Late Pleistocene Paleoceanography of the Kuroshio Current in the Area Offshore Southeast Taiwan

MIN-PEN CHEN[1], CHAO-KAI HUANG[1], LIH LO[1]
AND CHUNG-HO WANG[2]

ABSTRACT

The Kuroshio current flows from the southeast toward the northeast off eastern Taiwan at a speed of 1.5 – 2 knots. Its surface water maintains a temperature of 28 – 29° *C* in summer and 25 – 26° *C* in winter. The salinity of the surface water is in the range of 34.2 – 34.7‰. The paleoceanography of the Kuroshio current off southeast Taiwan is based on recent hydrographic data and planktonic foraminiferal assemblages which have been identified and counted from the core tops of 19 box-cored and 7 piston-cored sediments.

The deposited foraminiferal assemblages are divided into two major groups: neritic and pelagic groups. Besides four dominant species, *Globigerinoides ruber, G. sacculifer, Pulleniatina obliquiloculata and Neogloboquadrina dutertrei*, the remarkable species in the neritic group are *Globigerinita glutinata* and *Globigerina bulloides*. In the pelagic group, *Globorotalia tumida* and *G. menardii* are two prominent species.

During the last glacial epoch, the calculated water temperatures from the transfer function of the planktonic foraminiferal assemblages in two piston-cored sediments show that the surface water temperature fluctuated in the range of 28 – 29° *C* in summer, but the calculated temperatures invariably exceeded 29° *C* during the last interglacial period. In winter, the calculated temperature varied in the range of 22 – 25° *C*; however, the average temperature in the last interglacial epoch was only about 1° *C* greater than that in the period of the last glaciation.

From the calculation of oxygen isotopic data, the lowest stand of sea level was probably 150 *m* below the present mean sea level for 18,500 – 17,500 years B.P.. The highest stand of sea level was still about 10 *m* below the present level about 98,000 years ago. The Kuroshio current would have had a great speed if the sea level had been raised abruptly in a short period. The main axis of the Kuroshio current might have shifted toward the east as the current decelerated and the sea level still rose.

1 *Institute of Oceanography, National Taiwan University, Taipei, Taiwan, R.O.C.*

2 *Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, R.O.C.*

1. INTRODUCTION

The sediments on the sea floor off southeastern Taiwan show various characteristics due to several factors, including the complicated submarine topography, the distances to shore, and the influences of the Kuroshio current on the surface zone of the overlaying ocean. Different assemblages of planktonic foraminifera live in the seawater over the continental shelf, which can be penetrated by sunlight, because of the different physical and chemical conditions in the ocean. As these thanatocoenoses assemblages in the sediments were influenced by geological factors during the process of deposition, they may have been the cause of the syntheses of these influential factors. Therefore, the planktonic foraminifera in the sediments have become important resources for research in paleoceanography.

In our work, we attempted to evaluate Thompson's (1981) transfer function to the physical and chemical conditions, such as temperature and salinity on the area offshore southeast Taiwan and to determine whether it fits the deposited planktonic foraminiferal assemblages in the core tops. Then, we tried to use his transfer function to calculate the superficial sea-water paleotemperature beneath the Kuroshio current during the latest Pleistocene period. The assemblages of planktonic foraminifera in this study were counted from piston-cores OR102-6 and OR170-7 taken as the independent variables for Thompson's function combined with the data of $\delta^{18}O$ and carbon-14 dating ages. Besides the former data, the variation of the carbonate content, coarse fraction, and the absolute abundance of the planktonic foraminifera were also selected in the discussion of the paleoceanographic situations of the paleotemperature, the change of sea level and the paleocurrent of the Kuroshio current in the area off southeastern Taiwan.

Imbrie and Kipp (1971) first established the paleoecological transfer function. They estimated the paleotemperature based on the relative abundance of planktonic foraminiferal assemblage with statistical methods (including factor and regression analyses). Finally, they classified the Atlantic Ocean into five zones and calculated both the summer and winter paleotemperatures as well as the paleosalinities of the superficial seawater. In 1973, Imbrie and Kipp slightly modified this method and submitted another transfer function. CLIMAP (1976) used this method to derive the superficial sea water paleotemperature in August about 18,000 years ago, which was the maximum during the last glaciation period. CLIMAP estimated the paleotemperature in the equatorial Pacific in that age was 2 – 3 degrees lower than at present.

Epstein (1953) first established the relationship of temperature to various combinations of oxygen isotopes within calcite and sea water, which Craig (1965) modified and O'Neil *et al.* (1969) further modified to the form:

$$T = 16.9 - 4.38 \times (\delta^{18}O_c - \delta^{18}O_w) + 0.10 \times (\delta^{18}O_c - \delta^{18}O_w)^2$$

Thus the estimated formula for the paleotemperature has been developed completely. Although there exist related equations submitted by other scholars (Erez, 1983), the formulae submitted by Craig (1965) and O'Neil *et al.* (1969) are more commonly used.

2. OCEANOGRAPHY

The submarine topography in the area offshore southeast Taiwan is complicated. Chen *et al.* (1988) classified it into five physiographic zones; toward the east, they are the Hengchun Ridge, Southern Longitudinal Trough, Huatung Ridge, Taitung Trough and the Lanhsü Ridge, after which there is the Philippine Sea Basin with a depth of more than 4000 *m* (Figure 1).

The characteristics of the seawater off southeastern Taiwan are mainly influenced by the Kuroshio current. The width of the Kuroshio current is about 150 – 200 *km*; the mean velocity is about 1.5 – 2 knots (Chu, 1974).

In summer the temperature of the seawater is 28 – 29° *C*, whereas in spring it is 25 – 26° *C* (Figure 2). These temperatures exceed those of the western Pacific at the same latitude. The salinity reaches 34.2 – 34.7 ‰ (Figure 2) but is decreased to about 34.0 ‰ in the coastal zone because of the injection of fresh water (Fan, 1985, 1987).

Emery and Stevenson (1972) have shown that there exists an upwelling associated with the flow of the Kuroshio off southeastern Taiwan. Tominaga (1972) investigated the subsurface cold water appearing near the southeastern coast of Taiwan and discovered that the cold water was generally even in the case of wind stress, which is unfavorable for the generation of the upwelling phenomena. From the results of the nutrient content of sea water, Hung (1975) showed evidence of upwelling from the coast to 10 – 20 nautical miles offshore. Fan (1979) indicated that southerly or westerly winds and submarine topography were considered the reasons for the upwelling in this area.

The content of dissolved oxygen in ocean water is important for the distribution of marine zooplanktons. According to reported oceanographic survey data of the Kuroshio current (CNCOR, 1966-1970), the content of dissolved oxygen in the offshore Kuroshio current to the east of Taiwan in summer is 4.4 *ml / l* in the superficial layer but 2.4 *ml / l* at a depth of 800 *m*; in winter, it is 4.8 *ml / l* in the uppermost ocean layer but 2.1 *ml / l* at a depth of 1000 *m*. At depths from 800 – 1000 *m*, there may be some relation between the content and the intermediate current (Liu, *et al.*, 1986) which drifts southward, so that the Kuroshio current contains so much dissolved oxygen.

3. MATERIALS AND METHODS

7 piston cores and 19 box cores (Figure 1 and Table 1) were collected from an area offshore southeast Taiwan by *R / V Ocean Researcher 1* during her seven cruises: OR-102, OR-151, OR-170, OR-182, OR-215, OR-216 and OR-219 from 1987 – 1989. Cores of OR102-6 and OR170-7 were selected for this work because of their abundant planktonic foraminifera content in the sediments. The core OR102-6 (121°29' *E*; 22°17' *N*) was gathered from a submarine ridge located to the north of Lanhsü Island; and the core OR 170-7 (121°15' *E*, 22°6' *N*) was gathered from the Huatung Ridge (Figure 1).

The top thick surface sediment with a thickness of 2 *cm* from each of these 26 cores was selected for analysis, and the piston-core OR170-7 was selected for analysis by means

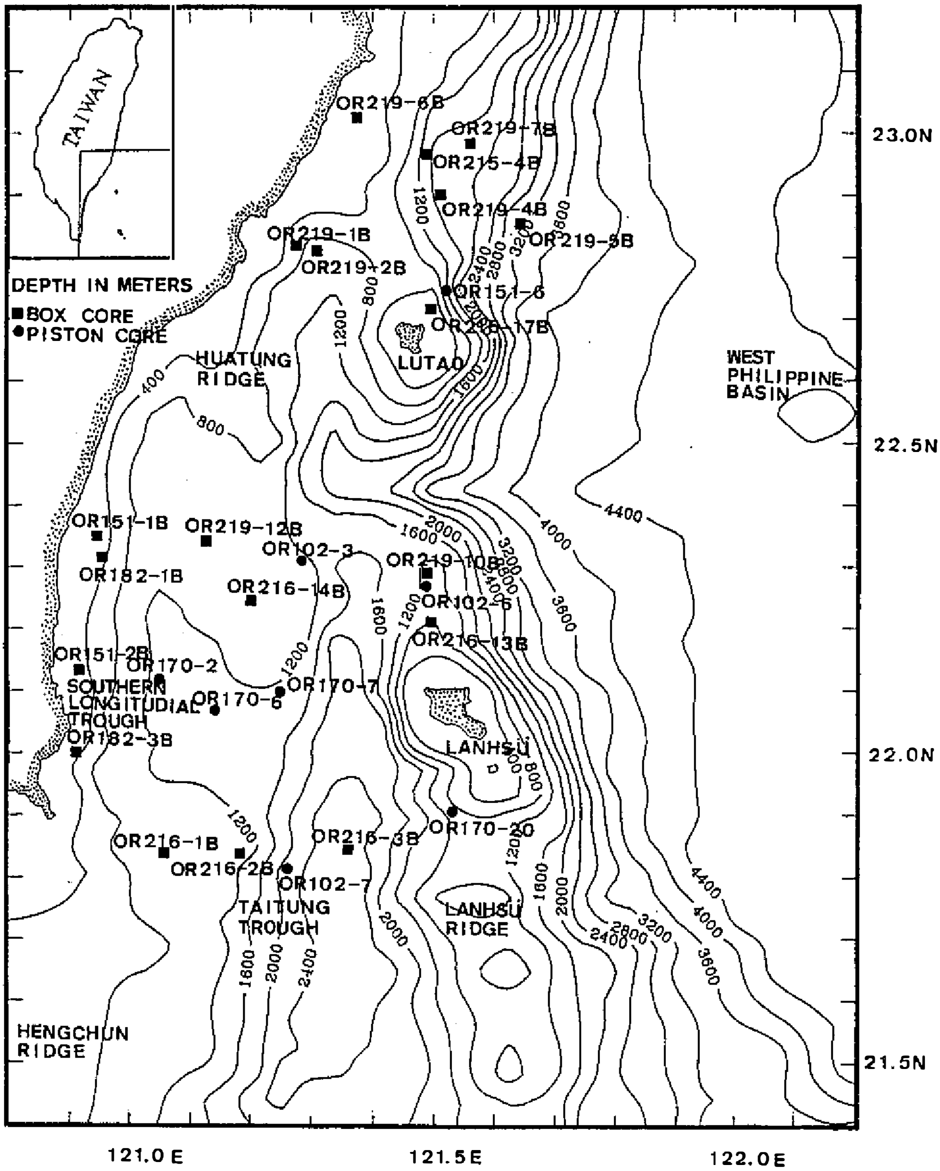

Fig. 1. Bathymetry and seafloor physiography off southeast Taiwan and the studied core numbers and their locations.

of samples 2 *cm* thick per 10 *cm* interval; core OR102-6, which consists of foraminifera ooze, was analyzed by means of samples 1 *cm* thick per 5 *cm* interval.

