

Variations in late Quaternary upper ocean structure of Okina wa Trough :A nannofossil approach *

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Abstract The relative abundance of *Florisphaera profunda* , a calcareous nannofossil species in lower euphotic zone , affords an opportunity to study variations in upper ocean structure such as thickness of mixed layer. As revealed by the nannofossil analysis in sediments since 20 ka B. P. from three Okinawa Trough cores , the percentage of *F. profunda* increased significantly from glacial to Holocene , with a declining event ca 4 ka B. P. in its southern part . Its downcore trend is similar to that of *Pulleniatina obliquiloculata* , a tropical planktonic foraminiferal species which lives in subsurface water below thermocline in the modern ocean. Their similar variations imply an eastward shift of the Kuroshio Current , a reduction in thickness of the mixed layer , a shallowing of thermocline and a possible increase of turbidity in the upper ocean during the glaciation. The eastward shift of the Kuroshio might be repeated again about 4 ka B. P.

Keywords : upper ocean , Okina wa Trough , calcareous nannofossil , nutricline , thermocline.

The upper layer is the most active part of the ocean in environmental changes. The surface-layer water of the ocean is homogeneous in depth due to the mixing processes caused by air-sea interactions , called the mixed layer. Below the mixed layer , vertical density gradient of water increases drastically , which is the pycnocline caused by sharp changes of temperature (thermocline) or salinity (halocline) . Waters below the pycnocline are not in contact and exchange directly with the atmosphere outside the high latitudes , displaying a greater stability in layering than the overlying water. There is a close relationship between the atmosphere and the vertical structure of the upper ocean. Variations in winds may cause changes in the mixed layer thickness and pycnocline depth , and surplus precipitation results in dilution and hence stratification of the surface water. The great progress in the upper ocean research in the mid-1980s has revealed the " Turbulent Boundary Layer (TBL) " as a physical process of the air-sea exchange , which not only controls the passage of momentum , energy and mass from the atmosphere into the ocean , but also influences the ocean productivity significantly by means of nutrients distribution^[1,2].

The progress of modern oceanography has stimulated the study on the history of upper ocean vertical structure in paleoceanography. Since thickness of the mixed layer and depth of the pycnocline are indicative of wind stress and ocean circulation , and the plankton assemblage is closely related to the depth of thermocline , the downcore variations in fossil plankton can be used to study the changes in upper ocean structure which in turn can provide information of paleocirculation in atmosphere and ocean. It has been recognized that shallow-dwelling species of planktonic foraminifers mainly lives in the upper part of the mixed layer , whereas deep-dwelling species inhabits the chlorophyll-maximum zone related to thermocline. Therefore , the variations in abundance ratio between the two groups of species can be used to indicate the fluctuations of paleo-

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thermocline^[3,4]. Another plankton used to explore the upper ocean structure is calcareous nannofossils. As primary producer, coccolithophorids are directly related and more sensitive than zooplankton to variations in nutricline, euphotic zone and other features in the upper ocean structure.

The open ocean structure in the Okinawa Trough is sensitive to the Kuroshio Current and Asian monsoon which experienced remarkable variation in the glacial cycles. The present paper aims to reveal the fluctuations of the thermocline depth and other upper-ocean conditions in the Okinawa Trough since 20 ka on the basis of the analysis of calcareous nannofossils with reference to planktonic foraminifers.

