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Foraminiferal shells in sediment traps: Implications of biogenic particle transport in the Kao-ping submarine canyon, Taiwan

Hui-Ling Lin[a,*], James T. Liu[a], Gwo-Wei Hung[b]

[a]Institute of Marine Geology and Chemistry, National Sun Yat-Sen University, Kaohsiung, Taiwan 804, ROC
[b]Laboratory of National Center for Ocean Research at Kaohsiung, Taiwan 804, ROC

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Abstract

Foraminifera collected from sediment traps deployed at two depths in the Kao-ping submarine canyon were analyzed to provide information on biogenic particle transport. The discovery of benthic foraminiferal shells in the collecting cups was unexpected because the sediment traps were deployed at levels of 54 and 104 m above the seafloor of 290 m depth. The presence of shelf-originated benthic foraminifera captured by the sediment traps suggests that the canyon is not only a conduit for delivering terrestrial materials into the ocean but also acts as a passage allowing particles of marine-origin to be transported toward the shore. Furthermore, during the passing of Typhoon Kai-Tak, the cups at both upper and lower levels collected a higher diversity of benthic foraminifera species than at other time intervals, while there was also an increased similarity in the species collected by all cups. Most of the benthic taxa found in collecting cups were also present at as forms living in surface sediments from the shelf and slope as determined by staining, supporting a shore-wards transport particles of marine origin in the submarine canyon. Nevertheless, the stable isotopic compositions of the benthic foraminifera *Cibicides wuellerstorfi* displayed a similar range of variation as the other planktonic foraminifera (*Globigerina bulloides, Globigerinoides sacculifer* and *G. ruber*), indicating these species dwelled at a relatively shallow depth (<50 m). The similarity of $\delta\,^{18}O-\delta\,^{13}C$ compositions for both planktonic and benthic foraminifera collected from the sediment traps and also from the underlying surface sediments implies that most of the foraminiferal shells precipitated their shells locally and were transported by either settling out of the water column from the adjacent shelf or resuspension from the underlying sea floor.

Keywords: Kao-ping submarine canyon; Sediment traps; Foraminiferal shells; Isotope

1. Introduction

Sediment traps are designed to collect sinking particles from the sea surface and hence are expected to provide information about particle transport prior to deposition (e.g., Honjo, 1982; Nair et al., 1989; Hung et al., 1999; Monaco et al., 1999). Unfortunately, lateral drift at continental margins often affects the descent of particles from the upper water column down to the ocean floor. For example, lateral transports from the shelf and upper slope were responsible for the low $^{210}Po/^{210}Pb$ activity ratio determined from the trapped particulates collected in a canyon off northeastern Taiwan (Hung and Chung, 1998). The planktonic fluxes of foraminifera

*Corresponding author. Tel./fax: +886 7 5255149.
E-mail address: hllin@mail.nsysu.edu.tw (H.-L. Lin).

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and coccoliths, associated with the occurrences of rare benthic foraminifera specimens, increased with the increasing depth of the collecting traps at the Okinawa Trough were attributed to the lateral transport of particles from the adjacent shelf edge and slope (Tanka, 1997; Yamasaki and Oda, 2003). The settling process is further complicated by tidal motions and the resuspension of particles by waves in the coastal zone (Lafuente et al., 1999; Ogston et al., 2000; Xu et al., 2002).

Rivers are major conduits of land-derived sediments to the coastal regime. Generally the dispersal of these riverine particles is influenced by the physical, geological, biogeochemical, and ecological characteristics and processes found in the coastal zone and beyond. Understanding the linkages between river sediment export and sediment dispersal on the continental shelf before eventual deposition on the sea floor is critical in coastal sedimentation. It is particularly important in a tectonically active region like Taiwan which has a high uplift rate (5–7 mm/year; Chen and Liu, 2000) and denudation rate (ca. 1300 g/m^2 year; Li, 1976). The head of the Kao-ping submarine canyon is located 1 km seaward of the mouth of the Kao-ping River on the southwest coast of Taiwan (Liu et al., 2002). In this active tectonic setting, the sediment-laden river effluent is directly spread over the submarine canyon. The river plume plays a major role in the delivery of terrigenous sediments to the edge of the submarine canyon. Once sediments enter the realm of the submarine canyon, the movement and distribution of particles will be governed by the combined effect of water movement in the canyon and the effective settling velocity (Hill et al., 2000).

The Kao-ping submarine canyon is located off the wave-dominated microtidal coastline of southwestern Taiwan and extends seaward from the mouth of the Kao-ping River down to the lower continental slope over a distance of 240 km (Yu et al., 1993; Fig. 1). It has been suggested the canyon is a trap and conduit for particle exchange between the Kao-ping River and the ocean (Liu et al., 2002). Previous workers examined the hydrodynamic settings that control the transport and deposition of both river-derived and offshore-originated sediments in the canyon based on field surveys (Liu et al., 2002) and time-series observations (Liu and Lin, 2004). They concluded that net sediment transport was landward inside the canyon based on grain-size analysis of lithogenic particles (Liu et al., 2002). Understanding the function of the submarine canyon itself in determining material sources and/or sinks will improve our current knowledge about the influence of fluxes from the Kao-ping River on coastal ecosystem function and productivity. On a larger scale, the canyon acts as a conduit for terrigenous material from southern Taiwan to enter the northeastern corner of the South China Sea Basin. As opposed to previous investigations, this paper focuses on the distribution and composition of non-lithogenic (biogenic) sediments in this river–sea system and evidence of the nature of generation and delivery of these particles.