The grain size and content of calcium carbonate in the selected sediments were analyzed. The dehydrated grains of size greater than 63 μm, were sieveded through a 150 μm (100 mesh) sieve and the planktonic foraminifera of size greater than 150 μm as well as other grains were retained for this study. Phleger (1960) pointed out that tests of planktonic foraminifera of size less than 150 μm are almost the same as larvae. Furthermore,

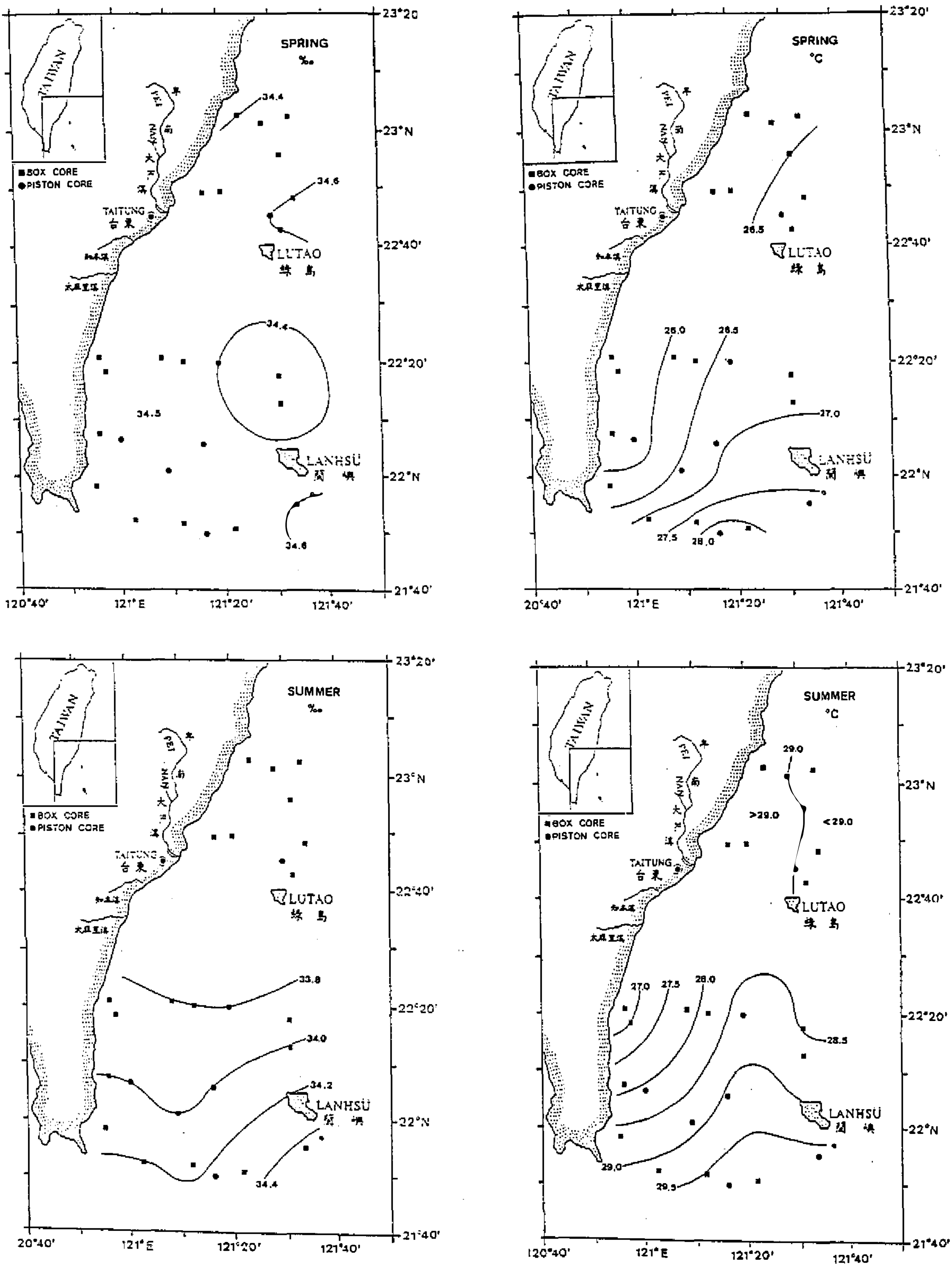

Fig. 2. Contour maps of spring and summer sea surface salinity and temperature off southeast Taiwan (data from Fan, 1985 & 1987).

Table 1. Piston and Box Core Numbers, Collection Locations, Sea Water Depths and Collection Dates

Code no.	Longitude (E)	Latitude (N)	Sea water depth (m)	Collection date
OR102-3	121°17'	22°19'	1309	4/20/87
OR102-6	121°29'	22°17'	495	4/20/87
OR102-7	121°16'	21°50'	815	4/21/87
OR151-6	121°30'	22°45'	1046	4/13/88
OR170-2	121°00'	22°07'	1260	8/1/88
OR170-6	121°09'	22°05'	1290	8/2/88
OR170-7	121°15'	22°06'	1500	8/2/88
OR170-20	121°33'	21°56'	1200	8/2/88
OR151-1B	121°56'	22°21'	118	4/14/88
OR151-2B	121°55'	22°08'	160	4/14/88
OR182-1B	121°57'	22°19'	315	10/2/88
OR182-3B	121°55'	21°59'	373	10/2/88
OR215-4B	121°29'	22°59'	2047	6/20/89
OR216-1B	121°02'	21°50'	1310	6/25/89
OR216-2B	121°11'	21°50'	1101	6/25/89
OR216-3B	121°21'	21°50'	2850	6/26/89
OR216-13B	121°30'	22°13'	900	6/27/89
OR216-14B	121°12'	22°20'	885	6/27/89
OR216-17B	121°30'	22°43'	757	6/27/89
OR219-1B	121°17'	22°50'	815	7/23/89
OR219-2B	121°19'	22°50'	715	7/23/89
OR219-4B	121°31'	22°55'	1795	7/23/89
OR219-5B	121°40'	22°48'	2900	7/23/89
OR219-6B	121°23'	23°01'	141	7/22/89
OR219-7B	121°34'	23°00'	2147	7/22/89
OR219-10B	121°30'	22°17'	370	7/24/89
OR219-12B	121°08'	22°21'	1128	7/24/89

the planktonic foraminifera and grains were continuously separated with using the bi-seperation method until there were about 300 planktonic foraminifers. We identified the different species of planktonic foraminifera under a binocular real-image microscope and counted their relative abundances; meanwhile, we counted the absolute content of planktonic foraminifera per gram of sediments. Before the stable oxygen and carbon isotope of planktonic foraminifera were analyzed, we removed the organic and other adhesive matter from the shells; we collected the carbon dioxide by reaction with pure (100%) phosphate acid under conditions of high vacuum (< 0.001 torr) and temperature 50° *C*, and then put the collected carbon dioxide into a SIRA-10 Mass Spectrometer for the analysis of the values of $\delta^{18}O$ and $\delta^{13}C$. To estimate the whole analysis process and the variation of specimen, we added three checking specimens (Merck, Hanawa and MBS).

Three samples of OR102-6 and two samples of OR170-7, each with a mass of about 25 *gm*, were selected for C-14 dating performed by the C-14 Dating Laboratory of the Department of Geology, National Taiwan University according to the conventional method.

4. RESULTS

C-14 Dating Ages

The sediments in the OR102-6 core were taken from the top, at 80 *cm* and at 163 *cm* (core bottom) for C-14 age dating. Their dated ages are 9,000 ± 200, 16,000 ± 500 and 36,000 ± 1,400 B.P. respectively. The sediments in the OR170-7 core were sampled at 20 *cm* and at 72 *cm* and were dated as 37,000 ± 3,000 and older than 50,000 B.P. respectively. The recent sediments of both cores were unsampled, the strong bottom current probably being the main cause (Liu *et al.*, 1986). The consistent ages in the OR102-6 core and the fluctuation patterns of the stable oxygen isotopes of both cores are the main reasons that the intervals between oxygen isotopic stages 2 – 5 remain reliable.

Carbonate Content of Sediment

The carbonate content of surface sediments on the seafloor offshore southeast Taiwan is smaller than that near the coastline; it is 10% less except for that of OR219-6B; even that of OR182-3B is 1.6% less. Offshore it increases gradually and reaches its highest value at Lanhsü Ridge; therein that of OR219-10B reaches as much as 91.3% (Figure 3).

The carbonate content at the top of the OR102-6 core is 47.4%, and then from the top to 45 *cm* it is between 49.9% (5 *cm*) and 28.6% (35 *cm*); subsequently, it increases abruptly from 50 *cm* to 155 *cm*, where it is between 85.4% (105 *cm*) and 59.4% (145 *cm*). Then, it decreases to 33.5% at the bottom (163 *cm*) (Figure 3).

The carbonate content at the top of the OR170-7 core is 29.6%; from 10 *cm* to 50 *cm* it decreases from 34.7% to 7.2%; subsequently, it increases gradually to 63.3% at the depth of 190 *cm*, and then down to 7.4% at the depth of 300 *cm*; it increases again to 42.5% at the depth of 350 *cm*, but then decreases to 31.9% at the bottom (360 *cm*) (Figure 3).

Coarse Fraction of Sediment (Greater Than 63 μm)

On the basis of the coarse fraction data of the 26 surface sediments, we divide them into four areas (Figure 4). (1) The Lanhsü area is located at the Lanhsü Ridge. Its coarse fraction is greater than 70%; there are grains of two kinds: one consists mainly of debris of volcanic rocks and the other consists mainly of planktonic foraminifera and debris of other marine microfossils. (2) The southern near-shore area is located in the coastal zone south of 22°30' *N*. Its coarse fraction is between 40% and 70% and consists mainly of continental matter, such as quartz and debris of slate. (3) The central area is located between the preceding areas. It has a coarse fraction of less than 20% and consists mainly of planktonic foraminifera and terrigenous matters. (4) The northern near-shore area is located in the coastal zone north of 22°40' *N*. Its coarse fraction is less than 20% and consists mainly of planktonic foraminifera. In OR215-4B core we found many diatoms. In the OR102-6 core, the coarse fraction portion has a maximum value 86.2% at a depth of 80 *cm* and a minimum value of 44.3% at the bottom of the core (163 *cm*) (Figure 4). It consists mainly of planktonic foraminifera, pteropod, fragments of bryozoa and coral.

Based on the distributions of coarse fraction in OR170-7 (Figure 4), this core is divided into four segments. (1) 0 – 70 *cm* : its coarse fraction starts at the minimum value, 19.0% at

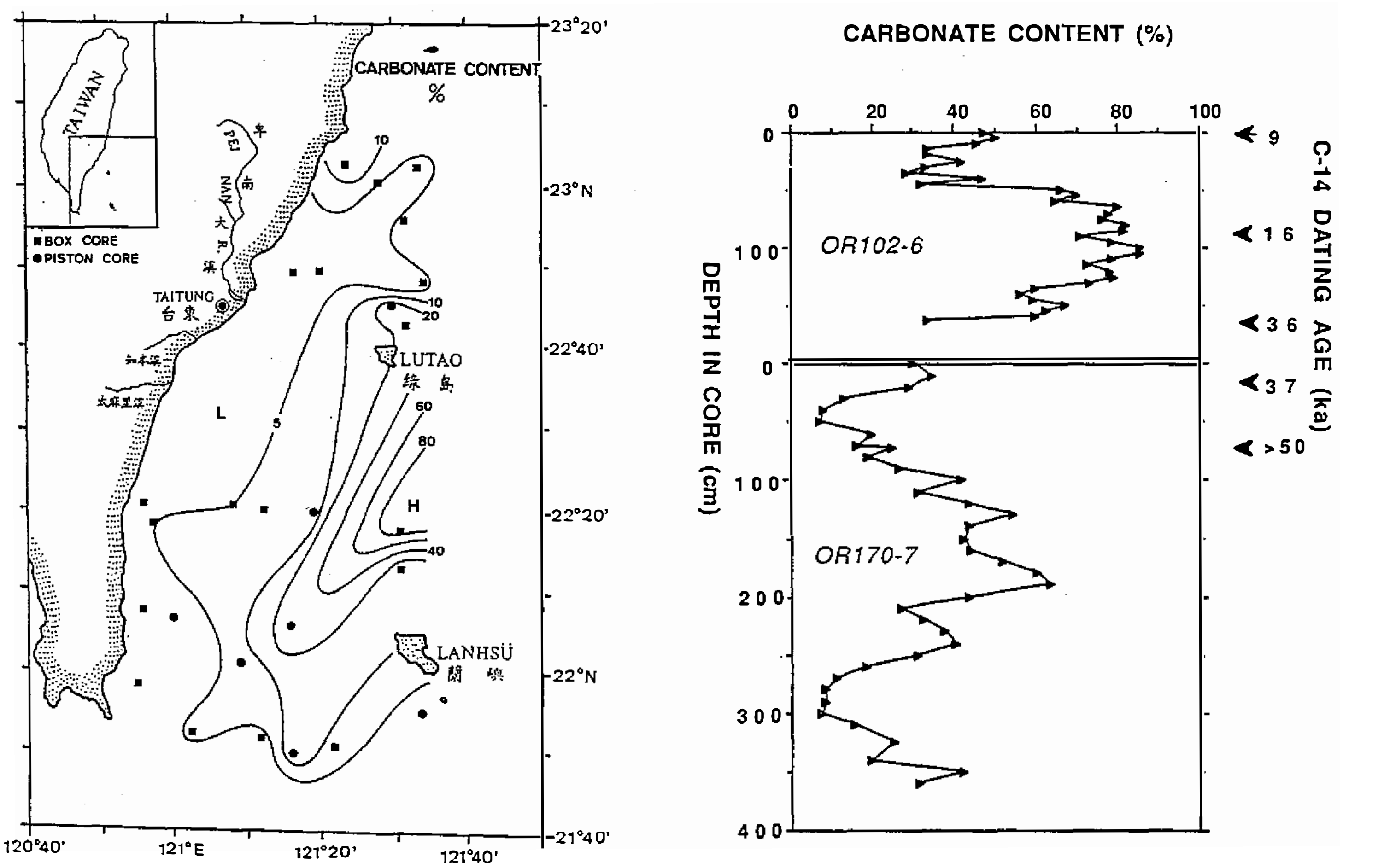

Fig. 3. Carbonate content distributions of core top sediments (left) and from piston-cored sediments of OR102-6 and OR170-7 (right).

