Experimental Study of the Use of the Stable Isotopic Composition of Calcareous Microfossils in Shallow Marine Sediments for Reconstructing Paleoenvironment, and a Comparison with the MART Index

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ABSTRACT

For reconstruction of paleoenvironments using the isotopic compositions of shallow-water microfossils, especially benthic microfossils at high latitudes, difficulties arise due to variation in environmental factors, including seasonal temperature, depth, water currents, and habitat. In this study, we applied a microscale technique to determine stable carbon and oxygen isotopic ratios in shallow-water calcareous benthic microfossils (foraminifera and bryozoans), in order to choose suitable species for reconstructing paleoenvironmental changes in a Pleistocene shallow marine setting. We compared isotopic trends in *Cibicides refulgens*, a shallow water epibenthic foraminifer, with the mean annual range of temperature (MART) based on bryozoan analyses. We found no strong trend in $\delta^{13}C$ composition in the foraminifers from stratigraphically sequential sediment samples of the Soebetsu Sandstone Member (~0.8 Ma) of the Pleistocene Setana Formation, but did find $\delta^{18}O$ isotopic fluctuation among samples that was larger than the range of isotopic variation among individual foraminifera. MART values were almost identical from two strata showing a large difference in $\delta^{18}O$ composition. We interpret our results to mean that the $\delta^{18}O$ isotopic composition of benthic foraminifera was affected mainly by global and/or regional environmental changes rather than local temperature variation on the seafloor, in contrast to MART analysis, which reflects only annual range in local temperature. Further studies are needed on possible correlations between MART values and microscale isotopic determinations for calcareous microfossils in high-latitude shallow-water paleoenvironments.

Keywords: Calcareous microfossil, Carbon, Oxygen, Shallow-water environment, Stable isotope, MART analysis

INTRODUCTION

The stable carbon and oxygen isotopic compositions ($\delta^{13}C$ and $\delta^{18}O$) of carbonate, especially biological calcite (e.g., foraminifera and corals), are useful as environmental tracers to reconstruct paleo-

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climates. However, evaluation of temperature fluctuation from the microfossil record is difficult in shallow-water environments, especially at high latitudes, for several reasons: seasonal and diurnal variations in temperature are larger than in deep water; ecological differences between individuals affect their isotopic compositions; and variation due to ocean currents is complicated. In situations where stable isotope analyses are unreliable, a proxy technique recently developed with bryozoans to estimate mean annual range of temperature (MART) [1] may provide information about paleoseasonality. In cheilostome bryozoan colonies, zooid size varies ecophenotypically with water temperature; the colder the water, the larger the zooids. This means that the greater the annual variation in temperature, the more variability there will be in zooid size within a colony. MART analysis measures the mean coefficient of variation among colonies of a bryozoan species in a particular environment and uses this to estimate the paleo-MART.

The aims of this study were as follows:

(1) To understand the microscale isotopic variability of shallow water calcareous microfossils using a microscale isotopic-analysis technique developed by Ishimura et al. [2].

(2) To determine reliable temperature and/or environmental indices in this shallow water environment by using calcareous benthic microfossils.

(3) To clarify whether the stable isotopic compositions of benthic foraminifera and bryozoans give estimates of trends in paleotemperature also reflected in MART values measured for bryozoans in a mid-Pleistocene deposit.

If we can use isotopic variation in foraminifera to validate the usefulness of MART as a paleoclimatic index, we then can justify the use of MART values in shallow depositional environments. It is noteworthy that neither isotopic compositions nor MART values indicate absolute paleotemperatures. Trends in changes in isotopic values can reflect warming or cooling of the environment. MART values provide a measure of degree of seasonality, such as temperate versus polar/tropical conditions. Similarly to isotopic values, a trend of change in MART values can indicate a change in climate.

MATERIAL AND METHODS

Material

We collected stratigraphically sequential samples of sediment, and of pebbles and macrobenthic fossils (mostly bivalve shells) encrusted by bryozoans, from the Soebetsu Sandstone Member in the Soebetsu Section (middle Pleistocene, ~ 0.8 Ma) of the upper Setana Formation [3–5] at Kuromatsunai (Figs. 1, 3), SW Hokkaido. We washed and dried the bryozoan-encrusted pebbles and macrobenthic fossils, and sorted foraminifera and bryozoans from the sediment samples.