Foraminifera, microorganisms of the Phylum Protozoa, inhabit the ocean from depths of five to over 5000 m and either live on the bottom (benthic) of the sea floor or float (planktonic) in the water column (Haq and Boersma, 1998). The characteristic ornamentation (morphology) of the foraminifera's carbonate shell provides the basis for taxonomy. In this study, foraminiferal shells recovered from sediment traps deployed in the Kao-ping Submarine canyon and surface sediments were applied as a proxy indicator of marine-origined, biogenic particles and were expected to also reveal information about the origin and transport of non-lithogenic particles.

2. Materials and methods

A sediment trap array formed part of a field experiment designed to examine the sediment dynamics in a submarine canyon. Sample collection was taken between June 20 and July 20, 2000 (Liu and Lin, 2004). With the water depth about 290 m, the deployment depths of the collecting cups were set at 186 and 236 m. A description of the sediment trap specifications is given in Hung and Chung (1998) while the procedures used to treat the trap samples are the same as those reported by Heussner et al. (1990). The collecting cups in the array were 250 ml in volume each with collecting time interval of 2.5 days (60 h). Because of the extremely high flux of particles, most of the collecting cups had overflowed before recovery (Liu and Lin, 2004). In addition, the particle fluxes for the second and third cups in the upper level were too low for a study of their foraminiferal content. Subsamples from the collecting cups were further divided for coarse-fraction and geochemical analyses, and picking of foraminifera shells. In addition to the trap samples, surface sediment samples were collected between

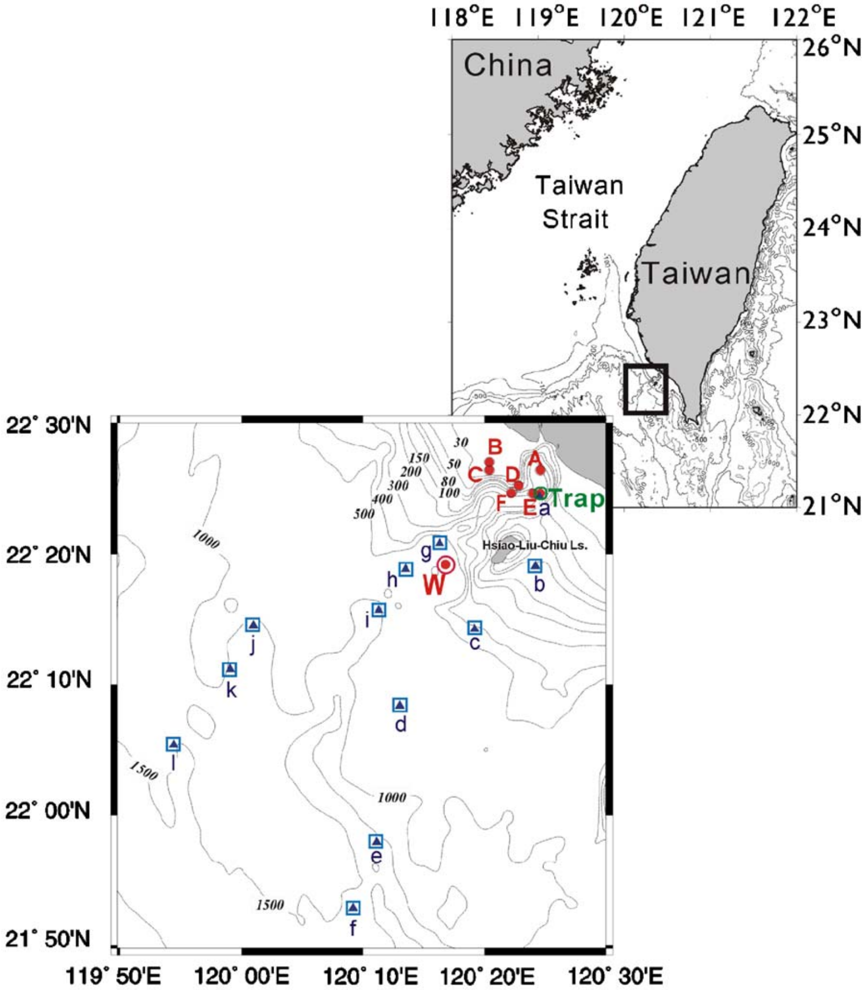

Fig. 1. Bathymetric maps showing the study area and sampling stations (provided by the Ocean Data Bank, National Center for Ocean Research in Taiwan). Characters A–F denote the localities from which surface water was sampled and "W" indicates the sampling station for sea water $\delta^{18}O$. Characters a–l denote the locations of stained surface samples collected during ORI-732 (September 30–October 4, 2004; *R/V Ocean Researcher I*-732).

March and May 1998 from the study area to act as a reference (Liu et al., 2002). Our study locations, symbolized as A–F in Fig. 1, are equivalent to positions B10, D5, D7, D10, E14, and F10 identified in Fig. 2 of Liu et al. (2002). Furthermore, in order to identify the sources of the benthic foraminiferal shells found in the trapped samples, Rose Bengal was applied to stain organisms in sediments that were alive at the time of collection. Locations for the 12 stained surface sediments collected during September 30–October 4, 2004 are shown in Fig. 1 (a, b, c, … l).

