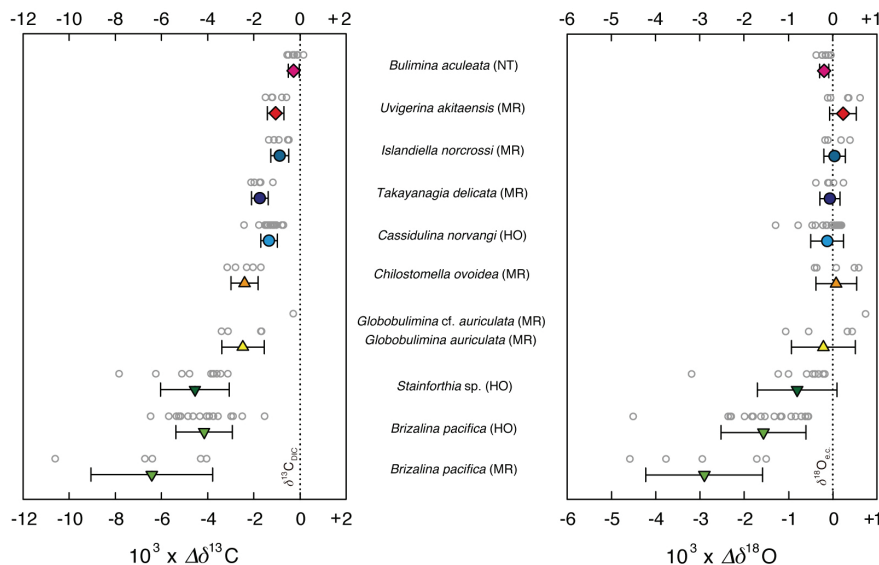


Fig. 3. Variations in $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$ values of individual benthic foraminifera together with average values. Open circles are individual isotopic values. Colored symbols are average values with standard deviations (error bars). Dotted lines indicate the $\delta^{13}\text{C}$ values of DIC in bottom water ($\delta^{13}\text{C}_{\text{DIC}}$) and the $\delta^{18}\text{O}$ values of calcite in equilibrium with bottom water ($\delta^{18}\text{O}_{\text{e.c.}}$). The $\delta^{18}\text{O}_{\text{e.c.}}$ values were calculated using the equation proposed by Friedman and O'Neil (1977). NT, Nankai Trough (1881 m); MR, Sea of Okhotsk (1208 m); HO, Sea of Okhotsk (870 m).

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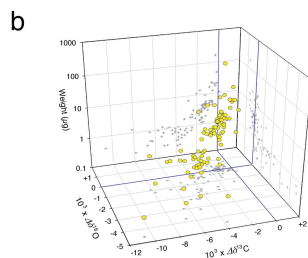
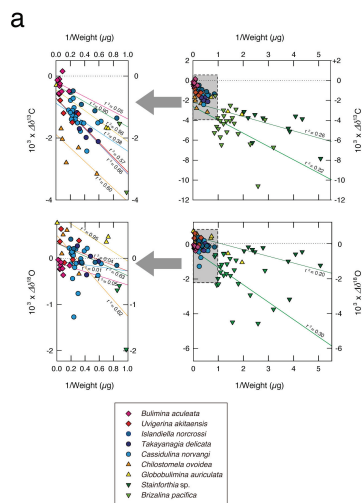


Fig. 4. Relationship between shell weight and $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$ values of individual benthic foraminifera **(a)** $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$ values of all individual benthic foraminifera analyzed plotted as a function of inverse shell weight. Lines are linear regressions fitted to each species. **(b)** Three-dimensional plot of $\Delta\delta^{13}\text{C}$, $\Delta\delta^{18}\text{O}$, and shell weight (animation available as Supplementary Fig. 1).