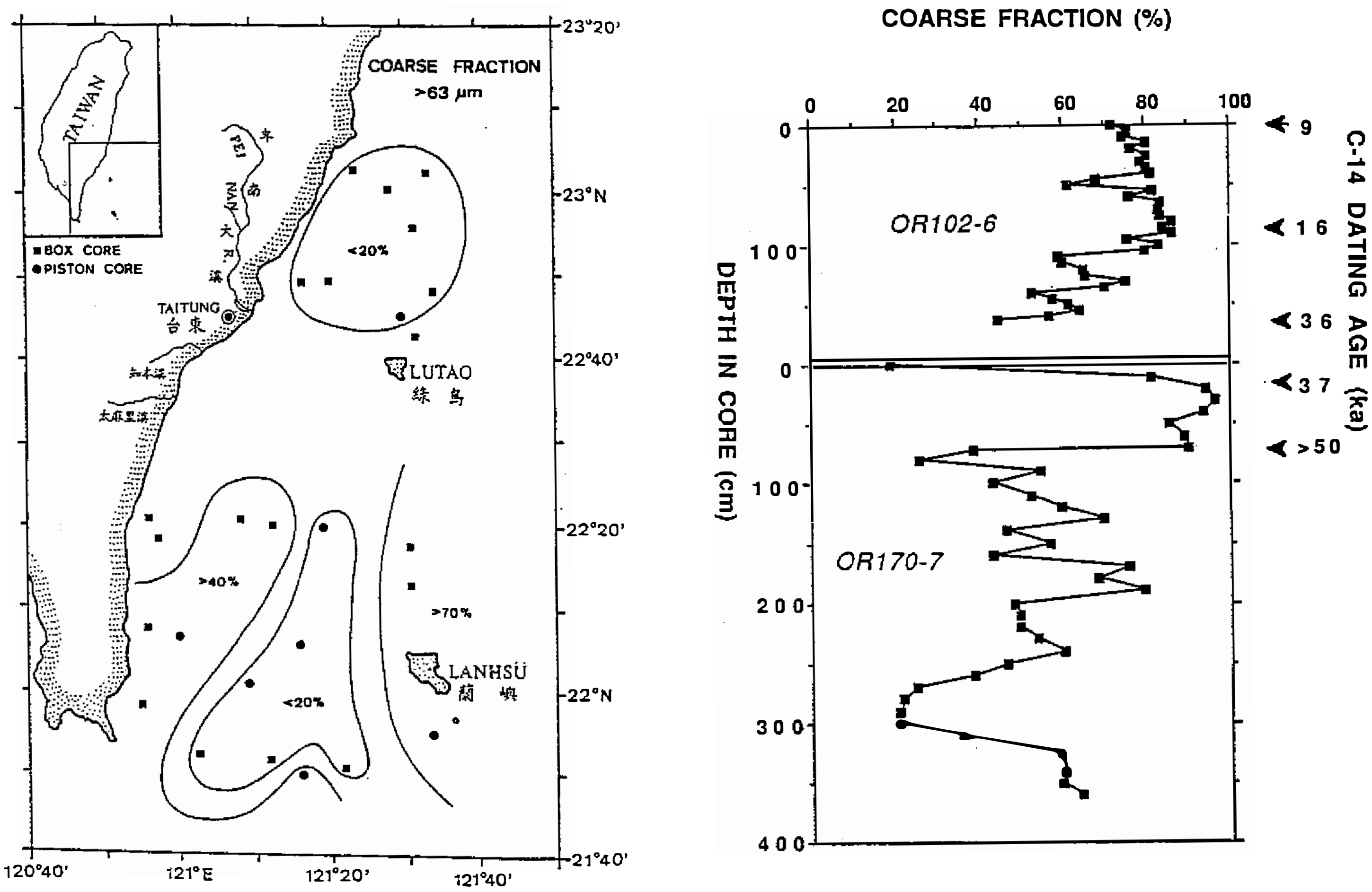

Fig. 4. Coarse fraction (> 63 μm) distributions of core top sediments (left) and from piston-cored sediments of OR102-6 and OR170-7 (right).

the top of the core, but increases abruptly to the maximum value, 96.3% at the depth of 30 *cm*. Except for the top 20 *cm*, which is made up mainly of planktonic foraminifera, the other part consists mainly of gravel (greater than 2 *mm* in diameter) of which the ingredient is debris of volcanic rocks. (2) 71 – 240 *cm* : coarse fraction is between 25.5% (80 *cm*) and 79.5% (190 *cm*) and mainly consists of planktonic foraminifera. (3) 240 – 300 *cm* : its coarse fraction decreases gradually from 60.0% (240 *cm*) to 20.5% (300 *cm*) but consists mainly of planktonic foraminifera. (4) 300 – 360 *cm* : its coarse fraction increases gradually from 20.5% (300 *cm*) to 64.0% (360 *cm*) but still consists mainly of planktonic foraminifera.

Absolute Abundance of Planktonic Foraminifera

The absolute abundance distribution of the planktonic foraminifera counted from the box-cored sediments (Figure 5) shows value less than 100 near the coastline. The minimum number 15 appears in OR219-6B. The absolute abundance increases in geometrical proportion far from the coast. The number of planktonic foraminifera per gram of sediments at the Lanhsü Ridge generally exceeds 100 except for some specimens which are mixed with debris of volcanic rocks. The number in OR 219-10B is 1,970 which is also the largest number in this area. Besides, there shows a low value west of the Lanhsü Ridge; therefore, there results NE-SW twisting isolines (Figure 5).

In OR102-6, the absolute abundance of the planktonic foraminifera has the maximum value both from the top of the core to the depth of 10 *cm* and from the depth 130 *cm* to the bottom of the core; here, it reaches 12,000 – 23,000. The other parts are only 5,000 (Figure 5).

In OR170-7, the absolute abundance of the planktonic foraminifera is greater than 6,000 except for the underlying three segments. The maximum value 11,104 appears at the depth of 180 *cm* (Figure 5). Within the top 5 *cm*, there only contain 1,391 per gram sediment. Within 20 *cm* – 80 *cm*, there are only 634 at the depth of 40 *cm*. The main composition of this segments is debris of volcanic rocks. From 270 *cm* – 325 *cm*, the minimum value for only 936 appears at the depth of 280 *cm*.

Assemblage of Planktonic Foraminifera

The planktonic foraminiferal thanatocoenoses from the 26 surface sediments of box-cores are divided into four groups: the neritic (N) group, upwelling (U) group, Lanhsü pelagic group (Pa) and the Lutao pelagic group (Pu) (Figures 6 & 7). The neritic group includes 10 cores, whose distribution region lies along the coastal zone south of 22°30' *N*, north of 22° *N* and west of the Huatung Ridge. The planktonic foraminifera assemblage in the neritic group is dominated by *Globigerina bulloides* 13.4%, *Globigerina glutinata* 21.5% and *Globigerina rubescens* 4.3%. The upwelling group includes 5 cores, which distributes over the coastal zone north of 22°40' *N*. The main species is *Globigerinoides sacculifer* of content 19.1%. Besides, the average content 15.9% of *Globigerinoides ruber* is the minimum of the four groups. The Lanhsü pelagic group includes 6 cores, which are distributed along the Lanhsü Ridge to the south of 22° *N*. The predominant species of this

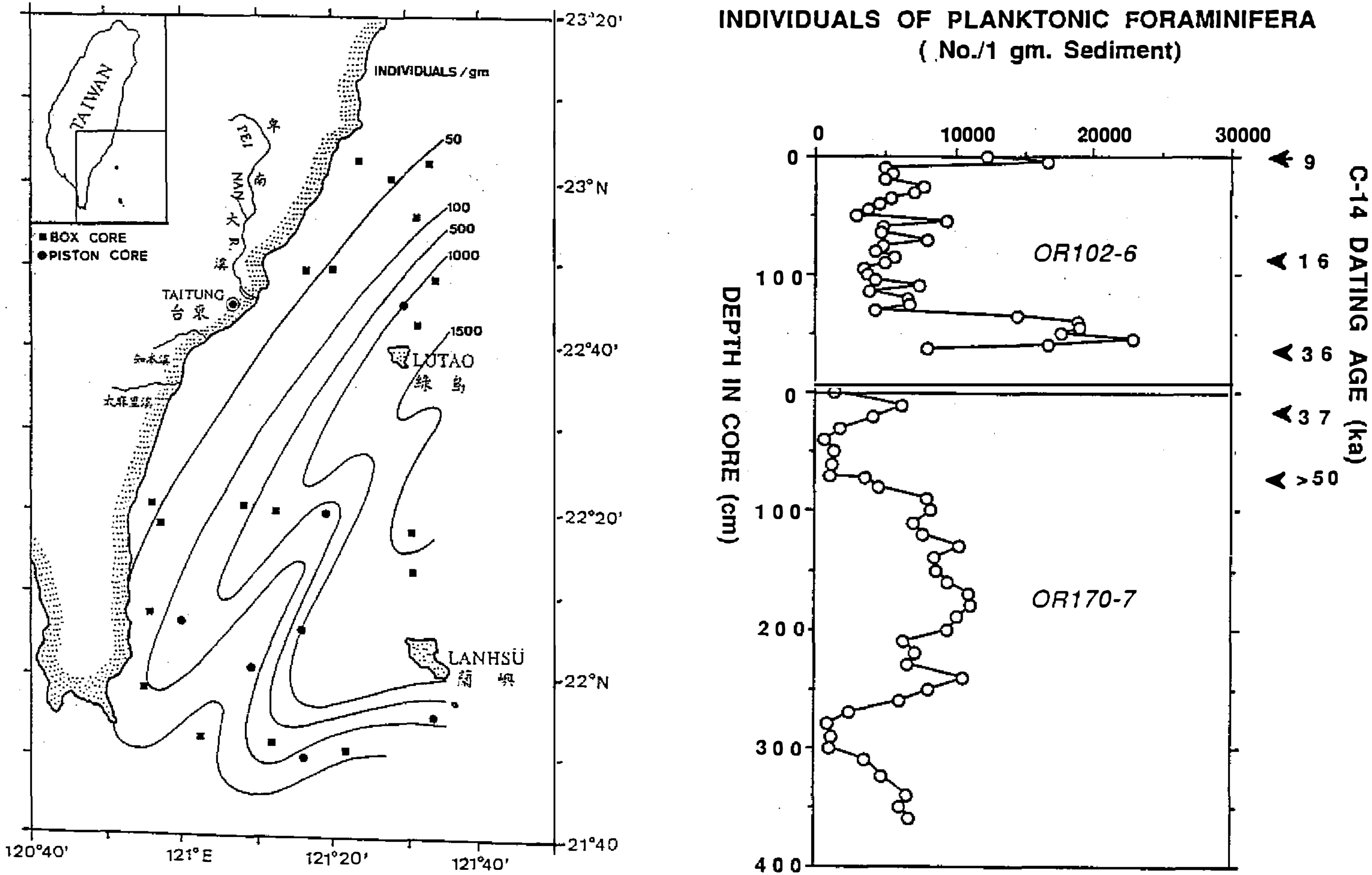

Fig. 5. Planktonic foraminifera absolute abundance distributions of core top sediments (left) and from piston-cored sediments of OR102-6 and OR170-7 (right).