Aliquots from each collecting cup were freeze-dried and then soaked in deionized distilled water. After washing through 63 μm sieves, the $>63\,\mu m$ fraction residue was collected, dried and then weighed. The weight percent of the coarse fraction was calculated by dividing the weight of the $>63\,\mu m$ fraction by the weight of the original sample. All foraminiferal shells, both planktonic and benthic, were then picked from the coarse fractions that were greater than 150 μm for faunal assemblage and stable isotope analysis. Calcium carbonate ($CaCO_3$) concentrations and total organic carbon (TOC) were measured using a LECO CS-244 carbon/sulfur analyzer. Prior to analysis the bulk sediment samples were dried and ground to a powder and two small samples were then weighed out (~0.1 g). One of the two weighed samples was directly measured to indicate the total carbon (TC) content of the sediment. This procedure involves heating the sample at 850 °C and measuring the combustion products by infrared energy detector. The second sample was digested with 2.4 N HCl to remove carbonates. The carbonate-free residue was washed thoroughly with deionized distilled water, dried, and then the residual carbon was measured. This value represents the TOC content of the sediment. The difference between the two carbon measurements (TC and TOC) is used to calculate the total inorganic carbon (TIC) content. $CaCO_3$ concentration is calculated by $wt\%CaCO_3 = wt\%\ TIC/12 \times 100$, assuming all of the inorganic carbon was present as calcite or aragonite. The precision of the analyses is better than 0.04% for the standard (bulk sediments from the South China Sea) and better than 0.10% for the sediment trap samples.

The foraminiferal shell sizes for stable isotope analyses were restricted within the range of 212–250 μm (or greater) for specimens of *Globigerina bulloides*, 355–300 μm for *Globigerinoides sacculifer*, and 250–300 μm for *G. ruber* (~15 specimens of *G. bulloides* were analyzed, while the larger *G. sacculifer* and *G. ruber* were analyzed in groups of 6–8 specimens). *Cibicides wuellerstorfi* shells were picked from the sediment fraction greater than 150 μm to produce a pool of 2–5 specimens. The separated foraminifera shells were cleaned in methanol in an ultrasonic bath to remove adhering fine particles followed by soaking in sodium hypochlorite (NaOCl, 5%) at room temperature for more than 24 h to further clean up any fine organic particles. Cleaning by deionized distilled water then followed, and the samples were oven-dried at 50 °C. Shells were roasted at 375 °C in vacuo and analyzed at 90 °C in an Isocarb common acid bath using a Fisons Optima isotope ratio mass spectrometer at the Department of Geology, University of California, Davis, with typical within-run precision of ±0.06 ‰ for $\delta^{18}O$ and ±0.05 ‰ for $\delta^{13}C$.

3. Results and discussion

3.1. Impact of typhoon

Changes in the coarse fraction content captured by the sediment traps over time are illustrated in Fig. 2a, which shows the coarse fraction contents of every individual cup for both levels (open symbols indicate upper level, solid symbols indicate lower level). Superimposed in Fig. 2 is a hatched area indicating the time interval when Typhoon Kai-Tak

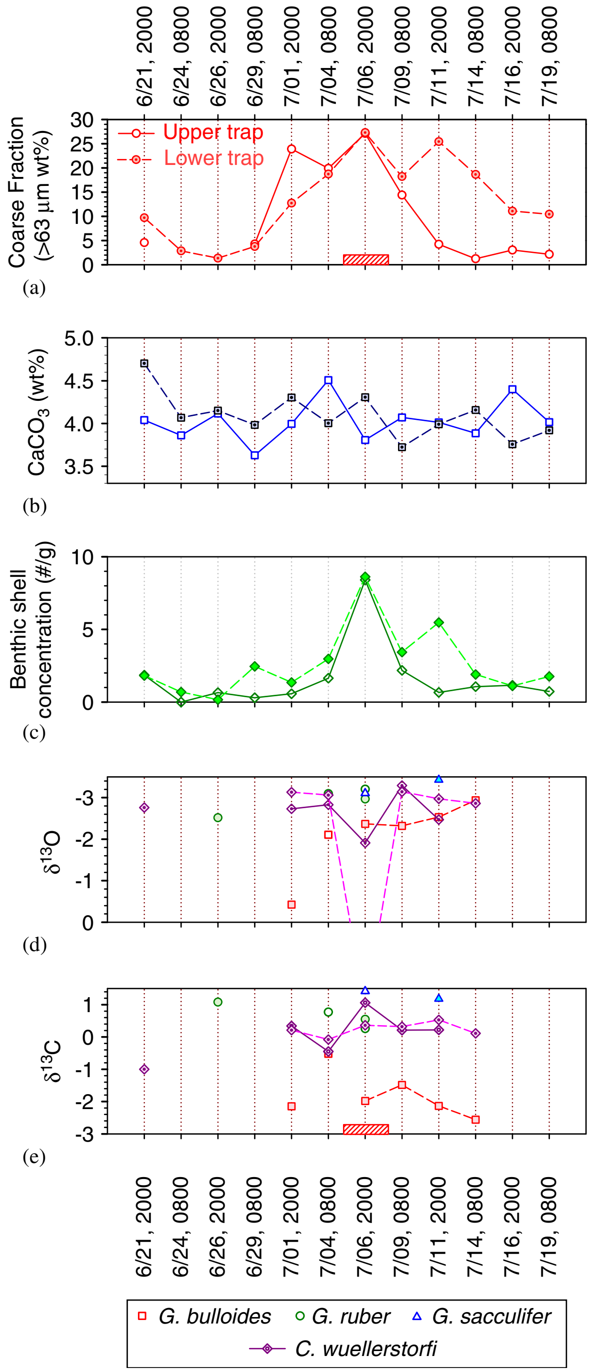

Fig. 2. Results, measured over time, for every individual cup at both sampling depths (60 and 100 m above sea floor). Coarse sediment fraction contents (>63 μm; a), carbonate (wt%; b), concentrations of benthic foraminiferal shells (#/g; c), foraminiferal $\delta^{18}O$ (d) and $\delta^{13}C$ (e) compositions. All data from the upper level trap cups are indicated by open symbols while lower level trap cups are denoted by solid symbols. Superimposed on the panel is a hatched area indicating the time interval when Typhoon Kai-Tak invaded Taiwan (ca. July 8–July 9, 2000; Liu and Lin, 2004). The time label for each cup is the middle point of the 60-h collecting period.

