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Tide-induced reworking of planktonic foraminifers on the outer shelf and slope off the Miyako Island, southern Ryukyus, Japan: Preliminary results

By

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with 3 tables and 3 figures

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Abstract: Significance of sediment reworking to a shallower environment is preliminarily discussed by occurrences and oxygen isotopes of planktonic foraminifer (*Globolotalia inflata*) tests collected from the sea bottom sediments on the insular shelf to slope, off the Miyako Islands, southern Ryukyus, Japan. The isotopic data and comparison with the present water temperature-depth profile indicate that vertical distribution of *G. inflata* with size of 300-355μm ranges from 135 to 250m (average 160m). Strong tidal currents between the East China Sea and the Pacific Ocean developed in the study area may induce the transpotation of sediment particles to a shallower environment. This is demonstrated by the occurrences of this species in sediment deposited in depth shallower than inhabiting depth. The analyzed tests were not altered by long-time contact with bottom water because they preserve surface structures and a narrow range of oxygen isotopic composition. Shortly after *G. inflata* died and settled on sea bottom, the tests were commonly transported to the shallower environment by the upwelling, which may result from strong tidal currents and the topographic feature of the Ryukyu Island Arc.

I. Introduction

The oxygen isotopic composition of fossil planktonic foraminifers in shallow-water carbonates can be an important tool for understanding the Quaternary paleoceanographic conditions of marginal seas, including coral reef regions (e.g., Sakai and Kano, 2001). However, planktonic foraminifers living in shallow water are normally transported before their burial into sediments, and their initial isotopic compositions can be altered by early diagenesis under a low sedimentation rate. In order to reconstruct environments by using the foraminifer isotopic signals, transportation processes and routes should be understood.

According to a research on sediment traps from shelf margin to continental slope areas in the East China Sea by Yamazaki et al. (2001), foraminifer tests in shelf margin to continental slope sediments were reworked mainly by tidal currents, and were buried in deeper and shallower environments. Brunner and Biscaye (1997), who studied sediment transportation in the Delmarva Peninsula offshore area (eastern USA), reported that the storm currents largely suspended and transported foraminifer-rich shelf sediments to shelf slope. These circumstances are also inferred in the study area, the shelf and shelf slope off the Miyako Islands, southern Ryukyu Island Arc, Japan. The Ryukyu Island Arc separates the East China Sea and Pacific Ocean. The tidal currents commonly flow across the arc from Pacific during high-tides, and from the East China during low-tides (e.g., Tsuji, 1993), and possibly transport foraminifer tests from the surface sediments. This study represents preliminary discussion on sediment transportation processes by investigating test