1 Calcareous nannofossils in lower euphotic zone

Unlike planktonic foraminifers, coccolithophorids that produce calcareous nannofossils are restricted to euphotic zone for photosynthesis. From ocean surface to the base of the euphotic zone, over 100 m deep in clear waters, light intensity decreases logarithmically to about 1 % of the surface intensity. Below this depth, light energy is too low for photosynthetic production to occur. Coccolithophorids usually live in the upper euphotic zone where light energy is high. Only 3 species can live in the lower euphotic zone according to the references collected so far. They are:

Florisphaera profunda Okada & Honjo (fig. 1)

Gladiolithus flabellatus (Halldal & Markali) Jordan & Chamberlain

Algirosphaera robusta (Lohmann) Norris

Okada and Honjo (1973) found these three species originally in surface water samples collected from the Pacific^[5]. Okada and Matsuoka (1996) also found them in sediments raised from the Indian Ocean^[6]. Among the three species, only *F. profunda* has been found wide-distributed. Because of the exceptional shape, the species had been ignored in nannofossil analysis until Okada (1980) found it in sediments^[7]. Therefore, its distribution is not available from the early literature.

Nevertheless, *F. profunda* is of particular value in paleoceanography as a rare and wide-distributed species living in lower euphotic zone. The investigations on horizontal and vertical distribution of coccolithophorids in the Pacific have shown that *F. profunda* is a low-latitude species, absent north of 40 °N and distributed in the lower euphotic zone over a 10—28 water temperature

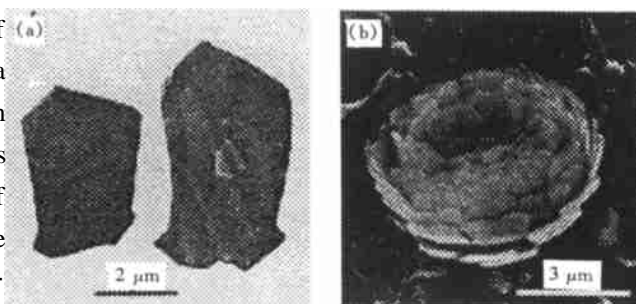


Fig. 1. *Florisphaera profunda* Okada & Honjo, a lower-euphotic nannofossil species. (a) Single coccoliths; (b) a coccosphere ((b) from Okada^[8]).

range. It lives usually below 100 m with its maximum at approximately 150 m^[5]. It was found that the relative abundance of the species in surface sediments increases with water depth and away from the shore, reaching some 50 % at 2 000 m of water depth. Hence, it was used as a deep-water indicator^[8,9]. However, our survey in the central and northern parts of the South China Sea has shown that its relative abundance in surface sediments increases with water depth until 2 000 m but decreases below^[10]. It was not discovered in water depth of 1 800 m in the Gulf of Elat (Aqaba), Red Sea^[11]. It is thus obvious that its relative abundance was not controlled

simply by water depth but dictated by ecologically complicated factors in the upper ocean.

Being a phytoplankton species, the distribution of *F. profunda* in sea water depends mainly on nutrients and light intensity apart from temperature. As shown by the nannofossil analysis in a north-south transect of surface sediment samples in the equatorial Atlantic, the depth of nutricline center changes from about 50 m to 150 m with the deepening of the thermocline. Meanwhile, the relative abundance of *F. profunda* increases from 30% and more to 50%–70%, suggesting that its percentage distribution was controlled by the depth of the thermocline^[12]. On the other hand, as it was revealed from a comparison between the areal distribution of its abundance in surface sediments and that of the surface water transparency at 204 sites south off Japan, northwest Pacific, the percentage of *F. profunda* increases with improved sea water transparency^[13].

Thus it can be seen that the relative abundance of *F. profunda* is controlled by the vertical structure in the upper ocean (fig. 2). If other conditions such as water temperature remain unchanged, a thick mixed layer, a deep thermocline and nutricline in the lower euphotic zone are

