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Preservation of Particulate Organic Matter in the Cold Basin Water in Funka Bay after the Vernal Phytoplankton Bloom

Kazuo KIDO* and Kiyotaka OHTANI*

Abstract

The behaviour of particulate organic matter was investigated through chemical observation of particulate organic phosphorus and microscopic observation of the particulate organic matter on the bottom of the Funka Bay region.

Much of the particulate organic matter produced in the vernal phytoplankton bloom sinks fast to the bottom and is preserved in the cold basin water, which contains much of undefiled phytoplankton cells and resting spores. The deposition of undefiled phytoplankton is a new food channel which directly connects the primary production and the benthic community. The resting spores contained in the POM might become an inoculum for the next vernal phytoplankton bloom.

Introduction

Most of particulate organic matter (POM) in the oceans, whether of animal or plant origin, is ultimately derived from phytoplankton.1)

Heinrich2) showed that the seasonal cycle of plankton biomass varied with location, and that the relation of phyto- and zooplankton did so also. According to his results, in the neritic zones of the arctic and subarctic regions, a high peak of phytoplankton biomass was found in summer once in a year. Depending on the latitudes (for example, Norwegian coast), the high peak was revealed in spring and a small peak was revealed in autumn. The peak of zooplankton biomass followed them with some delay period. Cushing3) qualified such a plankton community as an unbalanced one, and showed that the phytoplankton at this period was not fully utilized by the zooplankton. Steeman Nielsen4) also stated in his review that the phytoplankton produced in a explosive bloom was not devoured.

Therefore it is expected that the material flow corresponding to the seasonal variation of plankton community may exist, and that the phytoplankton saved from grazing sinks to the bottom and constitutes the nutritious source for the benthic community in addition to fecal pellet and other organic detritus in the neritic zones of the arctic and subarctic regions where the plankton community is unbalanced.

The oceanographic structure in Funka Bay varies similarly to those in the neritic zones of the northern North Pacific.5),6) The phytoplankton bloom occurs explosively in spring when the Oyashio Water (O&Oi) enters the bay.7),8),9) Soon after the bloom, the concentration of nutrients in the basin water10) begins to increase rapidly and dissolved oxygen conversely begins to decrease.10),11)

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Yanada et al.[11] attributed these chemical changes to the decomposition of organic matter sedimented on the bottom. The authors[10] suggested that the organic matter accumulated on the sediments contributed significantly to the material budgets and ecosystem in the bay.

In the Funka Bay region, sticky organic materials adhere to the submersible gillnets and other fishing gears which are set on the bottom after the vernal phytoplankton bloom. The fishermen in this region call the sticky material "Nuta" and are troubled with it. This phenomenon verifies that the POM produced in the vernal bloom is accumulated in the deep waters.

In this paper, the authors discuss the behaviour of POM through the chemical observation of particulate organic phosphorus and the microscopic observation of the Nuta and other organic materials, and propose a food channel which directly connects the primary production and the benthic community.

Observation and Methods

The oceanographic observations were conducted once a month from January 1978 through June 1980, at the stations shown in Fig. 1, on board R/V Ushio-Maru of Hokkaido University and R/V Tansei-Maru of University of Tokyo (May 1980; Cruise No. KT–80–6). Some of the observations were not completed because of the weather conditions.

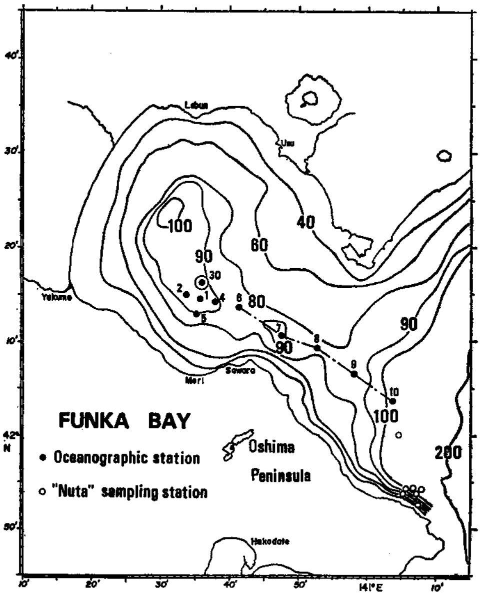

Fig. 1. Bottom topography in Funka Bay and the location of the oceanographic stations.