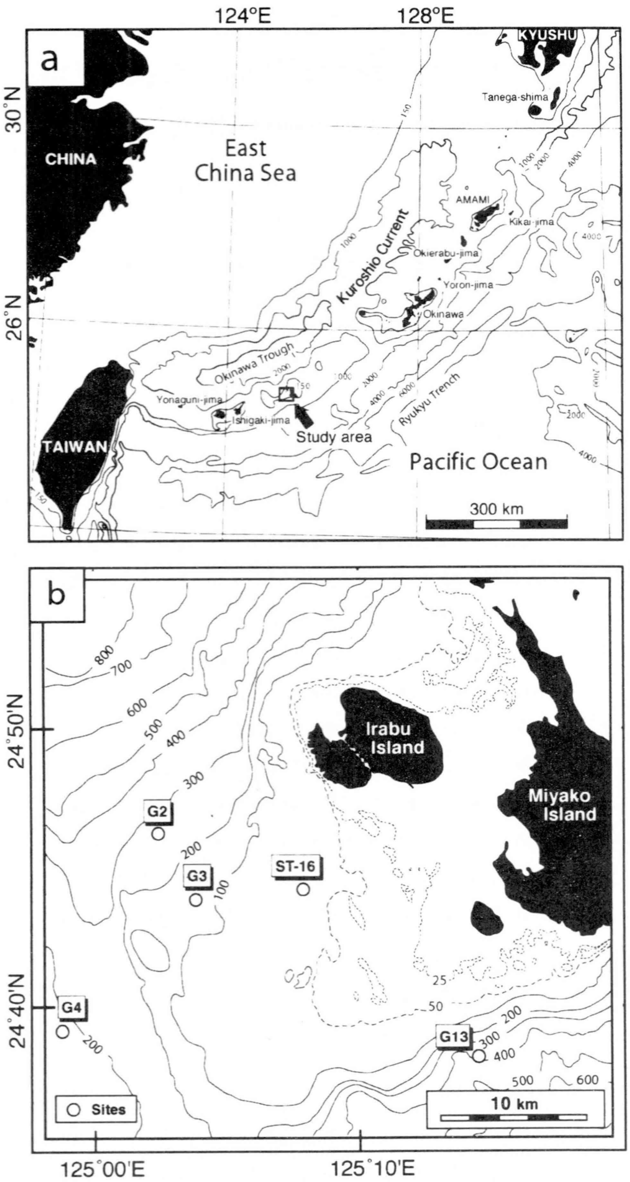

Fig. 1. Core location maps. a) The Ryukyu Island Arc, which extends approximately 1200 km from Kyusyu southwestward to Taiwan, rims the northwestern Pacific. b) Locality of the five surface sediments.

preservation and isotopic composition of planktonic foraminifers (*Globigerinoides sacculifer* and *Globorolatia inflata*). The tests of *G. sacculifer* and *G. inflata* record oceanographic conditions from two different water depth, as *G. sacculifer* lives primaly in the mixed layer of the upper 50 m, while, *G. inflata* is one of the deep-dwelling species predominantly living below 100 m (e.g., Bé, 1977).

II. Study area

The study area is the offshore area west of Miyako Island in the southern Ryukyus (Fig. 1). The Ryukyu Island Arc, extended approximately 1200 km from Kyusyu southwestwards to Taiwan, rims the northwestern Pacific, and is bounded by the Okinawa Trough to the northwest and the Ryukyu Trench to the southeast (Fig. 1a). Modern hermatypic coral growth and coral reef formation (typical fringing reefs) are active in the Ryukyu Islands (24°04'N to 29°15'N) (Nakamori, 1986). The reef distribution is extended to the northern islands, which are located several degrees in latitude more northern than the geographic limits of reef communities of other oceans by warming influence of northward-flowing Kuroshio current (Veron, 1992). The warm Kuroshio Current flowing Okinawa Trough acts as a barrier to terrigenous matter and low salinity cold-water mass from the Asian continent to the Ryukyu Island Arc (Fig. 1a). The southern realm including the study area, therefore, embraced by the current is under the tropical water mass all the year round (e.g., Koba, 1992). The tidal oscillation observed at Miyako Island ranges from more than 2 m at springs to less than 0.5 m at neaps (Maritime Safety Agency of Japan, Hydrographic Department, 1986).

The submarine topography of the study area comprises insular shelves and shelf slopes (Fig. 1b). The southern and northern parts of the area are characterized by slopes, which continue to the Ryukyu Trench and Okinawa Trough, respectively. The slopes are separated from the insular shelf by a shelf edge around 150 m in depth. On the eastern insular shelf, reef development nearly reaches to the sea-level and the water is very shallow in an area from south of Irabu Island to Miyako Island.

III. Materials and Methods

Five surface sediments were collected from the insular shelf and adjacent slopes off the west coast of Miyako Island of different water depths ranging from 69 to 400 m (Fig. 1b; Table 1). All samples were taken by two grab samplers; Smith-McIntyre sampler (Toyoshio-

Table 1. Location and sediment types of the samples recovered by smith-Mckyntre-type grab sampler of Toyoshio Maru (ST-16; No98-4 cruise), Hiroshima University, and by Okean-type grab sampler of Nagasaki Maru (G2, G3, G4, and G13; RN98 cruise), Nagasaki University.

Site No.	Date	Position		Depth (m)	Remarks
		Latitude (N)	Longitude (E)		
ST-16	May.22.1998	24º44'20	125º08'80	69	Calcareous sand and gravel, foraminiferal shells
G3	Nov.24.1998	24º43'59	125º04'03	114	Calcareous sand and gravel, foraminiferal shells
G4	Nov.24.1998	24º38'11	125º00'01	177	Fine to medium calcareous sand
G2	Nov.24.1998	24º45'58	125º01'73	259	Fine to medium calcareous sand
G13	Nov.24.1998	24º37'21	125º13'41	400	Fine to medium calcareous sand

Maru of Hiroshima Univ.) and Okean type grab sampler (Nagasaki-Maru of Nagasaki Univ.; Motoyama et al., 1999). The examined samples represent the uppermost 1 cm of collected sediment columns.