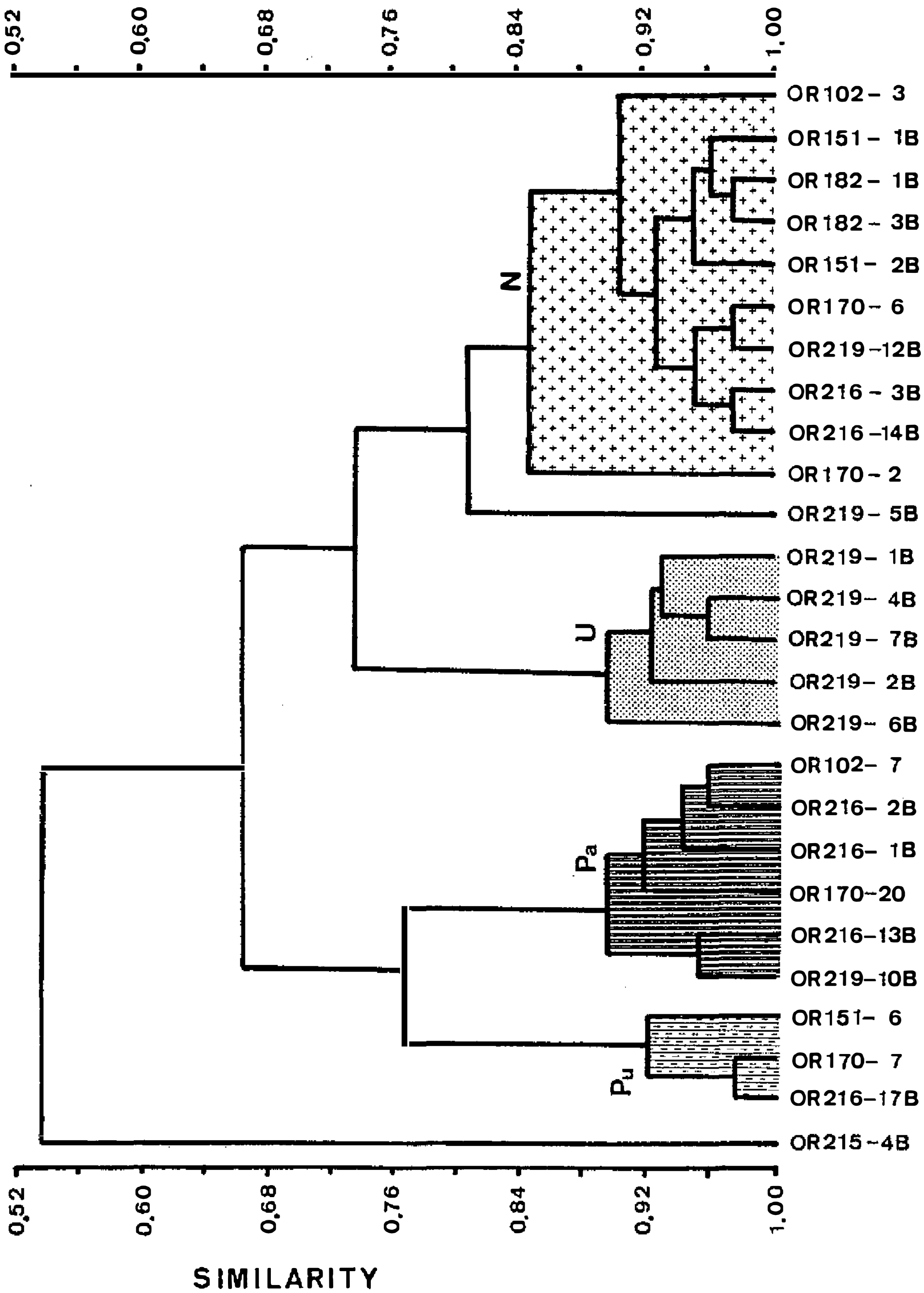

Fig. 6. Dendrogram of planktonic foraminifera assemblages within the core top sediments by cluster analysis.

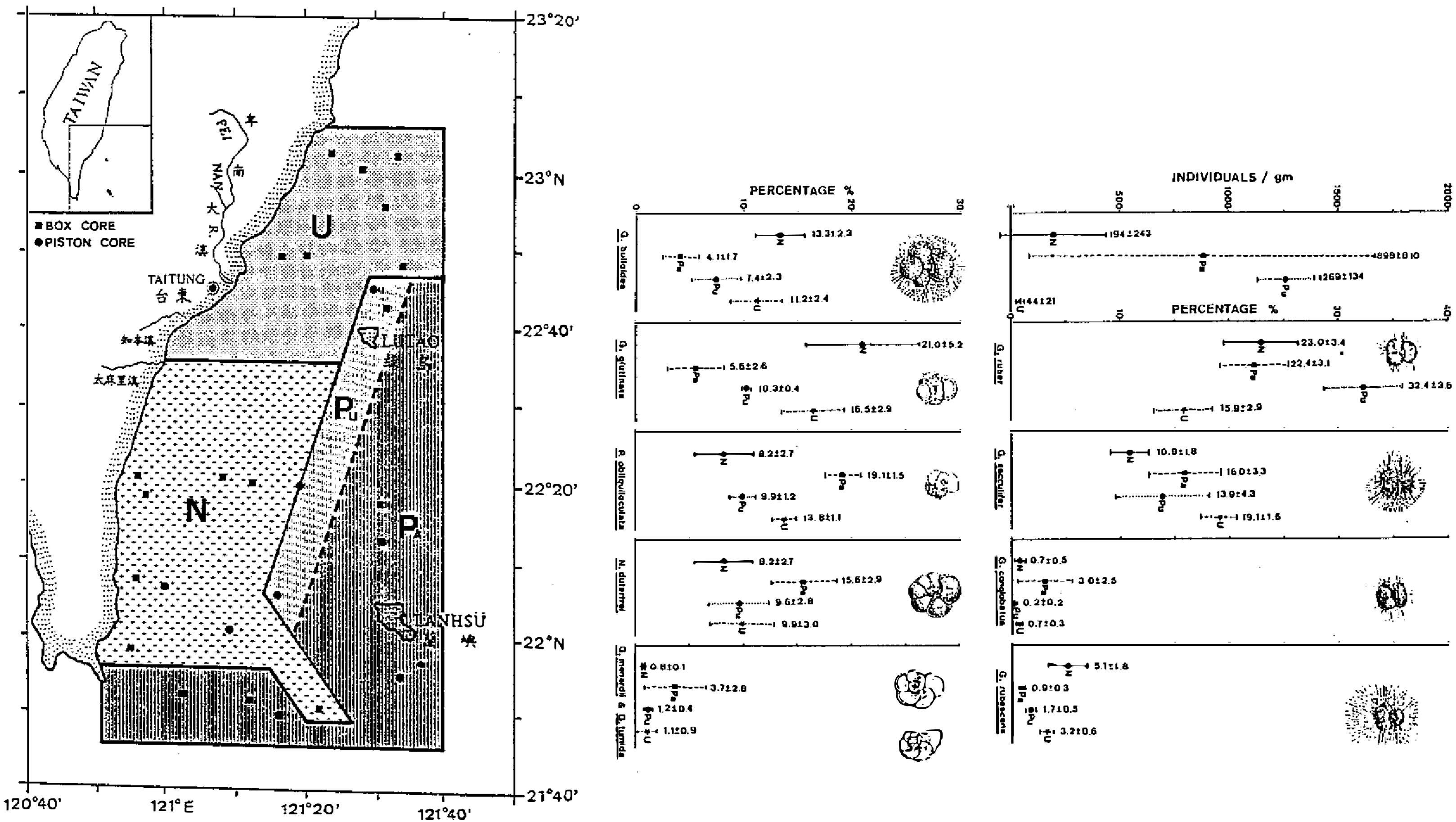

Fig. 7. Province of planktonic foraminifera assemblages within the core top sediments by cluster analysis (left) and the distribution of predominant species (right).

group are *Pulleniatina obliquiloculata* (17.3%), *Globigerinoides conglobatus* (1.8%), *Globorotalia menardii* and *Globorotalia tumida* (average content, 4.6%). The Lutao pelagic group includes 3 cores, which are distributed among the preceding three groups. The dominant species is *Globigerinoides ruber* of content as great as 32.4%.

OR102-6 is located within the region of the Lanhsü pelagic group. Its assemblages of planktonic foraminifera in the entire core resemble those of the Lanhsü pelagic group. The values of *Globorotalia crassaformis*, *Globorotalia inflata* and *Globorotalia tumida* in the core tend to increase toward the bottom. From the top of the core to the depth of 10 *cm* and from the depth of 80 *cm* to the depth of 140 *cm*, the relative abundances of *Globigerinella calida*, *Globorotalia obesa*, *Globigerinita glutinata*, *Globigerinella aequilateralis* and *Orbulina universa* are greater than those at other depths. At the depth of 120 *cm* the contents of *Neogloboquadrina incompta* and *Globorotalia truncatulinoides* are particularly great. The contents of *Globigerinoides ruber* and *Globigerina bulloides* at a depth above 45 *cm* exceed those in the lower segments (Figures 8 & 9).

OR170-7 is located within the region of the Lutao pelagic group. All the assemblages of planktonic foraminifera in the entire core differ greatly from those of the Lutao pelagic group. The species which have greater content than those of the Lutao pelagic group are *Noegloboquadrina dutertrei* (26.4%), *Globorotalia inflata* (3.3%), *Globorotalia crassaformis* (4.2%), *Globorotalia menardii* & *Globorotalia tumida* (6.1%) and *Pulleniatina obliquiloculata* (19.6%). The species which have lesser content values than those of the Lutao pelagic group are *Globigerinoides ruber* (14.5%), *Globigerina bulloides* (1.3%), *Globigerinella calida* (0.9%) and *Globigerinita glutinata* (4.4%) (Figures 8 & 9).

5. CALCULATED PALEOTEMPERATURE FROM TRANSFER FUNCTION

Thompson (1981) classified the planktonic foraminifera of the Northwest Pacific into six groups: Arctic-subarctic belt (consists mainly of *Neogloboquadrina pachyderma*), Transitional belt (consists mainly of *Globorotalia inflata*), Subtropical belt (consists mainly of *Globigerinita glutinata*), Tropical belt I (consists mainly of soluble species such as *Globigerinoides ruber*), Tropical belt II (consists mainly of insoluble species such as *Pulleniatina obliquiloculata*) and Gyre Margin (consists mainly of *Globigerina bulloides* and *Neogloboquadrina dutertrei*).

Using Thompson's transfer function to compare the temperature calculated from the assemblages of planktonic foraminifera in the surface sediments with the mean temperature by measurement, we found that its deviation is only 0.8° *C* (Table 2). The summer paleotemperature of the surface layer calculated from OR102-6 is in the range of 28.2 – 29.0° *C* with a mean of 28.5° *C* and a standard deviation of 0.2° *C*; from OR170-7, in the range of 28.7 – 29.8° *C* with a mean of 29.1° *C* and a standard deviation of 0.3° *C* (Figure 10). The winter paleotemperature of the surface layer is in the range of 21.0 – 24.5° *C* with a mean of 22.7° *C* and a standard deviation of 0.9° *C* from OR170-7, in the range of 22.1 – 26.8° *C* with a mean of 23.9° *C* and a standard deviation of 1.2° *C* (Figure 10).

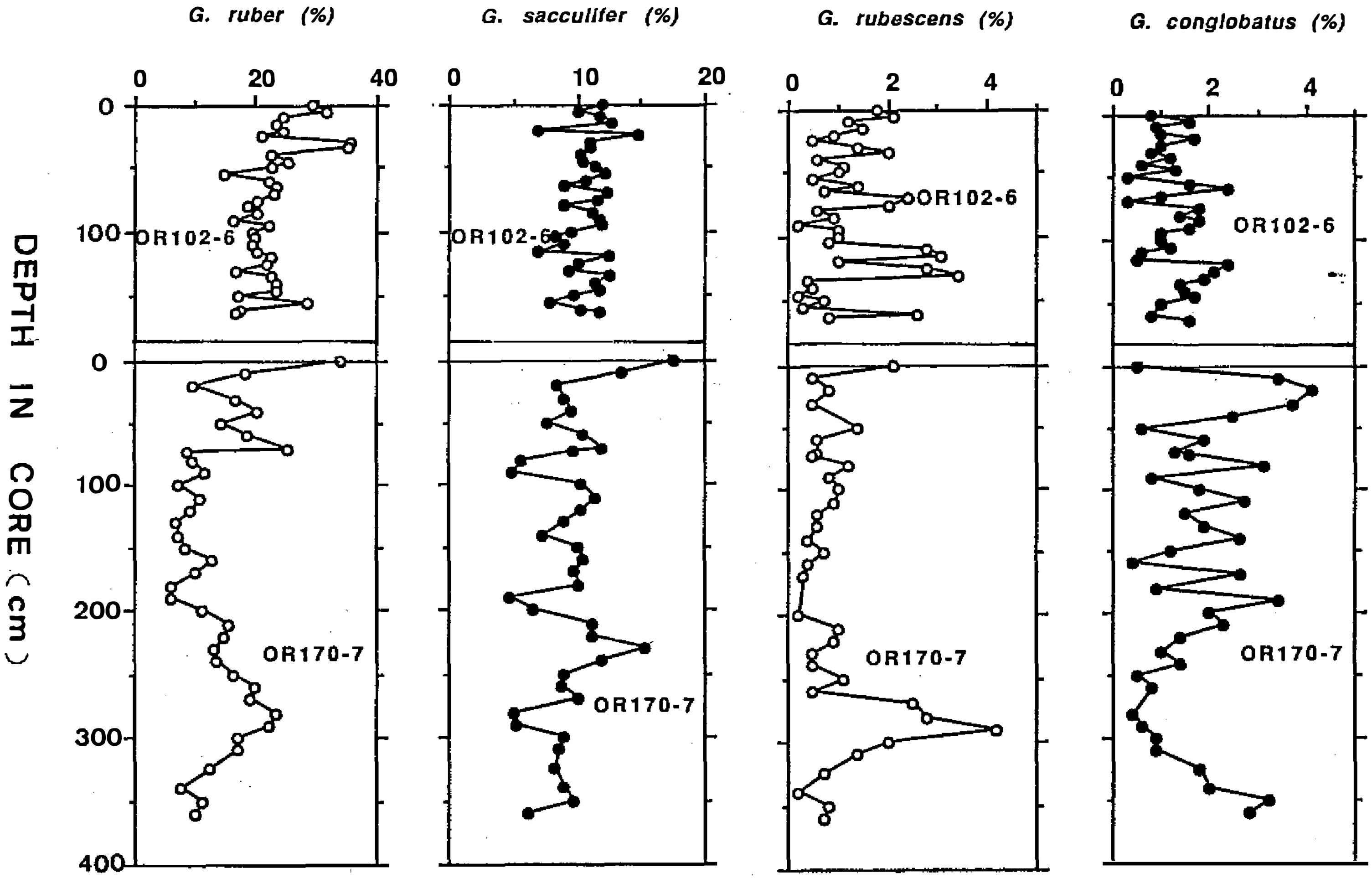

Fig. 8. The distributions of *G. ruber*, *G. sacculifer*, *G. rubescens* and *G. conglobatus* along the piston cored sediments of OR102-6 and OR170-7.