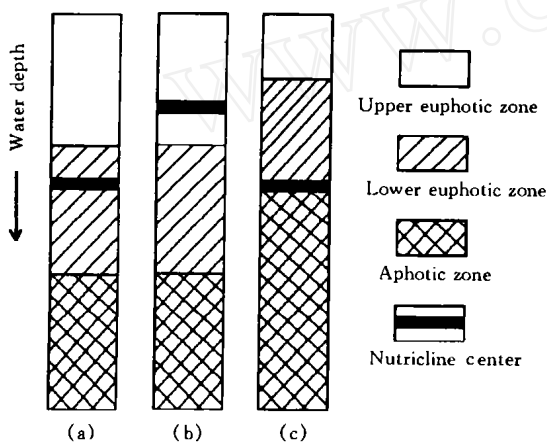


Fig. 2. Diagram showing different upper ocean structures leading to variations in abundance of *F. profunda* (after Molfino & McIntyre^[12]). (a) Deeper thermocline with nutricline center situated in lower euphotic zone, favorable to *F. profunda*; (b) shallower thermocline with nutricline center situated in upper euphotic zone, unfavorable to *F. profunda*; (c) thin euphotic zone, unfavorable to *F. profunda*.

favourable to *F. profunda*, and hence its production is enhanced relative to other coccolithophorids (fig. 2 (a)). A thin mixed layer, a shallow thermocline and nutricline in the upper euphotic zone are unfavourable to the production of *F. profunda*, and its abundance declines (fig. 2 (b))^[12]. In case the water turbidity in the upper ocean increases, in result of increased supply of terrigenous clasts or plankton production, the relative abundance of *F. profunda* decreases (fig. 2 (c)). The characteristic feature of *F. profunda* has been successfully applied to late Quaternary studies in the Atlantic^[12], Pacific^[13], Indian Ocean^[6] and the Mediterranean Sea^[14], and used to monitor variations of the upper ocean structure in glacial cycle, providing evidence for fluctuations of the nutricline depth and for therefrom the evolution of atmospheric

and ocean circulation.

2 Late Quaternary nannofossils in the Okina wa Trough

The Okinawa Trough lies in the East Asian monsoon area where the Kuroshio passes through. Either the monsoon variations or the Kuroshio shift in the glacial cycles can result in fluctuations of the upper ocean structure which can be deciphered from the nannofossil records.

Not much has been published on quantitative analysis of nannofossil sequences from the Okinawa Trough. The only core studied in this way is RN80-PC3 from the northern Okinawa Trough, 830 m in water depth^[15]. In the present study, we analysed two cores, Core 255 (water depth 1 574 m) and Core 170 (1 470 m) from the southern Okinawa Trough (table 1). The

sampling intervals for the three cores are 10, 20 and 12 cm, respectively. From each sample, 0.1 g of dry sediment was put into 6 mL of distilled water and a light microscope slide was prepared by spreading a drop of the slurry and a drop of polyvinyl alcohol on a cover glass (22 × 22 mm²). All samples were analysed under polarised light microscope (Leitz ORTHOLUX 2 POL BK). The number of calcareous nannofossils per 10 randomly selected fields of view at ×630 magnification was used as the abundance of calcareous nannofossils.

Table 1 Three cores from the Okinawa Trough used in the study

Core	Location	Water depth/ m	Core length/ cm	Number of samples analysed	Reference
RN80-PC3	29°04.1' N, 127°22.6' E	830	445	45	Li & Okada, 1985
170	26°38' N, 125°48' E	1 470	360	30	this paper
255	25°12' N, 123°06' E	1 574	655	34	this paper

Calcareous nannofossils were found in all samples from the cores although their abundances are different. For instance, there are 14–272 specimens every 10 fields in Core 255, with low abundances in the upper part above 200 cm and high in the lower part below 200 cm. The abundance of calcareous nannofossils in Core 170 varies from 86 to 590, again being lower in the upper part of the core and higher in the lower, with the boundary at about 120 cm.

Figure 3 shows the downcore variations of nannofossil abundance and the relative abundance of *F. profunda* in cores. As to the geochronology, the boundary between the glaciation and Holocene is set at the depth of 440 cm (¹⁸O stage 1/2) in Core 255 based on the ¹⁸O curve of benthic foraminifer and the AMS ¹⁴C dating^[16]. Cores 170 and 255 are similar in their downcore variations in relative abundance for some dominant species of planktonic foraminifers and in their paleo-temperature curves based on transfer function. Accordingly, the ¹⁸O stage boundary between 1 and 2 can be set at the depth of 238 cm for Core 170. The corresponding boundary is at about 180 cm for Core RN80-PC3 (figure 3).