The samples for planktonic foraminifers, collected from five surface sediments (Fig. 1b and Table 1), were washed on a 200-mesh (74-μm opening) sieve and dried. possible, more than 10 cells of planktonic foraminifers *Globigerinoides sacculifer* and *Globorotalia inflata* were picked per surface sample under a binocular scope. *G. sacculifer* and *G. inflata* of G2 sample (collected from water depth 256 m) were used for oxygen isotopic analyses in order to evaluate the inhabiting depth of the two species, and *G. inflata* of ST-16, G3, G4, and G13 samples were used for the oxygen isotopic analyses in order to evaluate the transportation processes of planktonic foraminifers. The planktonic foraminifer species normally change their inhabiting depth during the growth (e.g., Be, 1977). Therefore, the tests of limited size (300-355 μm) of these two species were used in this study in order to focusing a certain growth stage. To remove the secondary contaminants (e.g., carbonate cements) on the outer surface and inside of the picked tests of *G. sacculifer* and *G. inflata*, the tests were soaked in 3 % hydrogen peroxide solution, splitted into several pieces for each, and sonicated under a binocular scope. After recognizing removal of the cement, the tests were washed in distilled water and allowed to dry. Cleaned each specimen was reacted at 60.0℃ with an excess of 100% phosphoric acid, and CO_2 gas was purified in a glass-line connected with the mass spectrometer. Finnigan MAT delta S mass-spectrometer modified for ultra-small sample analysis (Research Center for Coastal and Lagoon Environments of Shimane University) was used to measure oxygen stable isotopes using the procedure of Wada et al. (1984, 1991). Analyses were calibrated to the PDB standard and average analytical error of $\delta^{18}O$ was less than ±0.05‰.

IV. Results

The measurement results of the planktonic foraminifers of G2 sample are shown in Fig. 2. *G. sacculifer* $\delta^{18}O$ values range from -2.84 to -1.80 ‰ (average is -2.45 ‰), and $\delta^{13}C$ values range from 0.63 to 2.64 ‰ (average is 1.35 ‰). *G. inflata* $\delta^{18}O$ values range from -1.31 to -0.42 ‰ (average is -1.05 ‰), and $\delta^{13}C$ values range from 0.01 to 1.20 ‰ (average is 0.74 ‰). These plots show that $\delta^{18}O$ values of *G. sacculifer* are generally lighter than *G. inflata* (Fig. 2 and Table 2). $\delta^{18}O$

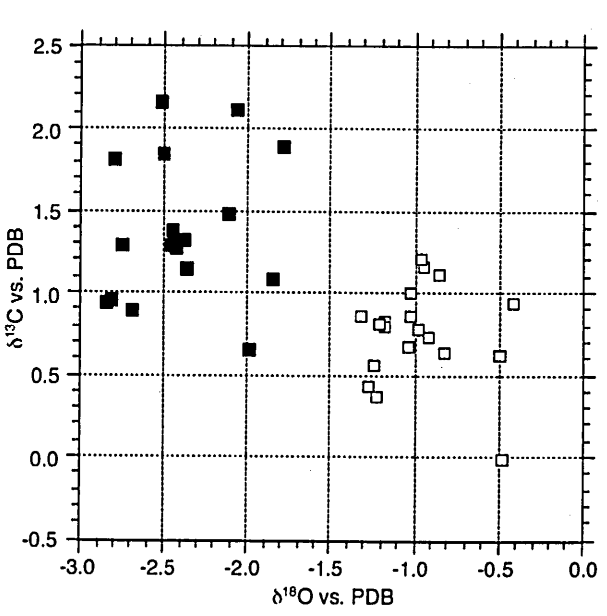

Fig. 2. Cross plots of $\delta^{18}O$ vs. $\delta^{13}C$ values (*G. sacculifer*; black squares, *G. inflata*; white squares) for tests of 300-355μm in diameter from the surface sediment (G2).

Table 2. The results of individual d18O measurements of G. sacculifer and G. inflata sampled from surface sediment at Site G2. Water temperatures and inhibiting depths are estimated from d18O values.