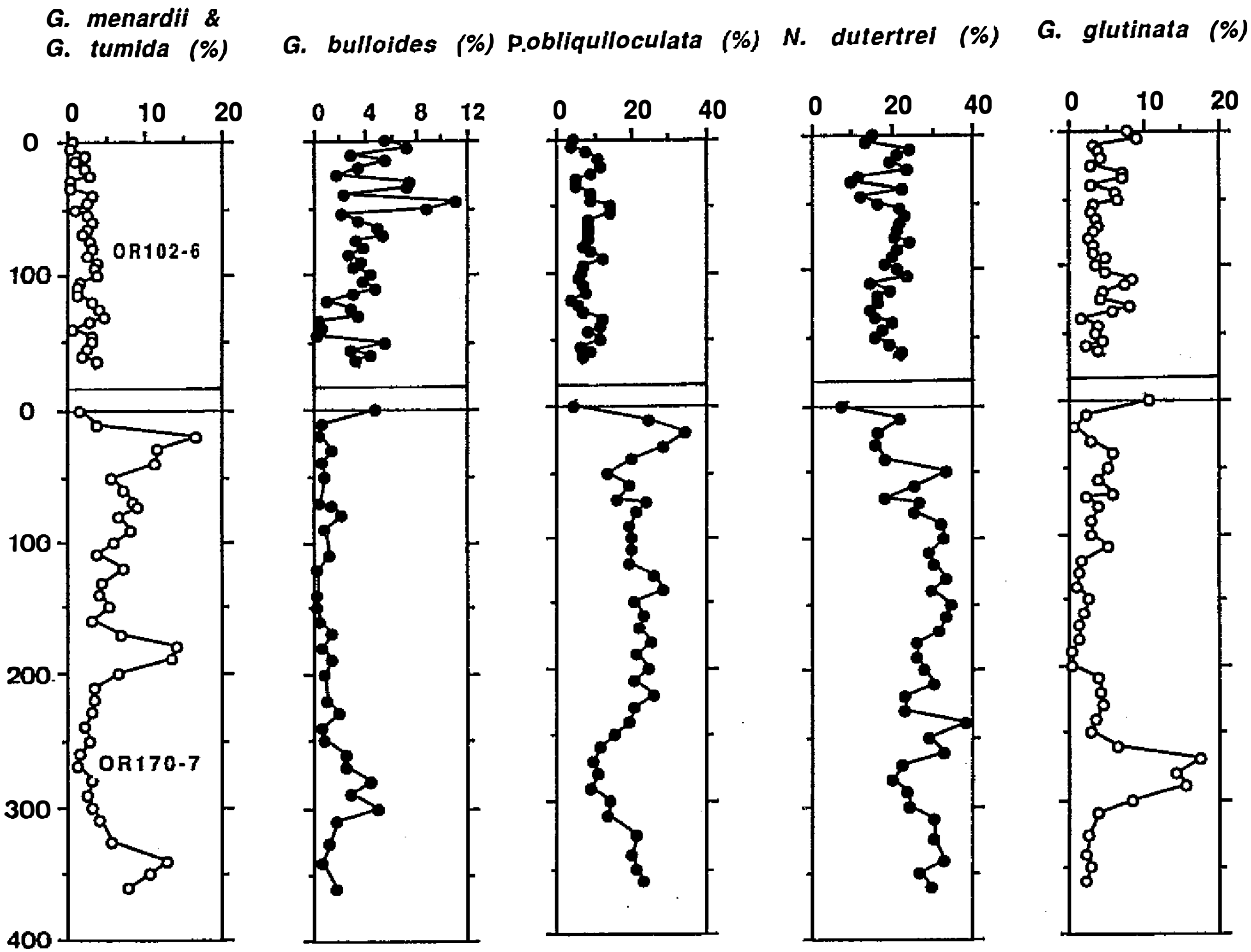

Fig. 9. The distributions of *G. menardii&tumida*, *G. bulloides*, *P. obliquiloculata*, *N. dutertrei* and *G. glutinata* along the piston cored sediments of OR102-6 and OR170-7.

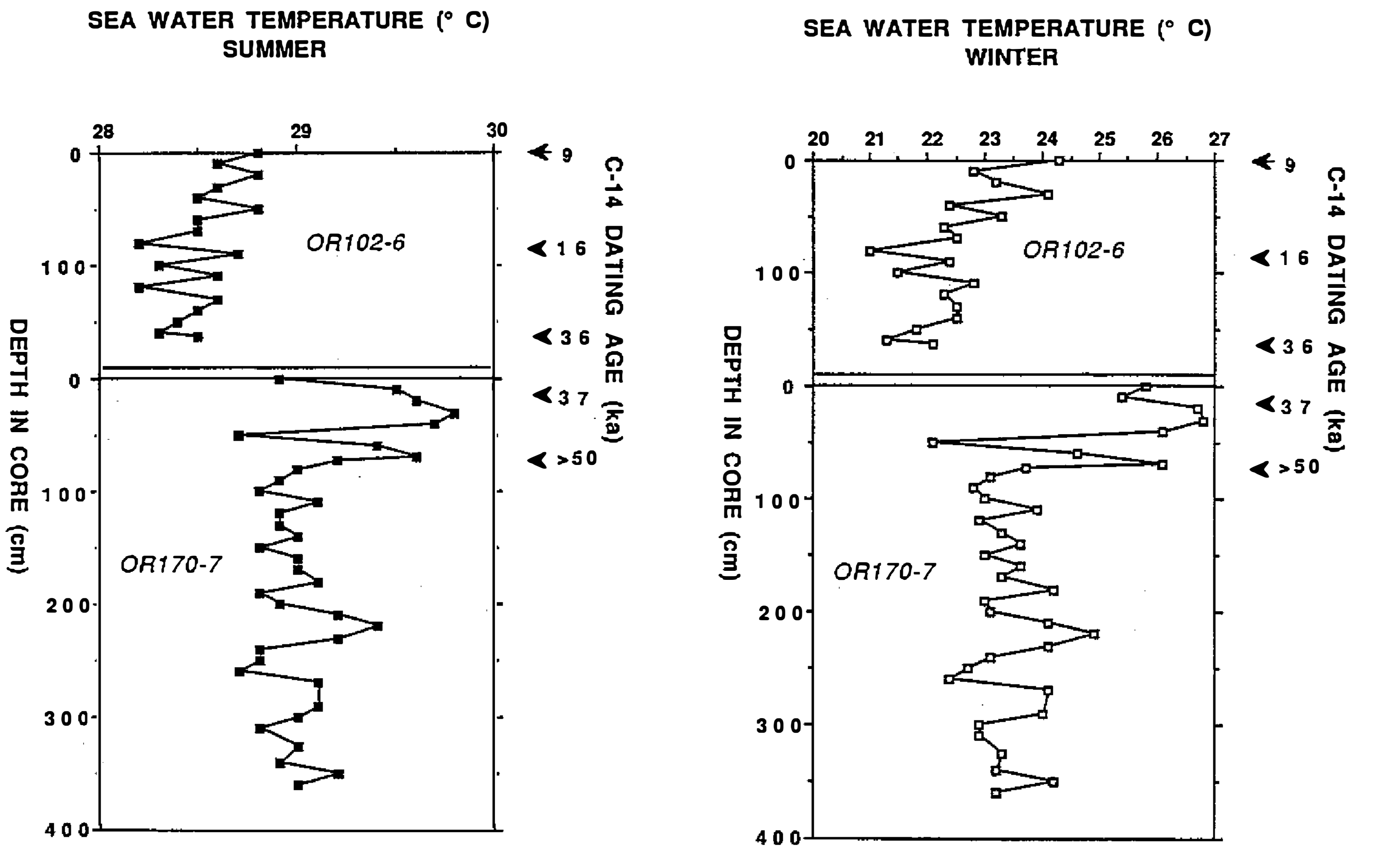

Fig. 10. Calculated sea surface summer and winter temperatures from Thompson's transfer function along piston cores of OR102-6 and OR170-7.

Table 2. Measured Summer Sea Surface Temperatures and Calculated Summer and Winter Sea Surface Temperatures from Thompson's (1981) Transfer Function

Code no.	Measured Summer surface temperature (°C)	Calculated Summer surface temperature (°C)	Difference (°C)	Calculated Winter surface temperature (°C)
OR102-3	28.7	29.5	0.8	26.0
OR102-7	29.6	29.2	-0.4	24.6
OR170-2	28.1	28.8	0.7	24.9
OR170-6	28.9	28.8	-0.1	23.7
OR170-7	29.1	29.2	0.1	26.3
OR170-20	29.7	29.2	-0.5	25.6
OR151-1B	26.9	28.6	1.7	23.4
OR151-2B	27.8	28.8	1.0	23.8
OR182-2B	27.0	28.6	1.6	23.4
OR182-3B	28.6	28.6	0.0	23.2
OR216-1B	29.3	29.4	0.1	25.2
OR216-2B	29.5	29.4	-0.1	25.3
OR216-3B	29.7	28.8	-0.9	24.8
OR216-13B	28.7	29.6	0.9	26.8
OR216-14B	28.2	29.1	0.9	25.0
OR216-17B	28.8	29.0	0.2	25.2
OR215-4B	29.0	27.8	-1.2	19.2
OR219-1B	29.1	28.6	-0.5	23.1
OR219-2B	29.1	28.8	-0.3	23.8
OR219-4B	29.0	29.1	0.1	25.4
OR219-5B	28.9	29.8	0.9	27.2
OR219-6B	29.1	28.9	-0.2	24.4
OR219-7B	28.9	29.1	0.2	25.1
OR219-10B	28.5	29.4	0.9	26.2
OR219-12B	27.8	28.7	0.9	23.5

6. $\delta^{13}C$ & $\delta^{18}O$ VALUES of *Globigerinoides sacculifer*

The distribution of the *Globigerinoides sacculifer* $\delta^{13}C$ and $\delta^{18}O$ values of the box-cored sediment is plotted in Figure 11. Because the area between 22°40' *N* and 22°20' *N* had no cored samples, the contour lines of the $\delta^{13}C$ and $\delta^{18}O$ values are discontinuous (Figure 11). The greatest value of $\delta^{18}O$ near Taitung is probably due to the upwelling effect which may bring the cold water to the sea surface (Fan, 1979). West of Lanhsü Island, the $\delta^{18}O$ values vary from −2.05‰ in the cores OR216-2B and 14B to −2.21‰ in the core OR216-1B whose differences are smaller than the values in the area north of Lutao. The contour lines of $\delta^{13}C$ values in the studied area are more or less parallel to the coast line which may be related to the primary productivity. The smallest value is closest to the coast, and then the values gradually increase eastward.