The water samples for analyzing the physical and chemical factors were collected with Nansen or Niskin water samplers with reversing thermometers. The waters within 75 cm above the bottom were collected with a sampler which has been designed to collect the waters at eight depths.[12] The analyzed factors and the periods of their observations are tabulated in Table 1.

The analyzing methods were, salinity: by Auto-Lab inductive salinometer, dissolved oxygen: Winkler's method, phosphate phosphorus: spectrophotometric method,[13] total phosphorus: as PO_4-P after oxidation by potassium persulfate,[14] particulate organic phosphorus: as total phosphorus after filtration through precombusted glass-fiber filter (Whatman GF/C), chlorophyll-a and phaeophytin-a: fluorometric method.[15],[16] The analytical precisions with replicated samples were 3% for PO_4-P and total phosphorus, and 7% for particulate organic phosphorus.

Table 1. *The analyzed factors and their observation periods. Sta. 30 belongs to Stas. 1-5.*

Period	Analyzed Factors	
	Sta. 1–5	Sta. 6–10
I Jan. 1978–Jun. 1979	Temperature Salinity Dissolved oxygen Phosphate phosphorus Total phosphorus Chlorophyll-a Phaeophytin-a	Temperature Salinity Dissolved oxygen Phosphate phosphorus Total phosphorus
II Jul. 1979–Jun. 1980	Particulate organic phosphorus added	

Samples of the Nuta adhered to the gillnets were collected by a fisherman at the authors' request from March through May 1981. The sampling stations are also indicated in Fig. 1.

Results

1. *Seasonal variation of the general hydrographic condition*

The hydrographic condition in the bay is regulated chiefly by the characteristics of two major water masses and by their periodic replacement.17) One of them is the salty and warm Tsugaru Warm Water (Tw) occupying the bay from late summer through winter, and the other is the cold and less saline Oyashio Water (O&Oi) from spring through summer.18)

In January 1978, the temperatures and salinities are at levels of 6.6°C and 33.8‰ respectively at all depths, as shown in Fig. 2. This homogeneous water is transformed from Tw in the bay by cooling and convectional mixing in winter.18) Its thermosteric anomaly is smaller than 150 cl/ton (26.55 kg/m^3 in sigma-t) and heavier than the waters outside of the bay at the same depth. Such a large density is found at depths deeper than 100 m outside of the bay. This characteristic water is named the Winter Funka Bay Water (Fw).

In March, the waters shallower than 70 m have been replaced by the cold and less saline O&Oi. The temperatures at mid-depth are lower than 1.0°C with the minimum below 0°C at 60 m. This might be attributed to the fact that the amount of drift ice in the Sea of Okhotsk and southeast of Hokkaido Island is greater than that in the ordinary year.19)

From April, the temperature in the upper layer begins to rise from the increases of the air temperature and insolation, and the salinity decreases from the increase of discharge of the rivers. Consequently, the oceanographic structure becomes strongly stratified from May. This stratified structure is maintained throughout the summer.