Species	Measurement number and range		$\delta^{18}O$ [‰]	Temperature [℃]	Estimated depth of test formation [m]
Globigerinoides sacculifer	18	min.	-2.84	28.7	0
		mean	-2.45	26.9	40
		max.	-1.80	24.0	80
Globorotalia inflata	19	min.	-1.31	21.8	135
		mean	-1.05	20.6	160
		max.	-0.42	17.7	250

decreases by 0.22 ‰ corresponds to 1°C increase in water temperature (Erez and Luz, 1983). This implies that lower $\delta^{18}O$ values of *G. sacculifer* result from their shallower living depth of higher temperature of surface water, and that the values of *G. inflata* are ascribed to lower temperature of deeper water. $\delta^{13}C$ value of *G. sacculifer* shows heavier than *G.inflata* (Fig. 2). Such pattern corresponds to the general tendency of the vertical gradient of the carbon isotopic composition ($\delta^{13}C$) of total dissolved inorganic carbon (DIC or ΣCO_2) of a productive ocean (Kroopnick, 1985).

The measurement results indicate that the mean *G. inflata* $\delta^{18}O$ values of the ST-16, G3, G4, and G13 samples are distributed in a small range from –0.83 ‰ to –0.91 ‰ and approximately agree with the mean *G. inflata* $\delta^{18}O$ values (-1.05 ‰) of G2 sample (Table 3). This consistency in the values from these geographically and topographically (especially water depth) different sampling spots, implies that *G. inflata* calcifies its test at relatively stable temperatures and salinity.

V. Discussion

A. Vertical distributions of planktonic foraminifers

The vertical distribution (depth stratification) of a species is evaluated by a simple $\delta^{18}O$-temperature relationship on a comparable temperature-depth profile of a water column, in which the species lives (Oba and Uomoto, 1989; Oba and Yasuda, 1992). In prior to evaluate the habiting depth from $\delta^{18}O$ values of *G. sacculifer* and *G. inflata*, it is important consider the effect of isotopic disequilibrium between the tests and seawater, known as the vital effect. The question of whether spinose species, such as surface-dwelling *G. sacculifer*, calcify in oxygen isotopic equilibrium with ambient seawater is still debated despite the efforts of many investigators over the past 30 yr. Several studies suggest that equilibrium calcification occurs (Williams et al., 1979; Curry and Matthews, 1981; Erez and Luz, 1982), although in many cases, scatter in the data allows for disequilibrium of up to ±0.5 ‰. Compelling support for equilibrium calcification is presented by Erez and Luz (1983), who showed experimental data from laboratory-cultured *G. sacculifer* (containing symbiotic algae). Nevertheless, many studies based on plankton tows, culture experiments, sediment traps, and core tops, suggested that spinose species fractionate in disequilibrium on the order of up to -0.6 ‰ because of the vital effects (e.g., Spero and Lea, 1993). Whereas, non-spinose species, such as deep-dwelling *G. inflata*, are known to calcify in oxygen isotopic equilibrium with ambient seawater (e.g., Fairbanks et al., 1980; Erez and Honjo, 1981), because these species lack symbiotic algae and are likely to have slower metabolic rates. In this study, the vital effects for $\delta^{18}O$ data of *G. sacculifer* are not adopted because of the conflicted debating.

The water temperature fluctuation is most related to difference in vertical distribution between *G. sacculifer* and *G. inflata* rather than the difference in water $\delta^{18}O$ (salinity). The degree of salinity influence for $\delta^{18}O$ is minor in comparison to water temperature based on a proportional relationship between salinity and $\delta^{18}O$ of surface water in the northwestern Pacific Ocean (Oba, 1988). A relationship between $\delta^{18}O$ of seawater and salinity in the western Pacific shows $\delta^{18}O$ increase of 0.20 ‰ for 1 ‰ (Oba, 1988). Hence, it is possible to

Table 3. The results of individual d18O measurements of G. inflata tests sampled from surface sediment of five sites. Water temperatures and inhibiting depths are estimated from d18O values.