In the core OR102-6, the value of $\delta^{13}C$ is between 1.44‰ (160 *cm*) and 2.07‰ (80 *cm*) and has a 0.63‰ difference. The value of $\delta^{18}O$ reaches 0.11‰ at the depth of 130 *cm* and has a minimum value −1.39‰ at the top of the core; its difference is 1.50‰. According to

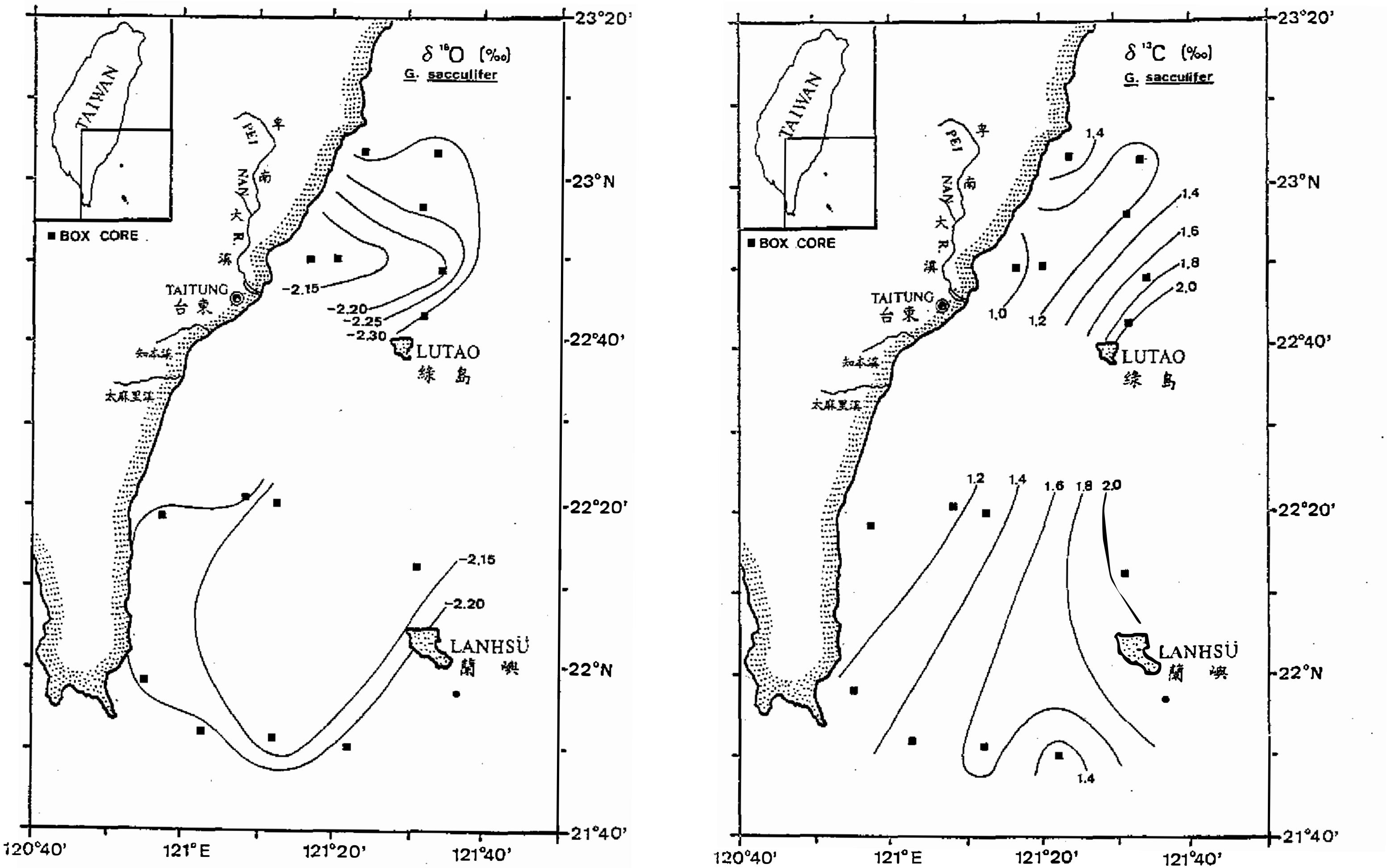

Fig. 11. Contour maps of $\delta^{13}C$ and $\delta^{18}O$ of *G. sacculifer* from the core-top sediments.

the data of the oxygen isotope and carbon-14 dating methods, it may belong to the oxygen isotopic stages 2 and 3; most sediments of the core are located at stage 2 (20 *cm* – 150 *cm*) (Figure 12).

In the core OR170-7, the value of $\delta^{13}C$ (Figure 12) is between 1.41‰ (50 *cm*) and 2.06‰ (110 *cm*), with a 0.65‰ difference. The value of $\delta^{18}O$ (Figure 12) reaches –1.02‰ at the depth of 72 *cm* and has a minimum value –1.78‰ at the depth of 20 *cm*; its difference is 0.76‰. The age at the depth of 20 *cm* is 37,000 ± 3,000 which is located within the oxygen isotopic stage 3. The small $\delta^{18}O$ value in this depth is probably due to mixing with modern microfossils. The age of the coring depth at 72 *cm* is greater than 50,000 years; owing to the uncertainty of carbon-14 dating, it is more difficult to determine at which stage of oxygen isotope it belongs. The curve of oxygen isotope at the depth of 72 *cm* has characteristics of the oxygen isotopic stage 4. For the rest of the core, it is reasonable to estimate that the period belongs to the oxygen isotopic stage 5. They show 5a at depth between 80 – 150 cm, 5b at depth between 150 – 210 *cm*, 5c at the depth between 210 – 310 *cm*, and 5d at depth greater than 310 *cm* respectively (Figure 12).

A specimen from the depth 240 *cm* was selected for repeated analysis (four times); from this the standard deviation of $\delta^{18}O$ is 0.07‰, and the standard deviation of $\delta^{13}C$ is 0.03‰.

7. SEA LEVEL CHANGE

We attempted from the paleotemperature equation (O'Neil *et al.* 1969) to find the value of $\delta^{18}O_w$ by using the measured value of $\delta^{18}O_c$ and the mean temperature calculated from the transfer function. Fairbanks *et al.* (1978) proposed that the value of $\delta^{18}O_w$ increases about 0.011‰ for every 1 meter of descent in sea level. Consequently, we derived the fluctuations of the sea level offshore southeast Taiwan.

The highest stand of sea level existed at the depth of 250 *cm* of core OR170-7. This value was 10 *meters* lower than at present. By interpolating the data from carbon-14 dating, the date is estimated to ben about 98,000 years before the present time (Figure 13).

The lowest stand of sea level existed at the depth of 110 – 130 *cm* of core OR102-6. This value was 150 meters lower than at present. By interpolating the data from Carbon-14 dating, the date is estimated to be about 17,500 – 18,500 years before the present time (Figure 13).

8. PALEOCURRENT OF KUROSHIO

After the preliminary analysis described above, the planktonic foraminiferal thanatocoenoses offshore southeast Taiwan are classified into four groups. Using the skill of transfer function, we can make use of it as not only the criterion for classifications but also the tool to discuss the paleoceanographical situation. Selecting seven main species of planktonic foraminifera among this region: *Globigerinoides ruber*, *Globigerinoides sacculifer*, *Globigerina bulloides*, *Globigerinita glutinata*, *Neogloboquadrina dutertrei*, *Pulleniatina*

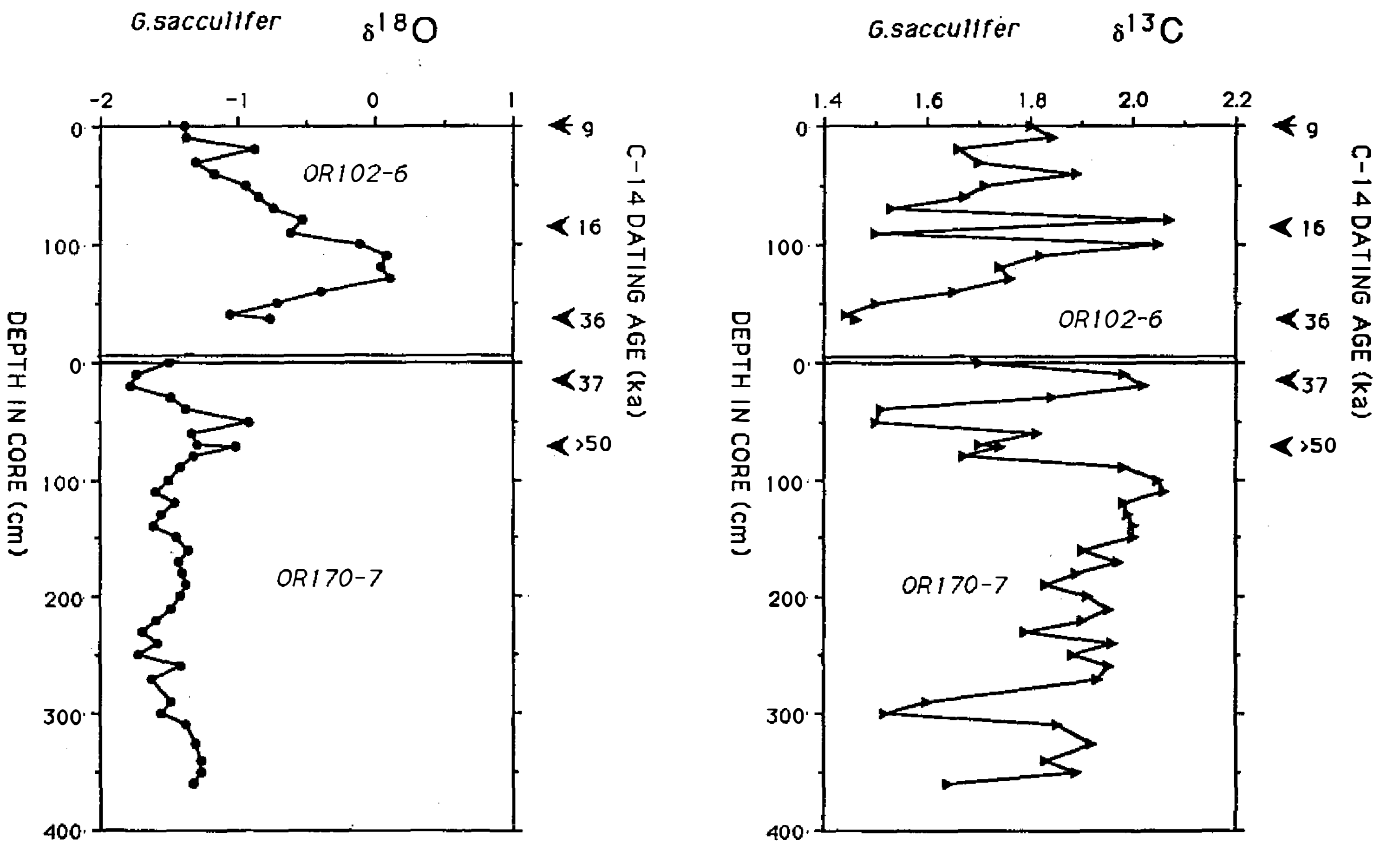

Fig. 12. Vertical distribution of $\delta^{18}O$ and $\delta^{13}C$ of *G. sacculifer* combining from the piston-cored sediments of OR102-6 and OR170-7.

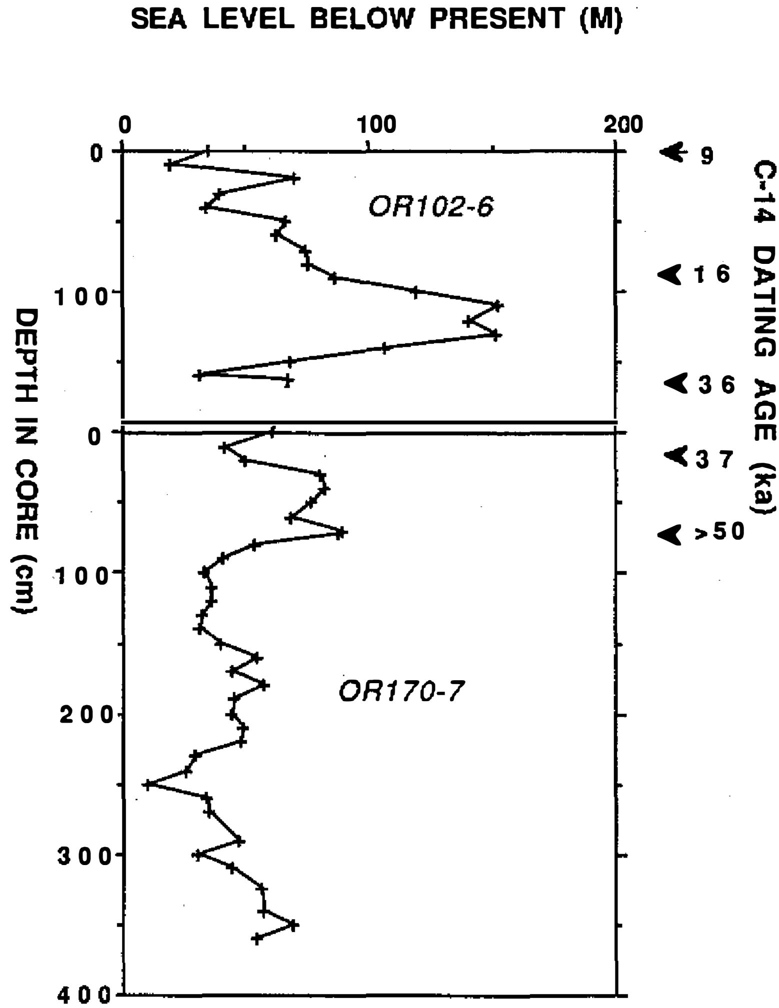

Fig. 13. Sea level fluctuations resulting from the stable oxygen isotopic data of piston-cored sediments of OR102-6 and OR170-7.