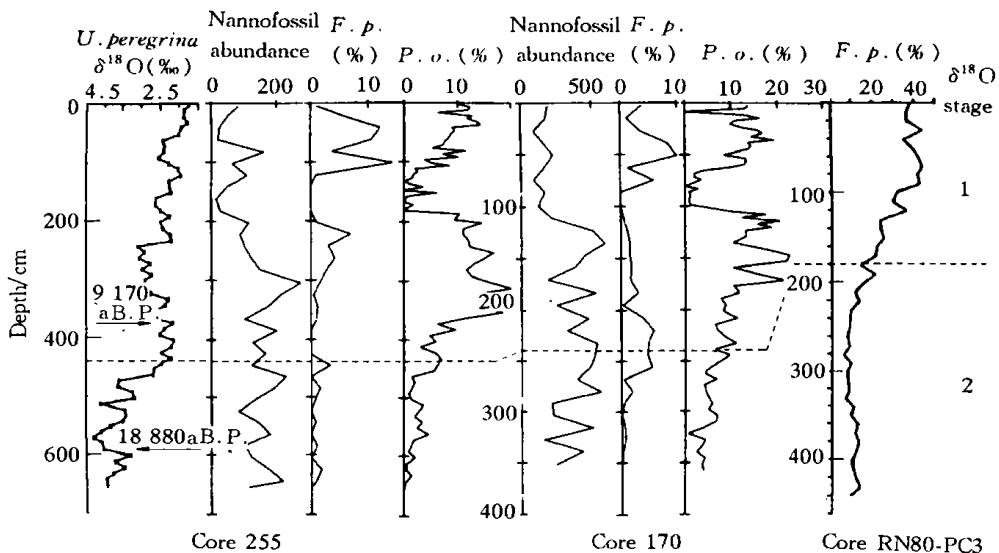


Fig. 3. Downcore variations of nannofossil abundance, *F. profunda* (*F. p.*) % and *P. obliquiloculata* (*P. o.*) % (planktonic foraminifer^[16]) in Okinawa Trough (data of RN80-PC3 from Li & Okada^[15]).

The species composition of calcareous nannofossils in these cores is similar, and dominated by *Gephyrocapsa oceanica* and *Emiliana huxleyi*, *Helicosphaera carteri*, *Calcidiscus leptoporus* and *Florisphaera profunda* are common, accompanied by such species as *Rhabdosphaera claviger*, *Pontosphaera* spp., *Syracosphaera* spp., *Ceratolithus* spp., *Braarudosphaera bigelowii*, *Umbellosphaera irregularis* and *Umbilicosphaera sibogae*. Prominent fluctuations in abundance is shown by *F. profunda*, which is the focus of the present study.

3 Upper ocean structure variation in the Okinawa Trough

The upper ocean structure in the Okinawa Trough has experienced profound changes in the glacial cycle. The relative abundance of *F. profunda* varied significantly in all the cores, from 0% to >10% in the southern part of the Trough, and from <10% to >40% in the northern part. It is the lowest in the glaciation and increased in the Holocene, but declined again about 4 ka ago in its southern part, followed by a steep rise thereafter (fig. 3). The general trend with the relative abundance of *F. profunda* lower in glacial and higher in Holocene is not limited to the Okinawa Trough, but also found in the equatorial Atlantic^[12] and in the Ryukyu Trench^[13]. At least two factors may be responsible for the decline of *F. profunda* % during the glacial: the shallower nutricline (fig. 2(b)) or the lower transparency (fig. 2(c)). The former explains the percentage fluctuations since 200 ka in the equatorial Atlantic, inferring that the variations in the tropical easterlies result from the precessional component of orbital insolation^[12]. The latter can explain what happened in Ryukyu Trench. The glacial increase of terrigenous material led to a higher turbidity and lower transparency, giving rise to its decline^[13]. Then to which of the two factors is the percentage variations of *F. profunda* in the Okinawa Trough ascribed? The depth of thermocline in the Okinawa Trough changes seasonally even contemporarily^[17]. Meanwhile, more significant fluctuations should be expected in the glacial cycles. Because the Okinawa Trough is closer to continent than the Ryukyu Trench, it is highly probable that more terrigenous material or nutrients caused a higher turbidity in the upper ocean. Therefore, an independent proxy other than *F. profunda* % is needed to make choice from the alternatives.