Sites No.	Species	Water depth [m]	$\delta^{18}O$ [‰]	Temperature [ºC]	Estimated depth of test formation [m]
ST-16	*Globorotali inflata*	69	-0.84	19.7	198
G3	*Globorotali inflata*	114	-0.83	19.6	200
G4	*Globorotali inflata*	177	-0.92	20.0	189
G2	*Globorotali inflata*	259	-1.05	22.8	160
G13	*Globorotali inflata*	400	-0.91	20.0	189

estimate $\delta^{18}O$ variations of seawater from salinity changes using the relationship. Salinity around the study area seasonally changes in water depths above 200 m at the study area vary from 34.4 to 34.9 ‰ (Japan Oceanographic Data Center). The corresponding $\delta^{18}O$ seasonal variations in seawater are very small (less than 0.10 ‰). Of the total range of 1.04 ‰ observed in the $\delta^{18}O$ values of *G. sacculifer* from the surface sediment (Site G2), only 0.10‰ is derived from the variation of the $\delta^{18}O$ of seawater. Therefore, more than 90% of the total $\delta^{18}O$ range of *G. sacculifer* is due to temperature variation near the surface water. By comparison with the measured $\delta^{18}O$ values of *G. sacculifer* with the seasonal water temperature change in the surface water in this area, it can be regarded that the lightest values (-2.84 ‰; Fig. 2 and Table 2) was formed at the highest temperature of the study area which is 28.7°C (the surface water temperature during the summer). If it is the case, the water temperature of which *G. sacculifer* and *G. inflata* inhabited can be obtained, based on the paleotemperature equation ($\delta^{18}O$ values of 0.22 ‰ is equivalent to 1°C; Erez and Luz, 1983; Table 2). Because *G. sacculifer* calcifies the tests mainly in summer (Bé, 1977), the inhabiting depth is considered by refering the temperature-depth profile of summer (August). It is concluded that *G. sacculifer* habits in depth about 40 m (ranging from 0-80 m). The same calculation is also accepted for *G. inflata*, which calcifies the test mainly in winter. The inhabiting depth, on the February temperature-depth profile, is around 160 m (ranging from 135-250 m).

B. Post-depositional transportation of *G. inflata* tests

Without reworking or transportation of sediment particles by moving water mass, a foraminifer species is not contained in the sediment deposited of water-depth shallower than its inhabiting depth. If so, *G. inflata* tests are expected to occur in sediments deposited in depths deeper than 135 m, but not in shallower environments. However, this is inconsistent to the fact that the sediments from ST-16 (69m) and G3 (114m) contain this species. The occurrences in the shallower-water sediments and $\delta^{18}O$ values of *G. inflata* (Tables 2 and 3) indicate the post-mortal reworking of this species.

The inferred inhibiting depth of *G. inflata* of the sea bottom sediment G2 is 160 m by $\delta^{18}O$values of -1.05‰. Applying similar calculation for the shallower sediments of ST-16 (69m), G3 (114m) and G4 (177m), their mean *G. inflata* $\delta^{18}O$values (-0.84‰, -0.83‰ and -0.92‰) correspond to water temperature 19.7℃, 19.6℃ and 20.0℃, respectively. These temperatures are further correlated to water depths of 198m (ST-16), 200m (G3), and 189m (G4) in considering temperature gradient of winter water column. These estimated depths are within the range calculated for the data of G2 (Table 3). It is concluded that the *G. inflata* tests of ST-16, G3 and G4 were calcified in depth of 190-200 m and were later transported from shelf slope to reef slope by water-mass movement. The tests in the sediment of G13 (400m in depth) are originated from a simple settlement or from downward transportation of sediments.

The *G. inflata* tests analyzed in this study preserve surface structures well and lack any altered textures (Fig. 3). However, bottom sediments of Miyako offshore area, of which depths range from 100 to 450 m, are known to contain altered foraminifer tests. Kodato and Nakagawa (1993) consider that sediment of this depth range was deposited in a slow rate and therefore has been long in a