obliquiloculata, then obtaining their individual summations with *Globorotalia menardii* and *Globorotalia tumida*, and including two variables which have relationships with the productivity, we found the carbonate contents and the absolute abundance of planktonic foraminifera (using the logarithm of this variable). With nine variables in total, we obtained a varimax matrix B_{ct} and a factor score matrix F by the Q-mode factor analysis. Combining B_{ct}, F with the core locations, these core sites were divided into three underlying areas (Figure 14): (1) the south near-shore area (Ns) consisting mainly of *G. bulloides* and *G. glutinata*; (2) the north near-shore area (Nn) *N. dutertri* and *P. obliquiloculata* as the dominant species; (3) the pelagic area (P), *G. ruber*, *G. menardii* and *G. tumida* as the prominent species. The carbonate content and absolute abundance of planktonic foraminifera in the pelagic area are more important than those in the other areas. Putting these three areas on the vertices as compositions, individually squaring the three factor loadings of every observing value in the B_{ct} matrix and dividing them by their common characteristics, then plotting them on the triangular map (Figure 14), the distribution of these cores and the region on which these three areas are distributed are shown in Figure 15. Moreover, from the triangular map we subdivided the pelagic area (P) into south pelagic area (Pa), central pelagic area (Pb) and north pelagic area (Pc). Thus, joining to the south near-shore area (Ns) and north near-shore area (Nn), we have in total five areas (Figure 15).

According to the B_c matrix of OR102-6 and OR170-7 as well as the triangular map (Figure 14), the sites of core OR102-6 and core OR170-7 are both located in the central pelagic area (Figure 15). According to the viewpoint of the velocity and position of the Kuroshio current, the data of the cores have different meanings due to the underlying five

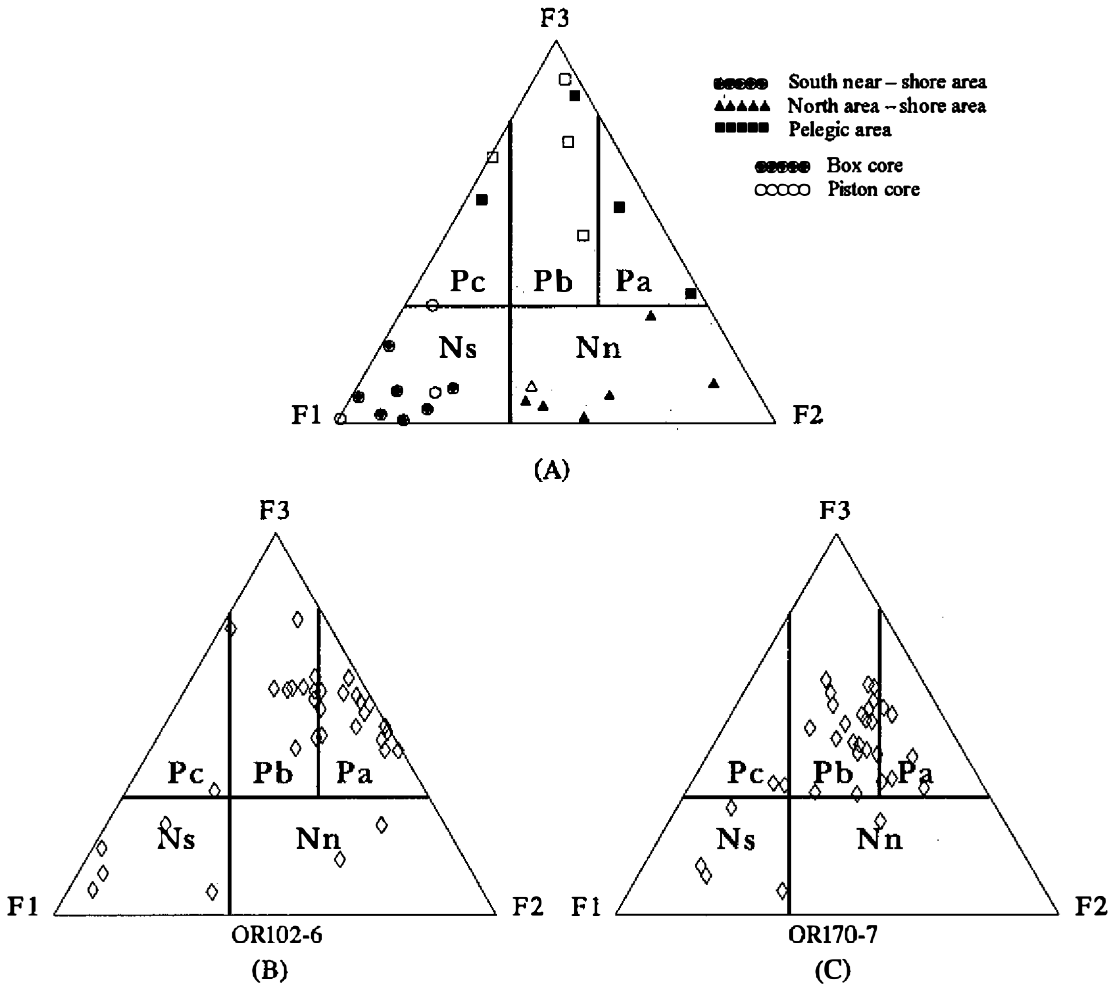

Fig. 14. Factor analysis results of planktonic foraminifera assemblages of core top sediments Three factors (F1, F2, F3) were chosen for this study. (A) and piston-core of OR102-6 (B) and OR170-7 (C) plotted against three factors; Pa: south pelagic area; Pb: central pelagic area; Pc: north pelagic area; Ns: south near-shore area; Nn: north near-shore area.

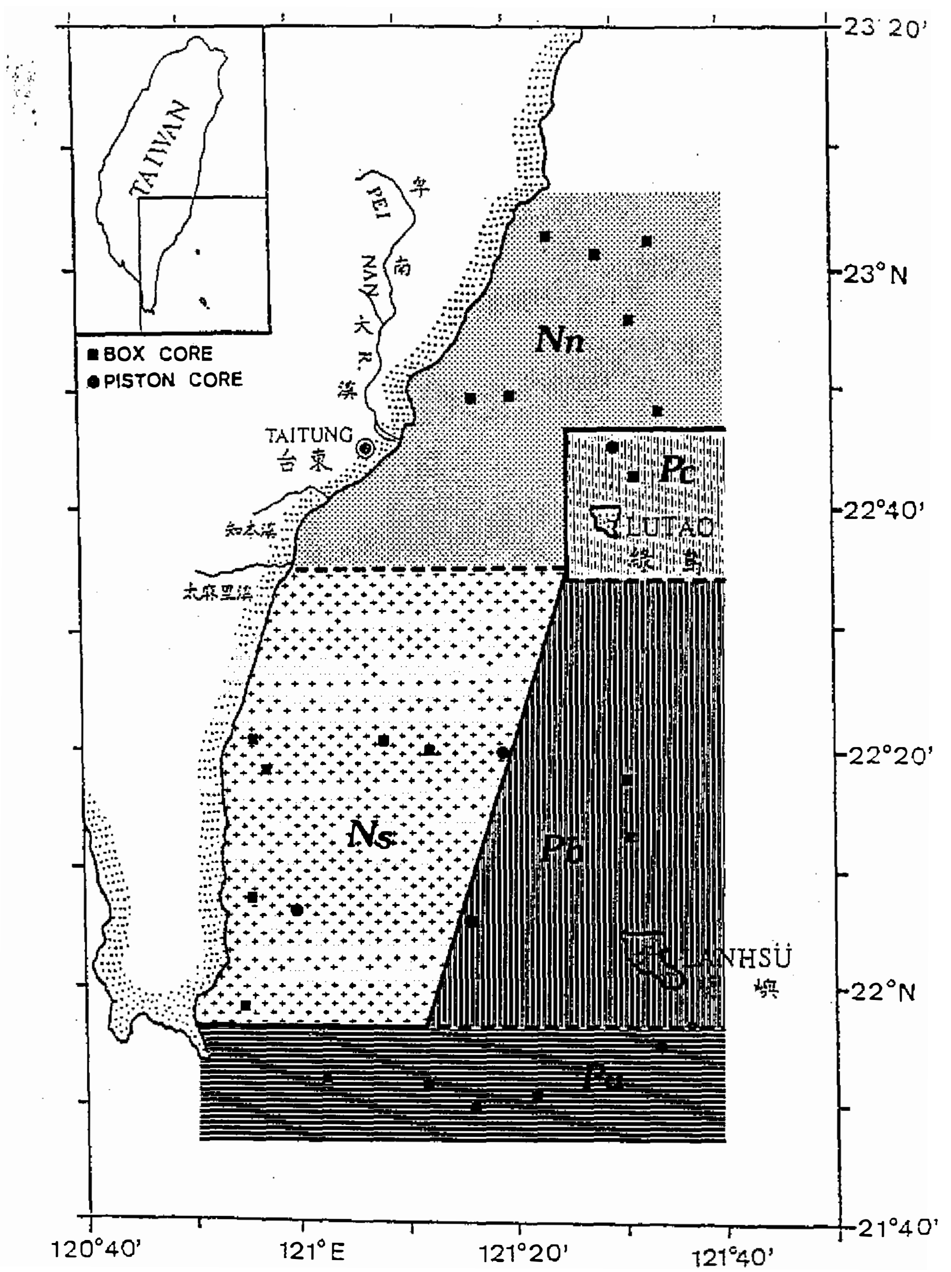

Fig. 15. The areal distribution of Pa, Pb, Pc, Ns and Nn; Pa: south pelagic area; Pb: central pelagic area; Pc: north pelagic area; Ns: south near-shore area; Nn: north near-shore area.

distinguishing areas. (1) In the central pelagic area (P_b): the velocity and position of the Kuroshio current during deposition were the same as those at present. Consequently, the biological characteristics of sediments accord with present conditions. (2) In the south pelagic area (P_a): the velocity of the Kuroshio current during deposition is more rapid than at present. Accordingly, the biological populations which originally should have been located in the south, because of the increase of velocity, are located in the present central pelagic area (P_b). The position of the Kuroshio current is unchanged. (3) In the north pelagic area (P_c): the velocity of the Kuroshio current during deposition was less rapid than present. As a result, the biological populations which originally should have been located in the north, because of the decrease of velocity, are located in the present central pelagic area (P_b). The position of the Kuroshio current is unchanged. (4) In the south near-shore area (N_s): the position of the Kuroshio current during deposition was east of its present position. Hence, the biological populations which originally should have been located to the west, because of the eastward displacement of position, are located in the present central pelagic area (P_b). The velocity of the Kuroshio current is unchanged. (5) In the north near-shore area (N_n): the position of the Kuroshio current during deposition was east of the present position. Consequently, the biological populations which originally should have been located to the northwest, because of the eastward displacement of position and the decrease of velocity, are located in the present central pelagic area (P_b).

9. SYNTHESIS OF PALEOCEANOGRAPHY DURING THE LATEST PLEISTOCENE

The latest Pleistocene paleoceanographic attitudes offshore southeast Taiwan recorded from the cores OR102-6 and OR170-7 can be classified into the underlying stages (Figure 16):

112,000 – 98,000 yr. B.P. (oxygen isotopic 5d – 5c stage)

The mean sea surface temperature in summer was about 29.0±0.2° C, and about 23.3±0.7° C in winter; the sea level ascended from –69 meters at about 112,000 yr. B.P. to –10 meters at about 98,000 yr. B.P.; at about 106,000 yr. B.P., the velocity and position of the Kuroshio were similar to the present conditions whereas after about 106,000 yr. B.P., the velocity of the Kuroshio had tended to gradually decrease according to the ascent of sea level.

98,000 – 76,000 yr. B.P. (oxygen isotopic 5c – 5/4 stage)

The mean sea surface temperature was about 29.0±0.2° C in summer, and about 23.5±0.6° C in winter; the sea level gradually descended after about 98,000 yr. B.P. and retained a stable state between –26 to –57 meters; the velocity and position of the Kuroshio current were similar to the present condition.