Another useful indicator for the vertical structure in the upper ocean is planktonic foraminifer. The reproduction depth is essential to the deep-living species of the planktonic foraminifers. Only when the lower boundary depth of mixed layer exceeds the depth at which reproduction occurs, can the offspring of the deep-living species be advected to surface water and can the species complete its life cycle^[4]. *Pulleniatina obliquiloculata* Parker & Jones is one of such deep-living species, and its highest abundance occurs at the chlorophyll maximum closely related to thermocline^[3], and its relative abundance increase indicates a deepening of the thermocline lower boundary. From the cores in the Okinawa Trough, foraminifers were analysed in two southern ones. The downcore variations of *P. obliquiloculata*^[16] in the cores are the same as those of *F. profunda*, being lower during the glaciation and higher during the Holocene, with a similar decrease at 4 ka B. P. (fig. 3). Thus, the thin mixed layer with a shallow thermocline in glacial and thick mixed layer with a deep thermocline during Holocene have been evidenced by both zooplankton and phytoplankton records, implying that the thermocline fluctuation (fig. 2(b)) should be a major aspect of the upper ocean structure variations in the Okinawa Trough during glacial cycles. On the other hand, *P. obliquiloculata* is a tropical species indicative of the

Kuroshio, and its variation in relative abundance in the Okinawa Trough indicates the shift of the Kuroshio. During the glacial time, with the emergence of the continental shelf and the eastward shift of the Kuroshio¹⁾, the area of Cores 255 and 170 was covered by coastal waters, the thermocline was shallow and the surface water temperature was low, both *F. profunda* and *P. obliquiloculata* were reduced in abundance. In the Holocene, the coastline retreated, the Kuroshio shifted to the continental shelf break, the Okinawa Trough became predominated by the Kuroshio waters, and, as a consequence, the percentages of both *F. profunda* and *P. obliquiloculata* have increased. Their decrease about 4 ka B. P. should result from the eastward shift of the Kuroshio. As compared with the coastal waters, the Kuroshio is characterized not only by high temperature and deep thermocline, but also by less suspended material and low productivity. With the glacial shift of the Kuroshio to the east, the Okinawa Trough was predominated by coastal waters, resulting in higher turbidity in the upper ocean. Therefore, the decline of water transparency (fig. 2(c)) cannot be excluded from the factors leading to the glacial decrease of the lower-photic nannofossils in abundance.

4 Conclusions

1) The relative abundance of lower-photic calcareous nannofossils represented by *F. profunda* is indicative of the variations in vertical structure of the upper ocean, including the depth fluctuations of the thermocline and the mixed-layer lower boundary. It may also imply the variations of water transparency in the upper ocean.

2) The sediment records since 20 ka B. P. in the Okinawa Trough show that the percentage of *F. profunda* increased remarkably from glacial to postglacial, with a decline again about 4 ka B. P. A similar trend of downcore variations has been shown by a deep-living planktonic foraminifer *P. obliquiloculata*.

3) The variations are caused by the shift of the Kuroshio Current in the glacial cycle, as the eastward shift of the Kuroshio during glaciation resulted in a thinner mixed layer and shallower thermocline.