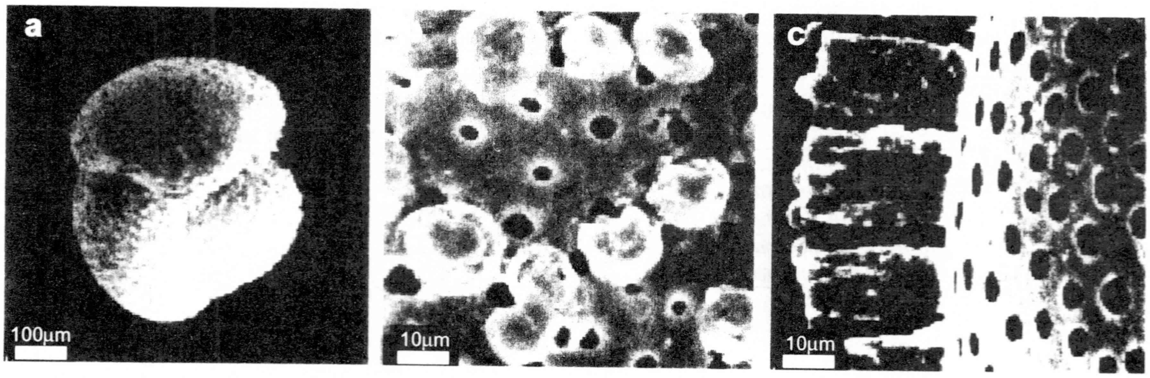

Fig. 3. Scanning electron microphotograph of G. inflata tests of recent specimens. The tests basically lack secondary calcite cement on the outer and inner surfaces and their primary structures are well preserved.

contact with bottom water. Alteration of tests is often related to early diagenesis due to a long-time contact with bottom water, as suggested by Schnitker (1971) who studied alteration processes found in shelf to shelf edge sediments off the North Calorina. Considering these previous studies, the well preserved tests in this study were transported to shallower environments shortly after they died and were settled on the sea bottom. They were not subjected to long-time exposure with bottom water, escaped from early diagenesis.

In the Miyako offshore area, strong currents by the tidal force were reported in a relatively deep sea bottom on shelf and shelf slope (Tsuji, 1993). The currents are accelerated when they pass the Ryukyu Islands, which act as a fence separated two basins; Pacific and the East China Sea. The acceleration is significant, especially near the island shelves. This was demonstrated by direct measurement of surface currents of 14 sites of different depths of sea bottom (19-804 m) for two weeks (Tsuji, 1993). The results indicate that return currents of the maximum rate of 65 cm/second occur in the direction of NNW-SSE on an island shelf, SW from Miyako Island. They can be regarded as tidal currents flowing between Pacific and the East China Sea. Dominant direction of the currents is switched twice per a day with tidal pattern observed in Hirara Port (southwestern Miyako Island). It is from south in high-tides, and from north in low-tides.

Tsuji (1993) consider that the tidal current drags upwelling. Probably the upwelling is the process, which is able to transport sediment particles to shallower environments. This oceanographic circumstances fit the results of this study. Strong water energy, mainly due to the tidal currents, reworks the sediment particles in a relatively deep environment. This is supported by the fact that the low mud-contents in the Miyako island shelf deposits distributed in the depths deeper than 100 m (Tsuji, 1993). Although it is out of the subject in this study, the higher water energy is suspected by frequent occurrence of storms. The Ryukyu Islands is the common passage of typhoons in summer and autumn. In these seasons, storm current also causes mass transport of bottom sediments, which carries some of the sediments to shallower environments. For understanding the transportation process of foraminifer tests, effects of storm currents are also necessary to be evaluated.

VI. Conclusion

Oxygen isotopic data ($\delta^{18}O$) of individual *Globolotalia inflata* tests collected from of a surface sediment (Site G2: water depth is 259m) on insular slope, off the Miyako Islands, southern Ryukyus, Japan, show that the vertical distribution of *G. inflata* in size ranging from 300-355µm is inferred to be 135-250m (average 160m) based on the comparison with the present water temperature-depth profile. *G. inflata* $\delta^{18}O$ data of the four surface sediments, collected from 400m to 69m around the insular shelf and slope (Site ST-16, G3, G4, and G13), agree with the *G. inflata* $\delta^{18}O$ values of Site G2 (-0.84~-1.0 ‰) and indicate the inhabiting depth are 190-200m. These evaluations are reliable because the preservation condition of *G. inflata* tests is very well. These findings imply that the currents in the water column suspended the *G. inflata* tests from the inhabiting depth to shallower environments. The most possible transportation process is the upwelling, which may be developed in association with strong tidal currents and the topographic feature of the Ryukyu Island Arc.

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