76,000 – 71,000 yr. B.P. (oxygen isotopic 5/4 – 4 stage)

The mean sea surface temperature was about 29.1±0.1° C in summer, whereas in winter it was about 23.3±0.4° C; after about 76,000 yr. B.P., the sea level descended from –40 to –72 meters (about 71,000 yr. B.P.); the velocity of the Kuroshio tended to increase acceleratively according to the ascent of sea level.

71,000 – 36,000 yr. B.P. (oxygen isotopic 4 – 3 stage)

The mean sea surface temperature was about 29.5±0.4° C in summer, and about 25.4±1.6° C in winter; the sea level was varying between –89 and –41 meters; the velocity

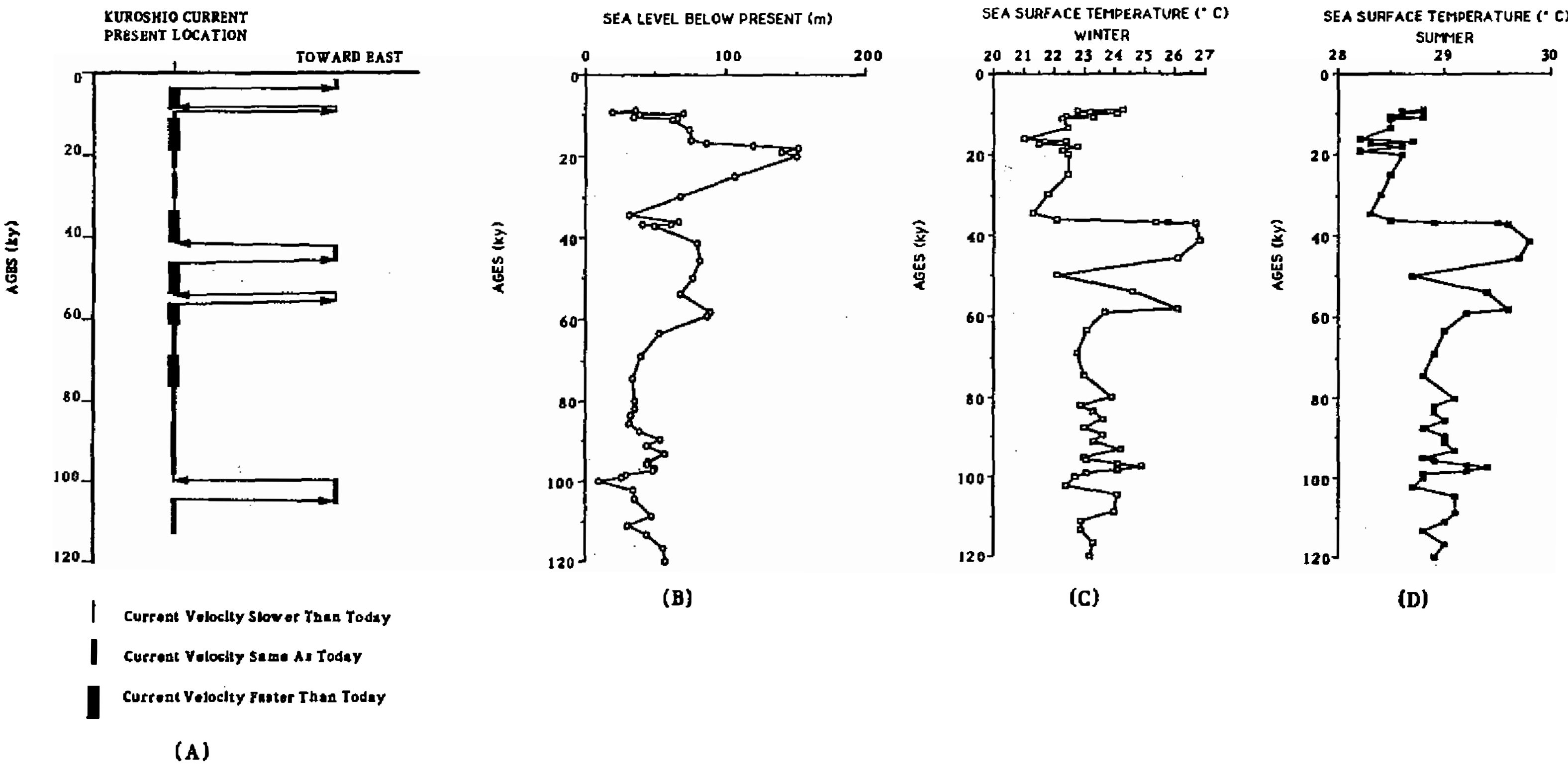

Fig. 16. During the past 120,000 years, the paleocurrent, sea level fluctuation, sea surface summer and winter temperatures offshore southeast Taiwan.

of the Kuroshio was greater than the present velocity; after about 71,000 yr. B.P., earthquakes occurred frequently in this area, and the bottom current was more rapid than at present.

36,000 – 19,000 yr. B.P. (oxygen isotopic 3 – 2 stage)

The mean sea surface temperature was about 28.5±0.1° *C* in summer, compared with about 22.2±0.7° *C* in winter; the sea level descended rapidly from –31 meters to –106 meters; the velocity of the Kuroshio changed from being more rapid than at present to being less rapid.

19,000 – 14,500 yr. B.P. (oxygen isotopic 2 stage)

The mean sea surface temperature was about 28.5±0.2° *C* in summer, and about 22.4±0.7° *C* in winter; the sea level descended from –106 meters about 19,000 yr. B.P. to –152 meters about 17,500 yr. B.P. It then swiftly ascended to –62 meters about 15,000 yr. B.P.; the velocity of the Kuroshio changed from being less rapid than at present to being more rapid.

14,500 – 9,000 yr. B.P. (oxygen isotopic 2 – 1 stage)

The mean sea surface temperature was about 28.6±0.1° *C* in summer, and about 23.3±0.8° *C* in winter; the sea level gradually ascended to –35 meters about 9,000 years ago; the velocity of the Kuroshio decreased to being less rapid than at present.

10. CONCLUSIONS

No matter whether it was summer or winter season, during the last glacial period the paleotemperature of the sea surface offshore southeast Taiwan decreased about 0.5 – 1° *C* lower than that of the last interglaciation and that at present.

During the last interglacial period, the highest sea level stand was still about 10 *meters* below the present sea level stand. However, the sea level stand descended about 150 *meters* in the last maximum glaciation.

When the sea level stand was descending, the velocity and position of the Kuroshio were similar to those at present. The current might have ascended during the period in which the sea level stand was ascending. When the ascending rate of sea level stand was slowed, the velocity of the Kuroshio not only decreased to less than that at present but also its main flow axis was probably shifted slightly toward the east.

Acknowledgements We thank Captain Wang and the crew members of *R/V Ocean Researcher I* for their help during the collection of cores, C-14 Dating Laboratory of the Department of Geology, National Taiwan University for their kind help in sample dating, Drs. Tunyow Huang, Jui-Tun Chou, K.-K. Liu, and Ju-Chin Chen for useful discussion and review of the manuscript. This research was financially supported by the National Science Council of the Republic of China, under grants NSC78-0209M-002a-13 and NSC79-0209-002a-04.

REFERENCES

Chen, Min-Pen, Y.-T. Shieh and C.-S. Shyr, 1988: Seafloor physiography and surface sediments off southeastern Taiwan. *Acta Geol. Taiwanica*, **26**, 333-353.

Chu, T.-Y., 1974: The fluctuations of the Kuroshio current in the eastern sea area of Taiwan. *Acta Oceanogr. Taiwanica*, **4**, 1-12.

CLIMAP, 1976: The surface of the ice age earth. *Science*, **191**, 1131-1137.

Craig, H., 1965: The measurement of oxygen isotope paleotemperatures. *Consiglio Nazional delle Ricerche*, **3**, 3-24.

Chinese National Committee on Oceanic Research (CNCOR), 1966: *Oceanographic Data Report of CSK No. 1, Academic Sinica*, R.O.C., 123 pp.

Chinese National Committee on Oceanic Research (CNCOR), 1968: *Oceanographic Data Report of CSK No. 2, Academic Sinica*, R.O.C., 126 pp.

Chinese National Committee on Oceanic Research (CNCOR), 1969: *Oceanographic Data Report of CSK No. 3, Academic Sinica*, R.O.C., 119 pp.

Chinese National Committee on Oceanic Research (CNCOR), 1970: *Oceanographic Data Report of CSK No. 4, Academic Sinica*, R.O.C., 111 pp.

Emery, K.O. and R.E. Stevenson (1972) Taiwan-a ship at sea. *Acta Oceanogr. Taiwanica*, **2**, 1-10.

Epstein, S. C. 1953: Revised carbonate-water isotopic temperature scale. *Geol. Soc. Am. Bull.*, **64**, 1315-1326.

Erez, J. and B. Luz, 1983: Experimental paleotemperature equation for planktonic foraminifera. *Geochim. Cosmochim. Acta*, **47**, 1025-1031.

Fairbanks, R.G. and R.K. Matthews, 1978: The marine oxygen isotope record in Pleistocene coral, Barbados, West Indies. *Quat. Res.*, **10**, 181-196.

Fan, K.L., 1979: On upwelling along the southeastern coast of Taiwan. *Acta Oceanogr. Taiwanica*, **10**, 151-159.

Fan, K.L., 1985: *STD measurements in the seas around Taiwan during 1977-1983*, Institute of Oceanography, National Taiwan University, Special Publication No. 44., 337 pp.

Fan, K.L., 1987: *STD measurements in the seas around Taiwan during 1983-1985*, Institute of Oceanography, National Taiwan University, Special Publication No. 51., 183 pp.

Hung, T.C., 1975: Chemical investigation of upwelling along eastern coast of Taiwan. *Acta Oceanogr. Taiwanica*, **5**, 77-94.

Imbrie, J. and N.G. Kipp, 1971: A new micropaleontological method for quantitative micropaleontology: application to a late Pleistocene Caribbean core. *In* : K. Turekian (ed.), *The Late Cenozoic Glacial Ages*, Yale University Press, New Haven, Conn., 71-181.

Imbrie, J., J. Van Donk and N.G. Kipp, 1973: Paleoclimatic investigation of a late Pleistocene Caribbean deep sea core: comparison of isotopic and fauna method. *Quat. Res.*, **3**, 10-38.

Liu, C.-T., S.-G. Liau, S.-C. Pai and K.-K. Liu, 1986: Water masses in the western Philippine Sea-physical aspects. *Acta Oceanogr. Taiwanica*, **17**, 1-17.

O'Neil, J.R., R.N. Clayton and T.K. Mayeda, 1969: Oxygen isotope fractionation in divalent metal carbonates. *J. Chem. Phys.*, **51**, 5547-5558.

Thompson, P.R., 1981: Planktonic foraminifera in the western North Pacific during the past 150,000 years: comparison of modern and fossil assemblages. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **35**, 241-279.

Tominaga, M., 1972: Brief analyses of the upwelling phenomena near the eastern coast of Taiwan. *Acta Oceanogr. Taiwanica*, **2**, 25-38.

台灣東南外海黑潮之晚更新世古海洋

陳民本　黃兆愷　羅立
台灣大學海洋研究所

汪中和
中央研究院地球科學研究所

摘　要

黑潮以1.5至2節的流速從台灣東南外海流往東北外海。其夏季的海表面水溫介於28°C與29°C之間，而冬季則降至25°C至26°C之間。黑潮洋流的表層鹽度介於34.2‰與34.7‰之間。本文對於台灣東南外海黑潮古海洋之研究是以現今的海洋狀況以及海床上所採的19個箱型岩心和7支活塞岩心的岩心頂部沈積物中所含的浮游性有孔蟲群集作爲研究的基礎。

沈積的有孔蟲群集可以分成近岸及遠洋兩群。除了*Globigerinoides ruber*, *G. sacculifer*, *Pulliniatinav obliquiloculata* 和 *Neogloboquadrina dutertrei* 四個含量較多的種之外，近岸群的重要種有 *Globigerinita glutinata* 和 *Globigerinoides bulloides*；遠洋群的重要種有 *Globorotalia tumida* 和 *G. menardii*。

在上次冰河期，兩支活塞岩心中所含的浮游性有孔蟲群集，再由轉換函數所計算出的夏季表層水溫仍介於28°C和29°C之間，上次間冰期的水溫甚至還高過29°C。但在冬季，上次冰河期的表層水溫介於25°C和22°C；不過間冰期冬季的平均表層水溫僅比冰河期高大約1°C。

從氧同位素資料的計算，在上次冰河期間18,500年至17,500年前的海水面最低時期，當時海水面比現今低了150公尺。在98,000年前，上次間冰期的海水面最高期的海水面仍比現今低10尺。海水面突然上升的時期，黑潮流速會加快，而當海水面持續上升但黑潮流速減慢時，黑潮主流有向東偏移的現象。