invaded Taiwan (ca. July 8–July 9, 2000; Liu and Lin, 2004). Abrupt increases in coarse fraction content were recorded for both trap levels before the typhoon, with a maximum content recorded by the seventh collecting cup on July 6 at 20:00, i.e., mid-point after the start of 60 h sampling. After the typhoon, the concentration of coarse grains decreased for cups in the upper level and returned to their previous low values after the eighth cup. In contrast, the lower level cups starting at the fifth cup recorded high concentrations of coarse sediments for a longer period of time until the 10th cup was collected on July 14 at 2 p.m. Interestingly, the carbonate contents of samples collected from the lower level cups did not vary much with an average value around 4 wt% (Fig. 2b). Usually, coarse fraction samples from the pelagic realm are expected to contain mostly biological remains (shells), especially carbonate foraminiferal tests. The low carbonate contents found in this study therefore suggest that during Typhoon Kai-Tak the coarse fraction sample was dominated by lithogenic particles.

Originally the sediment traps were designed to catch settling particles from the sea surface and were expected to provide information about the transport of particles before their final burial on the sea floor. In this study, there is a 50 m gap between upper and lower level cups and another 54 m gap to the seafloor. Under normal conditions, the benthic foraminifera would be the last part of the organic remains to be found in the collecting cups. Yet results for benthic foraminiferal shell concentrations (numbers of individuals per gram, #/g; Fig. 2c) in the samples show a similar, typhoon-influenced pattern over time to the samples' coarse fraction content (Fig. 2a), with a common peak at the seventh cups (02:00, July 8) of both levels. The high correlation between coarse fraction content and benthic shell concentrations indicates a closely related source and similar particle transport system for these two parameters. Nevertheless, the maximum values for both measurements occur during the interval when Typhoon Kai-Tak swept Taiwan, suggesting the importance of lateral transport and resuspension processes in the Kao-ping submarine canyon.

Field experiments undertaken during the deployment of the sediment traps suggested that river effluent and wave resuspension of the shelf sediments were major mechanisms governing the delivery of coarse (larger than 100 μm) lithogenic grains to the canyon (Liu and Lin, 2004). Foraminiferal shells examined in this study are all greater than 150 μm in size and hence fall in the coarse sediment category described above. Unfortunately, on their own, lithogenic grains do not reveal source information about whether the collected sediments have a terrestrial or marine origin. Biogenic particles on the other hand, particularly benthic foraminiferal shells, provide information on the origin of particles. The occurrence of benthic foraminifera captured by the sediment traps suggests that the Kao-ping canyon is not only a conduit delivering terrestrial material into the ocean but also acts as a passage allowing the advance of marine particles to the shore. Several benthic foraminifera genera found in collecting cups are listed in Table 1 in alphabetical order. Similar taxa that were also present as stained specimens (i.e., living shells) at the shelf and slope are marked at its recovery site (locations a–l as shown of Fig. 1). *Ammonia* and *Elphidium* frequently dominate inner shelf assemblages in many latitudinal zones (Sen Gupta, 1999). It is then not surprising to find them at the shallow sites along the coast (a–c in Fig. 1; Table 1). Some low oxygen foraminiferal assemblages (LOFAS; Sen Gupta, 1999) found in traps, such as *Brizalina*, *Bulimina*, and *Uvigerina*, were also disseminated at the shelf and slope as stained shells (Fig. 1). The comparisons between the trapped and stained foraminiferal taxa support a shelf/slope origin for those benthic shells collected in the sediment trap.

This is not the first report regarding the presence of benthic foraminiferal shells in sediment traps. Benthic foraminiferal shells were found in traps at 10–40 m above the sea floor at sites from the continental shelf to the shelf edge in the East China Sea (Yamasaki and Oda, 2003). Delivery of both benthic and planktonic foraminifera from the shelf to the slope was thought to be dominated by storms and associated resuspension based on the sediment trap study (Falkowski et al., 1994; Brunner and Biscaye, 1997). These reports, however, argue for down-slope movement of shelf-origin particles, including benthic shells. Our observations in the Kao-ping Canyon are significantly different because they indicate that particles in our study area were transported by upslope movement from a distal slope to the coast.