Stable isotope determination

Using an analytical method [2] that determines the stable carbon and oxygen isotope ratios in minute amounts (< 10 μg) of calcite, we determined the isotopic compositions of individual foraminifera and

Fig. 1 Map of Hokkaido Island, Japan, showing the location of Kuromatsunai, where samples were collected from deposits of the Setana Formation.

fragments of bryozoan colonies. Some foraminiferan species initially showed large individual variation in isotopic composition, which is affected by multiple factors in shallow-water environments. Therefore, we conducted preliminary measurements to determine the species with highest homogeneity in isotopic composition for comparison with MART values. We also measured the isotopic composition for one species of bryozoan, *Microporina articulata*, chosen for analysis because detached internodes of this branched, flexible, erect species were common in most of the sediment samples (this species was reported from the Setana Formation over seventy years ago [6]). For isotopic analysis, we carefully chose internodes for which microscopic observation showed no secondary addition of carbonate. For one of those internodes, we measured the isotopic composition of the outer wall and the freshly exposed (by cutting) inner wall to check for differences.

MART analysis

Bryozoans from the sediment samples were too few to provide the recommended [1] five colonies per species. We utilized a modified method called SL-MART (specimen-limited MART, described in ref. [7]) for the Soebetsu samples. Even then, there was sufficient bryozoan material to perform SL-MART analyses for only two of the strata that gave oxygen isotopic values divergent from one another (SOE017 and SOE023, the latter inferred to have a low value from measurements of adjacent strata SOE022 and SOE024). We also conducted standard MART analyses of two species (*Porella concinna* and *Escharoides hataii*) from specimens collected from the Nakasato Conglomerate Member in the nearby Utasai (Kokemushi Paradise) Section of the lower Setana Formation [5, 7].

RESULTS AND DISCUSSION

Stable isotopes

Though the isotopic dispersion (i.e., variation) in several foraminiferan species was as great as or greater than that which reflects warm-cool environ-