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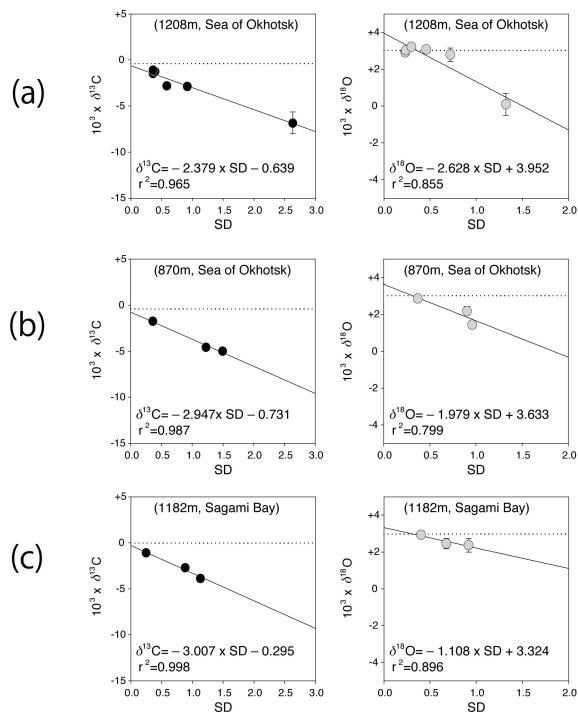


Fig. 5. Relationships between average $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values and inter-individual variations (SD; standard deviation) for each species of benthic foraminifera analyzed. **(a)** Sea of Okhotsk, 1208 m bottom depth; **(b)** Sea of Okhotsk, 870 m; **(c)** Sagami Bay, 1182 m. Solid lines and equations are linear regression results. Dotted lines represent $\delta^{13}\text{C}_{\text{DIC}}$ and $\delta^{18}\text{O}_{\text{e.c.}}$ at each site. Error bars indicate the range of standard error for each species.

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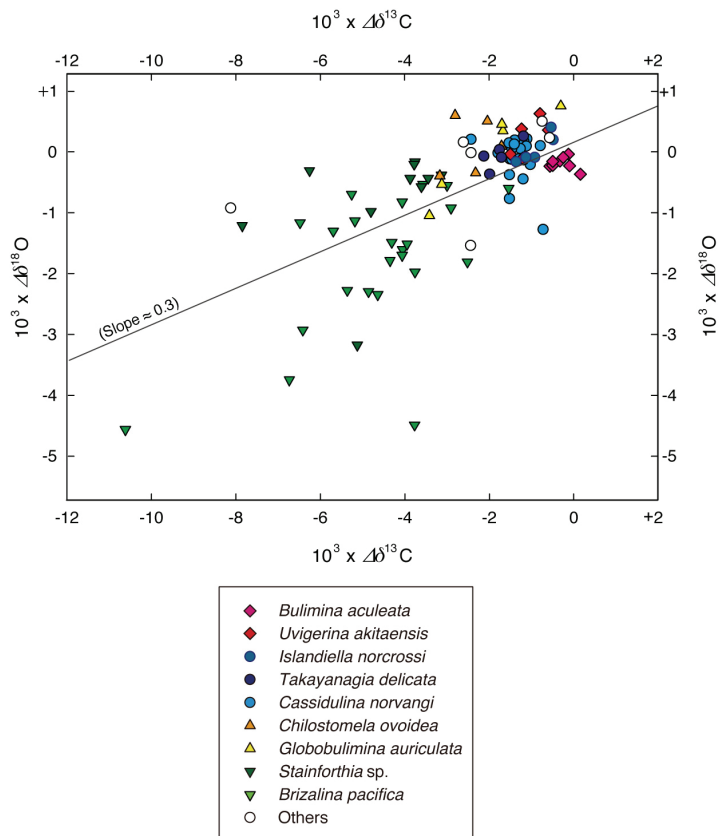


Fig. 6. Relationship between $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{18}\text{O}$ of individual benthic foraminifera. Solid line indicates the reported trend of the isotopic shift caused by the carbonate ion concentration effect (Spero et al., 1997).