Fig. 3 is the comparison of the amount of the same taxon found in upper and lower level cups. The higher similarity of taxa in the upper and lower level cups indicates the stronger agitation in the

Table 1
Common species found in both trap samples and stained surface sediments

Species	Station (depth)											
	a (350 m)	b (115 m)	c (415 m)	d (824 m)	e (1562 m)	f (1776 m)	g (622 m)	h (975 m)	i (1156 m)	j (1004 m)	k (1513 m)	l (1630 m)
Ammonia		√	√									
Amphicoryna sp.			√					√				
Amphistegina sp.		√										
Bolivinita sp.	√		√	√	√		√		√	√	√	√
Brizalina sp.	√		√									
Bulimina sp.		√	√	√	√	√	√	√	√	√	√	√
Cibicides sp.	√	√	√	√		√				√	√	√
C. wuellerstorfi			√	√	√				√			√
Elphidium	√	√										
Fissurina sp.			√			√				√	√	√
Heterolepa sp.	√	√	√									
Lenticulina sp.		√	√	√	√	√					√	√
Nonion sp.		√			√							
Reussella sp.	√											
Uvigerina sp.	√		√	√	√	√				√	√	√

water column due to the typhoon invasion. The same calculation was applied to cups over consecutive time intervals as shown in Fig. 4. The high degree of similarity between benthic species collected from cups both during and after Typhoon Kai-Tak indicates the duration of the disturbance to the water column. Both Figs. 3 and 4 clearly demonstrate the impact of Typhoon Kai-Tak on sedimentation in the Kao-ping canyon.

3.2. Foraminifera isotopic signals

Foraminiferal isotope analyses have been widely applied in paleoceanography since the pioneering study of Emiliani (1955). Oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopic compositions from carbonate separated from the foraminiferal shells yields information about the surrounding hydrography (e.g., Imbrie et al., 1992; Linsley, 1996; Bemis et al., 1998; Lea et al., 2000) and surface water fertility (e.g., Curry and Crowley, 1987; Charles and Fairbanks, 1990; Thunell et al., 1992; Spero and Lea, 1996), respectively. Therefore, it is interesting to compare the isotopic composition of foraminiferal shells from the traps with shells from the surface sediments in the vicinity of the canyon. Figs. 2d and 2e show the $\delta^{18}O$ and $\delta^{13}C$ measurements from three planktonic (squares for *G. bulloides*, triangles for *G. sacculifer*, and circles for *G. ruber*) and one benthic foraminifera sample (dotted diamonds for *C. wuellerstorfi*). Unfortunately, complete records for these species could not be obtained due to the low counts of foraminiferal shells found in the collecting cups. Generally, both $\delta^{18}O$ and $\delta^{13}C$ values for each individual species fluctuate in a narrow range except for two data points showing distinctive $\delta^{18}O$-enrichment. The narrow range of isotopic values indicates that most of the foraminifera secreted their shells under similar hydrographic settings. This result was expected because the sediment traps were only deployed for a total of 1 month. On the other hand, the similar range of $\delta^{18}O$ between *C. wuellerstorfi* and that of other planktonic foraminifera is intriguing. It seems reasonable to infer that the *C. wuellerstorfi* benthic foraminifera precipitated their shells at shallow water depths (<200 m) similar to those depths where planktonic foraminifera grew their shells. The two outlying points measured for *G. bulloides* in the fifth cup and *C. wuellerstorfi* in the seventh cup, suggest these shells formed at cooler temperatures, at least 8 °C (~1.7 ‰) and 19 °C (~4‰), respectively, than the foraminifera found in the other cups without considering the salinity effect (Bemis et al., 1998). Although the heaviest value of $\delta^{18}O$ (2.09 ‰ for *C. wuellerstorfi*; Fig. 5) looks extremely abnormal compared to the other data presented in this study, it is actually the same as the benthic $\delta^{18}O$ composition from a coretop collected at a water depth of ~1000 m in the South China Sea (Lin,

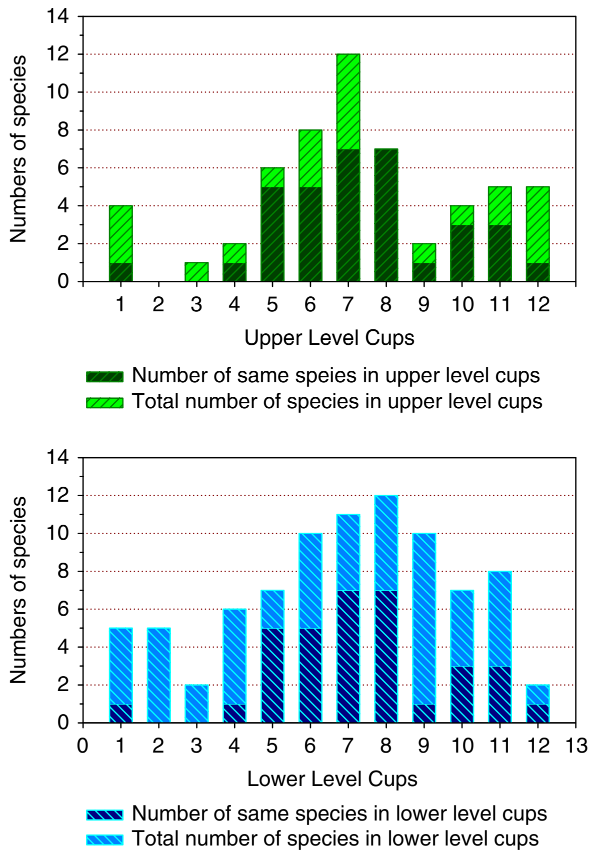

Fig. 3. Comparison of number and type of benthic foraminifera species collected in upper and lower level cups from the sediment traps. The height of each column indicates the total number of all species found in each trap cup. The dark portion within each column indicates the total number of the same species found in both upper and lower level cups for each collecting interval.