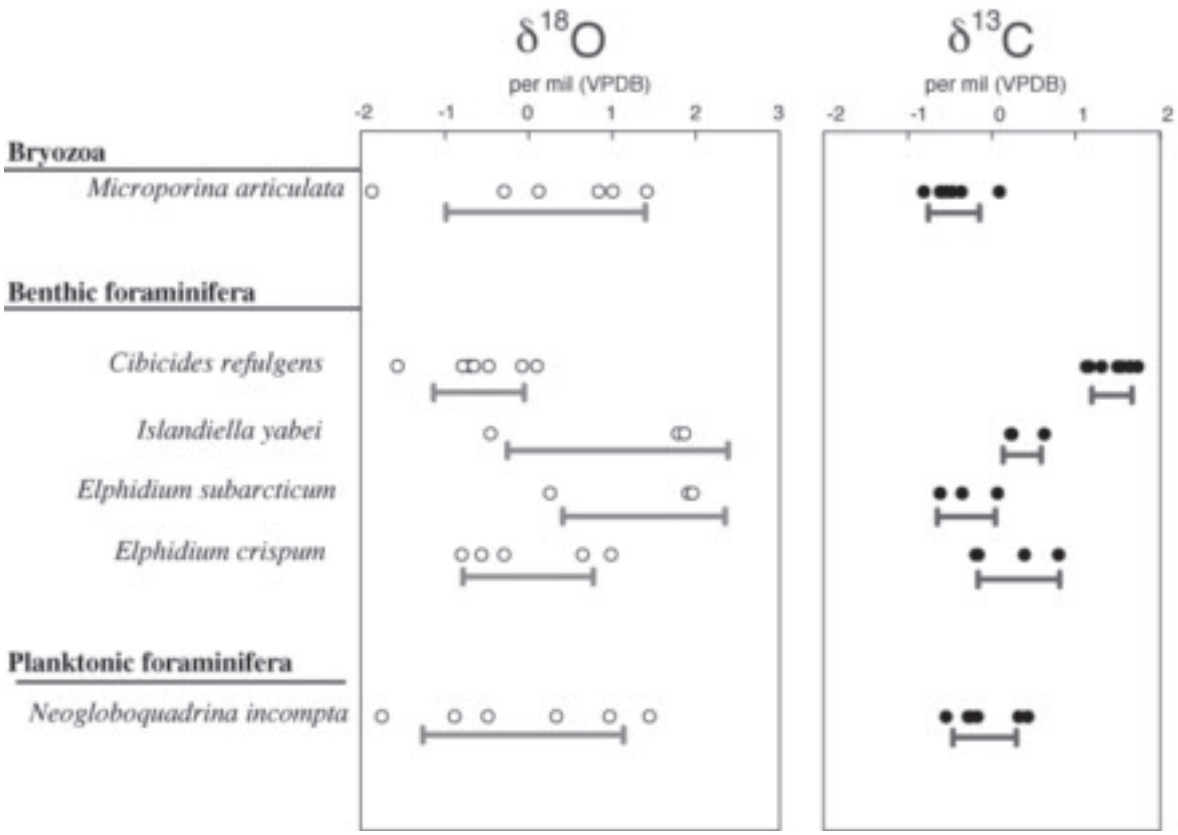

Fig. 2 Stable oxygen and carbon isotopic dispersions of calcareous microfossils collected from SOE039 (the sample horizon is shown in Fig. 3) with 1-sigma standard deviations (bars). Analytical values (circles) are from analyses of single individuals of benthic and planktonic foraminifera, and of separate internodes of the bryozoan *Microporina articulata*.

mental changes (i.e., the "noise" was equal to or greater than the "signal"), the benthic foraminifera *Cibicides refulgens* showed less heterogeneity in individual isotopic composition than the other species examined (Fig. 2). Inter-individual variation in the bryozoan (*Microporina articulata*) was as pronounced as in the most heterogeneous foraminiferan species studied. In addition, we found a large difference (1.3 per mil) in the $\delta^{18}O$ values between the inner and outer walls of a single internode of this species.

Cibicides refulgens initially showed the least heterogeneity in individual isotopic composition, and we analyzed multiple specimens (one or three individuals per measurement) of this species from each sample to clarify the isotopic dispersions and average values of isotopic composition. We found $\delta^{18}O$ isotopic fluctuation among samples that was larger than the range of isotopic variation among individual foraminifera (Fig. 3) in some of the samples. That is, the best-fit curve through the $\delta^{18}O$ sample points ranged from around + 0.4 per mil (SOE055) to