In view of the complexity of the upper ocean structure, the present study is the first attempt at revealing the variations of upper layer in the Okinawa Trough. Much more data are needed for a more precise conclusion and deeper understanding.

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References

- 1) Weller, R. A., Mixing in the upper ocean, *Nature*, 1987, 328(2):13.
- 2) Müller, P., Mixed layer dynamics: progress and new directions, *EOS, Transaction, AGU*, 1988, 69:2, 10.
- 3) Ravelo, A. C., Fairbanks, R. G., Philander, G., Reconstructing tropical Atlantic hydrography using planktonic foraminifera and an ocean model, *Paleoceanography*, 1990, 5:409.
- 4) Lohmann, G. P., Increasing seasonal upwelling in the subtropical South Atlantic over the past 700,000 yrs: Evidence from deep-living planktonic foraminifera, *Marine Micropaleontology*, 1992, 19:1.
- 5) Okada, H., Honjo, S., The distribution of oceanic coccolithophorids in the Pacific, *Deep-Sea Res.*, 1973, 20:355.

1) Wang, P. et al., *WESTPAC Paleogeographic Maps (LGM)*, UNESCO/IOC Publication, Shanghai, 1995.

- 6 Okada, H., Matsuoka, M., Lower-photic nanoflora as an indicator of the late Quaternary monsoonal palaeo-record in the tropical Indian Ocean, *Microfossils and Oceanic Environments* (eds. Mokuilevsky, A., Whatley, R. C.), University of Wales: Aberystwyth Press, 1996, 231—245.
- 7 Okada, H., Calcareous nanofossils from Deep Sea Drilling Project Sites 442 through 446, Philippine Sea, *Init. Rep. DS-DP.*, (eds. de Vries Klein, G., Kobayashi, K.), Washington D. C., 1980, 58:549.
- 8 Okada, H., Modern nanofossil assemblages in sediments of coastal and marginal seas along the western Pacific Ocean, *Utrecht Micropaleontological Bulletin*, 1983, 30:171.
- 9 Okada, H., Biogeographic control on modern nanofossil assemblages in surface sediments of Atsumi Bay, Ise Bay and Kuramano-nada, off coast of Central Japan, *Mem. 1st. Geol. Mineral, Univ. Padova*, Padova, 1992, 43:431.
- 10 Cheng Xinrong, Calcareous nanofossils in surface sediments of the central and northern parts of the South China Sea, *Journal of Micropalaeontology*, 1992, 11(2):167.
- 11 Winter, Z., Reiss, A., Luz, B., Distribution of living coccolithophore assemblages in the Gulf of Elat (Aqaba), *Marine Micropaleontology*, 1979, 4:197.
- 12 Molfino, B., McIntyre, A., Precessional forcing of nutricline dynamics in the Equatorial Atlantic, *Science*, 1990, 249:766.
- 13 Ahagon, N., Tanaka, Y., Ujiie, H., *Florisphaera profunda*, a possible nanoplankton indicator of late Quaternary changes in sea-water turbidity at the northwestern margin of the Pacific, *Marine Micropaleontology*, 1993, 22:255.
- 14 Castradori, D., Calcareous nanofossils and the origin of eastern Mediterranean sapropels, *Paleoceanography*, 1993, 8(4):459.
- 15 Li Wenjin, Okada, H., Relations between floral composition of calcareous nanofossils and paleoceanographic environment observed in three piston cores obtained from the equatorial Pacific, East China Sea and Japan Sea, *Bull. of Yamagata Univ., Nat. Sci.* (in Japanese with English abstract), 1985, 11(2):177.
- 16 Jian, Z., Li, B., Pflaumann, U. *et al.*, Late Holocene cooling event in the western Pacific, *Science in China, Ser. D*, 1996, 39(5):543.
- 17 Chern, C. S., Wang, J., Influence of seasonal thermocline on the intrusion of Kuroshio across the continental shelf northeast of Taiwan, *Journal of Oceanography*, 1994, 50:691.