2003). It is likely that those benthic shells caught in the seventh cup were transported from distal and deeper sources than the other cups during the invasion of Typhoon Kai-Tak. Alternatively, the explanation for the anomalously heavy $\delta^{18}O$ could be that these represent reworked shells of glacial age from a much shallower location. But this possibility is ruled out because most of the sea floor of the Taiwan Strait off the west coast of Taiwan is relatively shallow, <100 m deep and with an average water depth of about 60 m (Boggs et al., 1979; Yu and Song, 2000). A 120 m sea-level drop (Fairbanks, 1989) would have exposed most of the sea floor west of Taiwan, leaving no space to accommodate planktonic foraminifera in the water column. Besides, only fresh and intact shells were picked for stable isotope analysis in this study. Reworked particles are easily distinguished and avoided during our laboratory processes.

Fig. 5 is a comparison of carbon and oxygen isotope data for foraminifera collected in the sediment traps with isotope data for foraminifera collected in the surface sediments from the study area. Data indicated solely by symbols are from the sediment traps (squares for *G. bulloides*, triangles for *G. sacculifer*, circles for *G. ruber*, and diamonds for *C. wuellerstorfi*) while data indicated by characters inside symbols represent the surface sediments, with the location of all samples shown in Fig. 1. Surface samples were collected from March to May in 1998 (Liu et al., 2002). In addition, isotopic compositions from two living planktonic foraminifera (crossed triangle for *G. sacculifer* and crossed circle for *G. ruber*) collected by towing in March 2002 are shown in Fig. 5. Even though the collection of surface sediment samples and sediment trap samples occurred 2 years apart, the distribution of $\delta^{18}O$–$\delta^{13}C$ of the foraminifera (both planktonic and benthic) from the traps overlaps those from the surface sediments with the exception of the isotopic composition of *G. sacculifer*. This similarity suggests that most of the foraminiferal shells found in trap cups were precipitated locally in the water column. In addition, the $\delta^{18}O$ contents of *G. sacculifer* from the traps (upper seventh and lower ninth collecting cups) are relatively depleted compared with those from the surface sediments and the plankton. The difference in $\delta^{18}O$ could be a reflection of seasonal effects due to different hydrographic settings present when the specimens were collected. The difference in *G. sacculifer* $\delta^{18}O$ values between samples from the traps and surface sediments suggests either warmer temperatures of at least 2–3 °C (Bemis et al., 1998) or about 0.3 lower salinity (Lin et al., 2004) than ambient seawater.

3.3. Foraminiferal calcification depths

Various equations describing the environmental temperature for biogenically precipitated calcite based on culture experiments have been published over the past several decades (e.g., Epstein et al., 1953; Erez and Luz, 1983; Spero and Lea, 1996; Bemis et al., 1998). Therefore, it is possible to estimate the calcification depth for our foraminifera samples by considering the published relationship between temperature and $\delta^{18}O$ compositions and then comparing these with our measurements. Fig. 6 includes three predicted shell $\delta^{18}O$ compositions

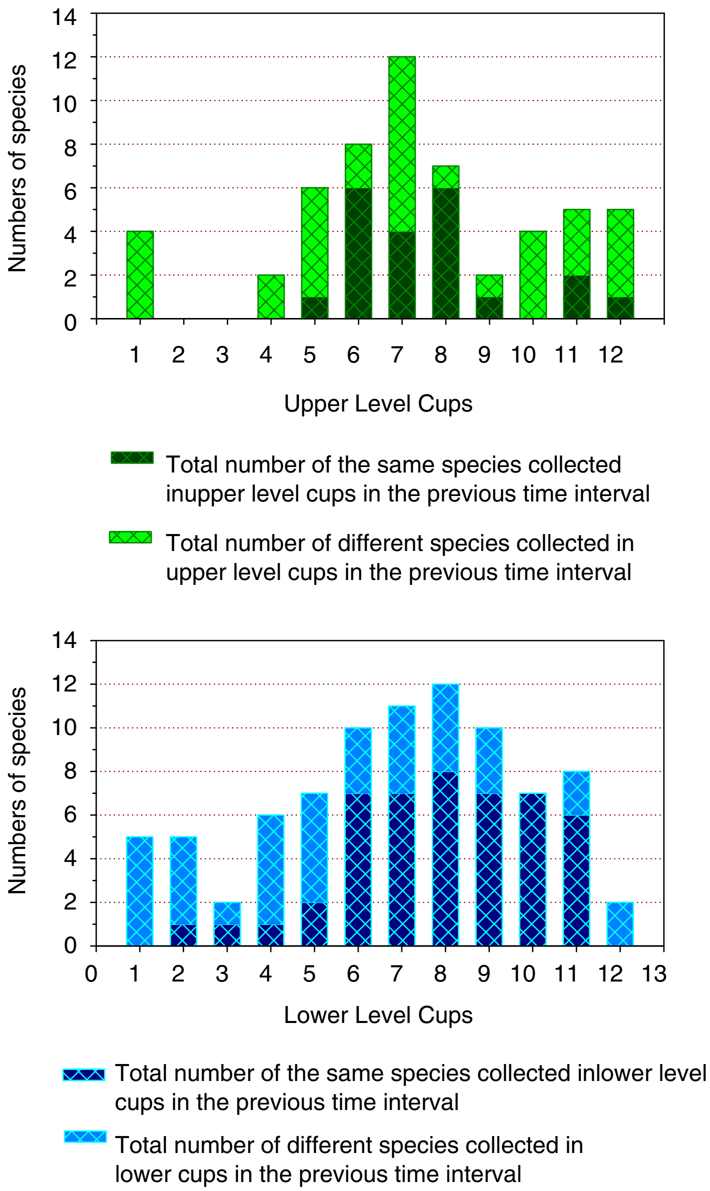

Fig. 4. Comparison of the change in number and type of benthic foraminifera species collected at consecutive time intervals in the same cups from the sediment traps. The height of each column indicates the total number of all species found in each trap cup. The dark portion within each column indicates the total number of the same species found in previous collecting interval.