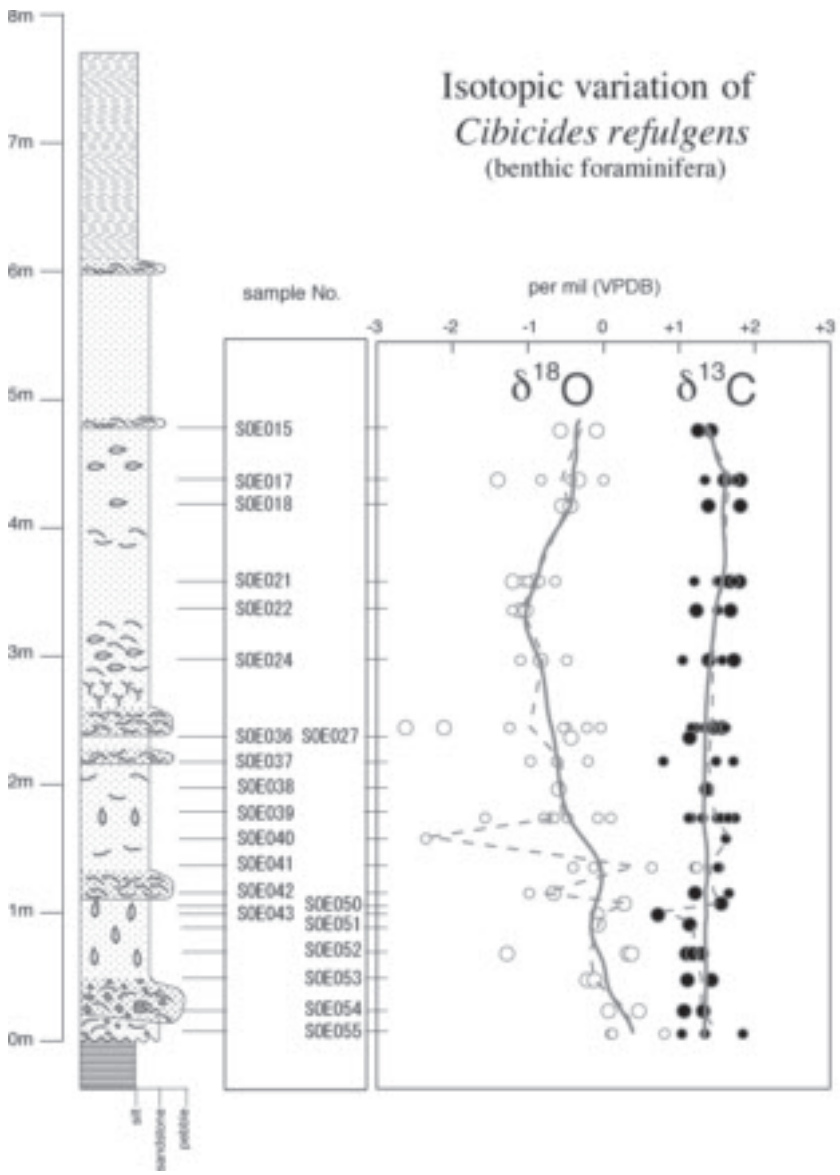

Fig. 3 Column (left) of the Soebetsu Sandstone Member in the Soebetsu Section [5], corresponding sample numbers (center), and variation in the stable oxygen and carbon isotopic compositions of *C. refulgens* (right). Larger and smaller circles indicate 3-individual and 1-individual measurements, respectively. Gray line was fit to both the $\delta^{18}O$ and $\delta^{13}C$ values; single low value of $\delta^{18}O$ for SOE040 was ignored. For both sets of values, dashed lines connect weighted averages.

−1.1 per mil (SOE022), whereas some samples like SOE018, 022, 053, and 054 show much narrower dispersions. The larger isotopic dispersions in other samples (e.g., SOE17, 39, 41, 52 and especially SOE036 in condensed section) may have been influenced to a greater or lesser extent by the reworking of sediment, invisible carbonate contamination, and/or local environmental factors.

In general, the $\delta^{18}O$ values of benthic calcareous shells are significantly affected both by local temperature variation (seasonal changes and depth variation) on the seafloor and by global changes in $\delta^{18}O$ values in seawater that are controlled by polar ice volumes. We interpret the trends evident in the $\delta^{18}O$ values of *C. refulgens* to primarily reflect the latter, for several reasons. First, the $\delta^{18}O$ fluctuation in *C. refulgens* shows a magnitude and trends similar to regional and/or global warm-cool fluctuation previously found at the same locality [8] using other proxies (Fig. 4). Furthermore, many benthic fora-