based on different equations for *G. bulloides* (11-chambered shell; $T(^{\circ}\mathrm{C}) = 12.6–5.07\ (\delta c-\delta w)$), *C. wuellerstorfi* (low-light; $T(^{\circ}\mathrm{C}) = 16.5–4.80\ (\delta c-\delta w)$), and *G. sacculifer* (linear regression of Erez and Luz, 1983; $T(^{\circ}\mathrm{C}) = 17.0–4.59\ (\delta c-\delta w)$, Bemis et al., 1998). Both temperature and δw ($\delta\,^{18}$O of sea water) were collected at station W indicated in Fig. 1 during cruises undertaken in August 2001 and another in January 2002 (Lin et al., 2004). A seasonal signal is clearly reflected by the $\delta\,^{18}$O composition of the sea water (i.e., the δc values from the above equations) in the upper water column (ca. ~1.5‰ in the surface layer between August and January; Fig. 6). Superimposed on the predicted shell $\delta\,^{18}$O profiles are three ellipses indicating the $\delta\,^{18}$O ranges measured for corresponding species in this study. The distribution range of predicted shell $\delta\,^{18}$O of *C. wuellerstorfi* is very similar to that of *G. sacculifer* and both are about 0.5 ‰ heavier than *G. bulloides*. *G. bulloides* is a non-symbiotic spinose

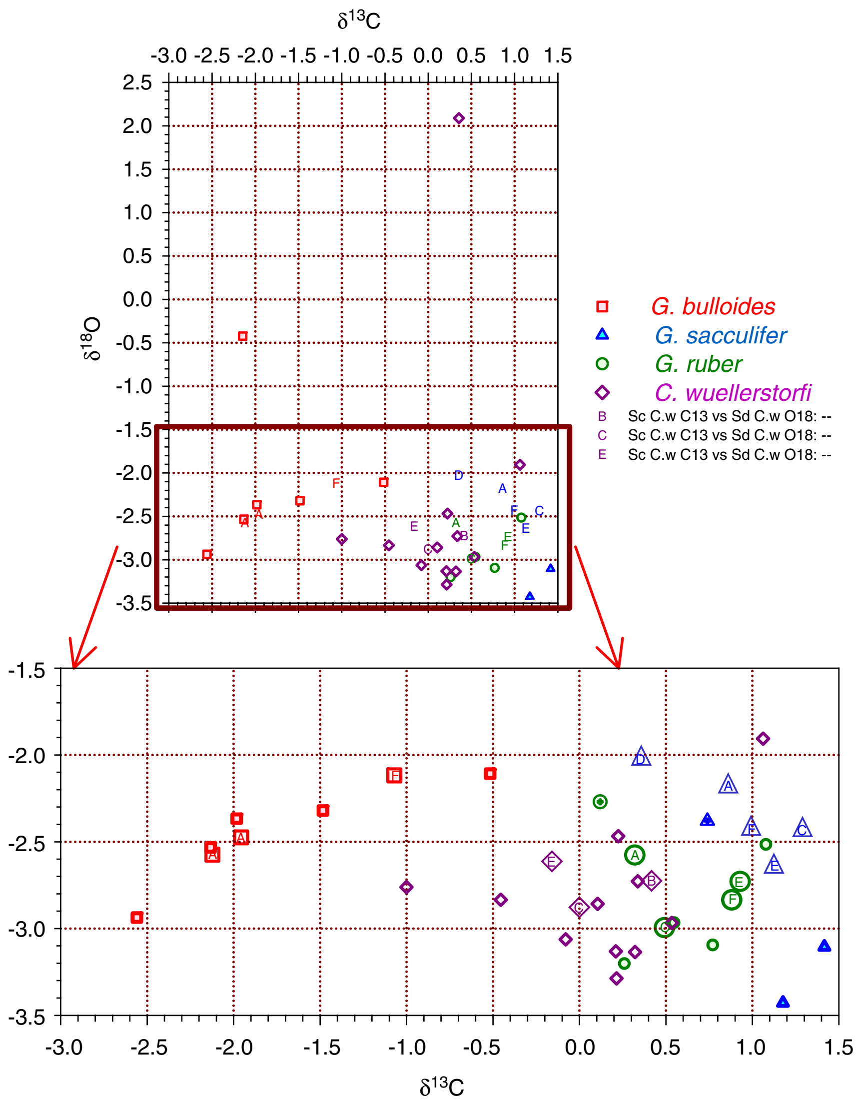

Fig. 5. Foraminiferal carbon and oxygen isotope compositions of samples collected from the sediment traps compared with the isotopic compositions of samples from the surface sediments disseminated in the study area. Trap data are indicated by symbols (squares for *G. bulloides*, triangles for *G. sacculifer*, circles for *G. ruber*, and diamonds for *C. wuellerstorfi*) while sediment samples are denoted by characters (the same as those used to show locations in Fig. 1). Our study locations, symbolized as A–F, are equivalent to positions B10, D5, D7, D10, E14, and F10 identified in Fig. 2 of Liu et al. (2002). Two additional data points (crossed circle for *G. ruber* and crossed triangle for *G. sacculifer*) were derived from plankton samples collected by towing in March 2002.