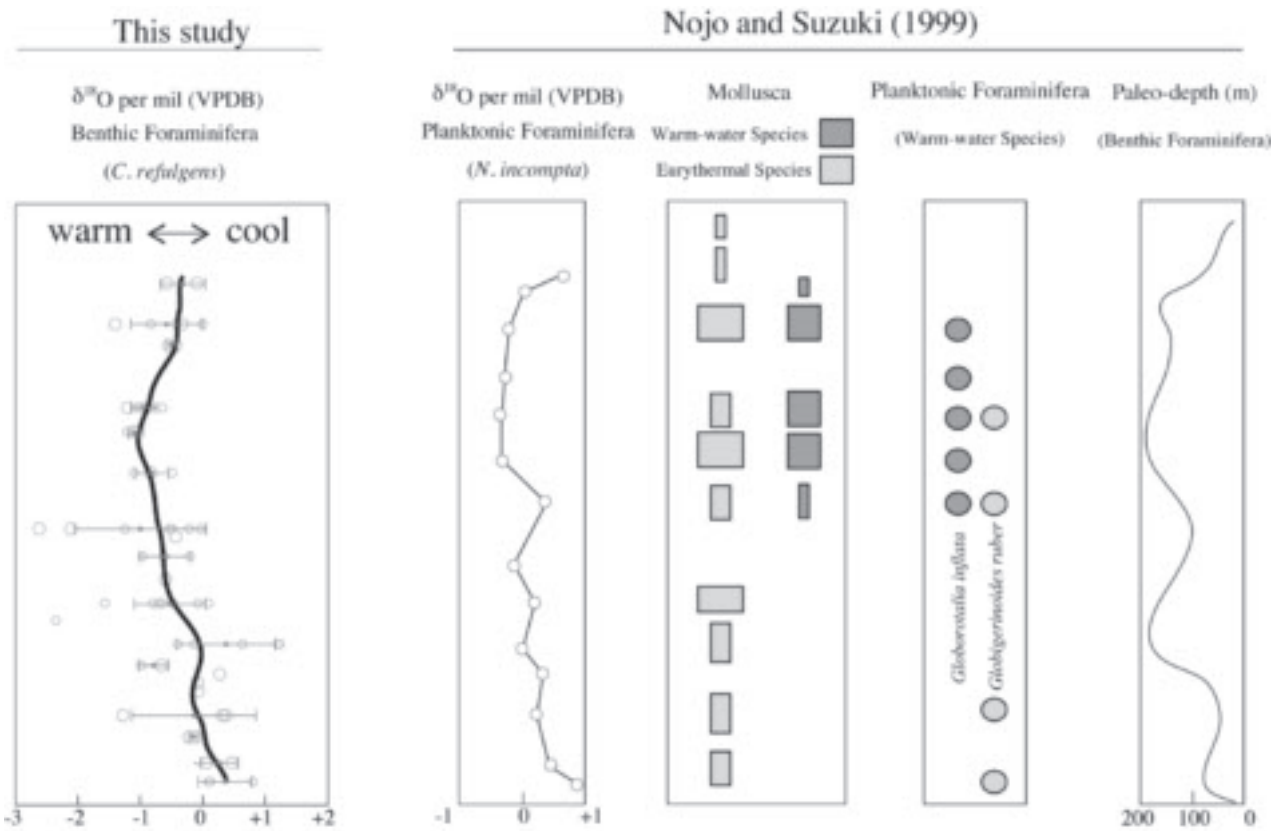

Fig. 4 Comparison of the $\delta^{18}O$ trend observed in this study with the paleoenvironmental reconstruction proposed by Nojo and Suzuki [8].

Table 1 MART values estimated from fossil bryozoans from the Soebetsu River and Utasai (Kokemushi Paradise) Sections, Kuromatsunai, SW Hokkaido, Japan (Table adapted from ref. [7]).

Locality	Formation (Age)	MART-analysis Type	Sample No.	Species	Calculated MART (°C)	Average MART (°C)
Soebetsu River	Upper Setana (0.6 ~ 1.0 Ma)	SL-MART	Stratum SOE-017	—	8.9	
Soebetsu River	Upper Setana (0.6~1.0 Ma)	SL-MART	Stratum SOE-023	—	8.2	
Kokemushi Paradise	Lower Setana (1.0~1.2 Ma)	Standard	—	*Porella concinna* *Escharoides hataii*	11.5 11.9	11.7

minifera reproduce and grow seasonally during a preferred temperature range, rather than year-around, which would tend to reduce the local contribution to variation in $\delta^{18}O$ values; if this is true for *C. refulgens*, then trends in $\delta^{18}O$ over the time interval of the strata examined should largely reflect fluctuation due to global changes. Finally, the paleo-depth at the time of deposition of SOE21–24 was estimated [8] to be deep (Fig. 4), and if colder temperatures at depth were strongly affecting $\delta^{18}O$ values, these values should have been positive rather than negative.

Mart analyses

MART values (Table 1) for the two bryozoan species from the Utasai (Kokemushi Paradise) Section of the lower Setana Formation were 11.5°C and 11.9°C (average = 11.7°C). The molluscan fauna suggests that this member was primarily deposited in a cool-temperate, shore-face environment, though the lower part of the member contains subarctic faunal elements [5]. Cool-temperate to subarctic environments should yield sea-surface MART values of around 15–16.5°C [4, 7]. Our reconstructed MART was lower, and the reason for this discrepancy is unknown. One explanation could be deposition at greater depth than thought, which would have reduced the MART.

The SL-MART values from strata SOE017 and 023 of the Soebetsu Member were also very similar to one another (8.9 and 8.2°C, respectively) and did not seem to show a strong trend parallel to the difference in oxygen isotopic value of around 0.6 per mil observed between these strata (compare SOE022/024 with SOE017 in Fig. 3), although unfortunately MART values were obtained for only the two strata. The MART values from the lower-Setana Utasai Section were higher than those from the upper-Setana Soebetsu Section, indicating reduced seasonality (environmental cooling?) between the lower- and upper-Setana strata sampled.

SUMMARY

Although some calcareous benthic microfossils show large isotopic variability, we can select suitable species, those having small isotopic dispersions, for paleo-environmental studies. The $\delta^{18}O$ values of *C. refulgens* indicate warm-cool environmental fluctuations in the Setana Formation. The SL-MART values did not seem to parallel changes in oxygen isotopic values of benthic foraminifera observed in this study, which is still in progress. The isotopic analysis of microgram amounts of calcite is a new technique, and this study represents its first practical application. Further data on the isotopic compositions of the bryozoans and foraminiferans under study, and a better understanding of how environmental factors in modern nearshore waters affect isotopic composition will improve the resolution in this study.

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