planktonic foraminifera that is usually found in temperate, sub-polar and upwelling environments (Sauter and Thunell, 1991; Spero and Lea, 1996). The apparent calcification depth for *G. bulloides* is the deepest of the three species according to the depth that the ellipse intersects with the calculated δc curves (Panel A on Fig. 6). Therefore, the *G. bulloides* shells caught by the sediment trap were transported either from inside the canyon or by the distal slope area where the water depth is deeper and temperature is cooler, being consistent with the species habitat preference. Additionally, the cold-water surge that was observed at the head of the Kao-ping submarine canyon in late spring and summer by Wang and Chern (1996) could also be a favorable setting for *G. bulloides*. The benthic foraminifera *C. wuellerstorfi*, on the other hand, seems to precipitate its shell at water depths shallower than 50 m, i.e., the continental shelf based on the predicted shell $\delta^{18}O$ profile (Panel B in

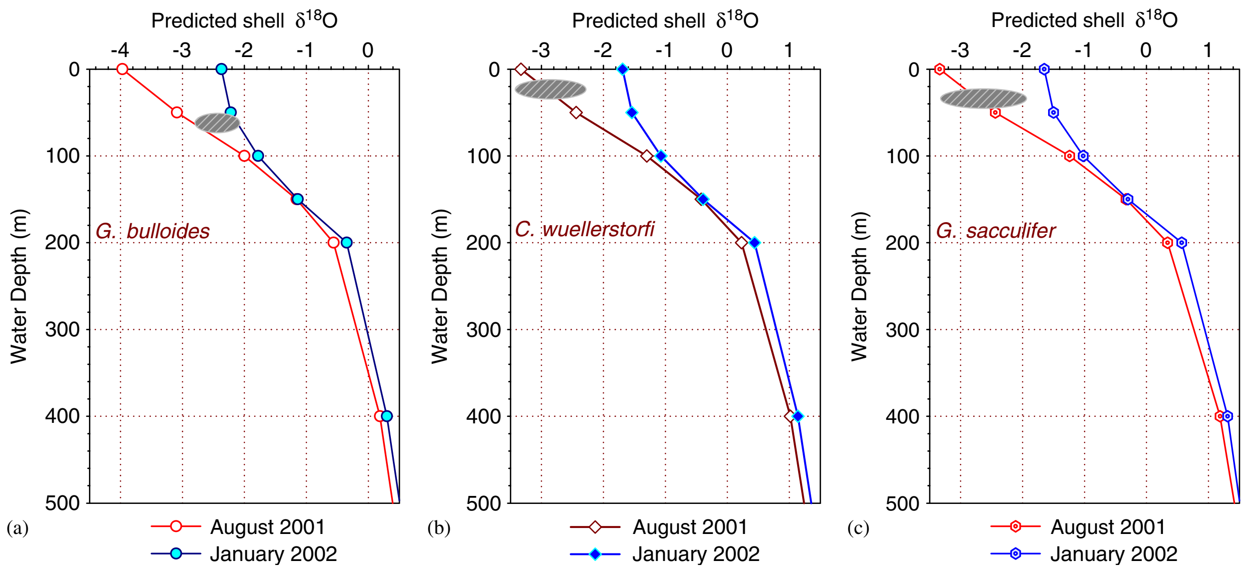

Fig. 6. δ^{18}O profiles calculated for foraminiferal shells based on different equations for *G. bulloides* (11-chambered shell; $T(^{\circ}C) = 12.6–5.07\ (\delta c - \delta w)$), *C. wuellerstorfi* (low-light; $T(^{\circ}C) = 16.5–4.80\ (\delta c - \delta w)$), and *G. sacculifer* (linear regression of Erez and Luz, 1983; $T(^{\circ}C) = 17.0–4.59\ (\delta c - \delta w)$, Bemis et al., 1998). Both temperature and δw (δ^{18}O of sea water) were collected at station W (Fig. 1) during two cruises undertaken in August 2001 and January 2002 (Lin et al., 2004).

Fig. 6). Both *G. sacculifer* and *G. ruber* are common species that usually grow in low latitude (warm) surface waters (Fairbanks et al., 1980, 1982; Spero and Lea, 1996). Although their δ^{18}O distribution range is comparable to that of C. *wuellerstorfi*, symbiotic and motile characteristics (planktonic) make the source of these two planktonic foraminifera possible anywhere in the water column within the upper 70 m.

4. Summary

Foraminiferal shells collected from sediment traps deployed in the Kao-ping submarine canyon were used as a proxy indicator of the transport of biogenic particles originated elsewhere. The occurrence of benthic foraminifera in the collecting cups was used to infer levels of agitation and lateral transport in the water column where the traps were located, 54 and 104 m above seafloor. In addition, the calcification depth of foraminiferal shells was proposed based on a comparison of their oxygen isotope composition with that of the predicted shell δ^{18}O values calculated from the seawater δ^{18}O. The source of *C. wuellerstorfi* and other associated benthic foraminifera was likely to be from the proximal continental shelf (<50 m). *G. bulloides*, a planktonic foraminifera that favors cool temperatures, was probably originated from a habitat deep inside the canyon. Other planktonic foraminifera may have either been deposited from surface water or from resuspension of surface sediments. Nevertheless, the shelf/slope origin of benthic foraminiferal shells found in the traps provides supporting evidence of cross-shelf transport from deeper water depths toward the shore.

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