On the other hand, Fw still remains in the basin after the replacement with O&Oi and gradually changes its characteristics as affected by the overlying O&Oi. The temperature and salinity of Fw become the minima in June or July

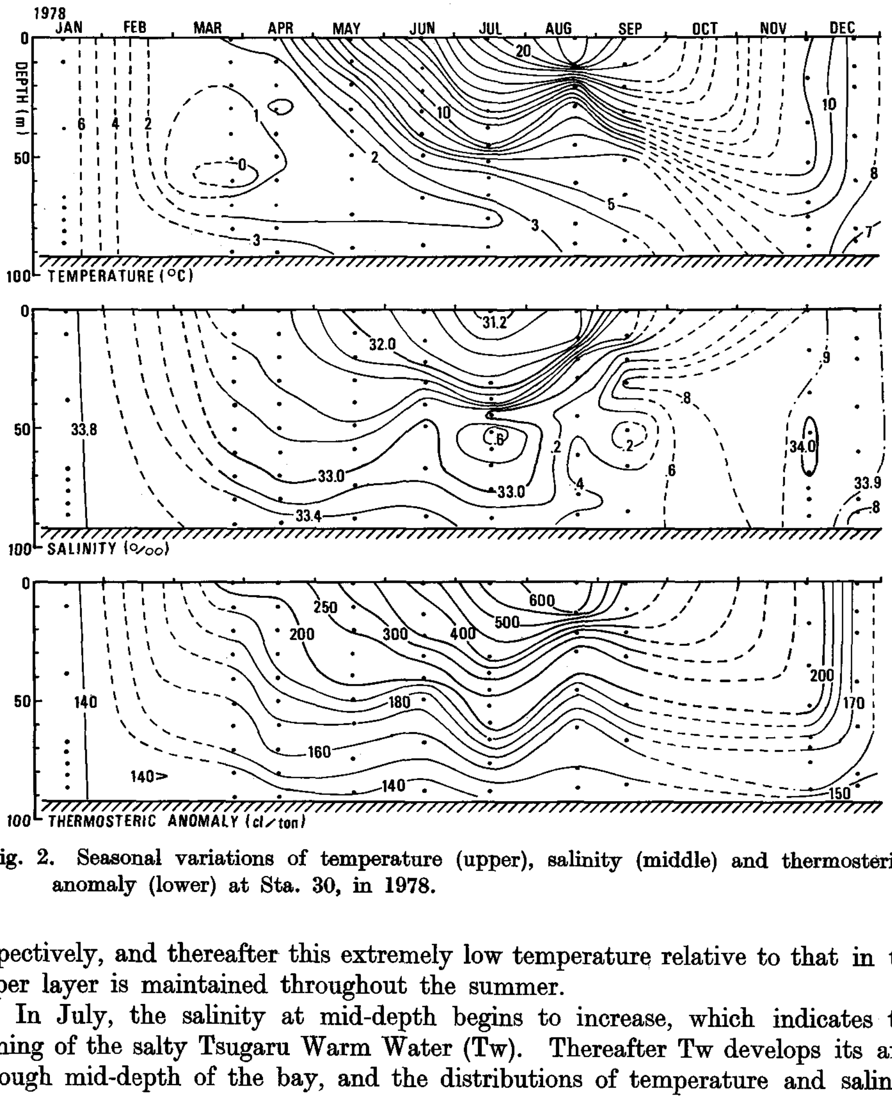

Fig. 2. Seasonal variations of temperature (upper), salinity (middle) and thermosteric anomaly (lower) at Sta. 30, in 1978.

respectively, and thereafter this extremely low temperature relative to that in the upper layer is maintained throughout the summer.

In July, the salinity at mid-depth begins to increase, which indicates the coming of the salty Tsugaru Warm Water (Tw). Thereafter Tw develops its area through mid-depth of the bay, and the distributions of temperature and salinity reveal a complicated multilayer structure.

After September, the temperature at the surface begins to decrease from cooling, and the waters in the bay become vertically homogeneous from convectional mixing. At the end of November, the waters shallower than 60 m have been homogenized, and the temperature and salinity in this layer are about 11°C and 33.9‰ respectively. It is January or February when the waters in the bay become wholly homogeneous.

Fig. 5 shows the typical oceanographic structures in winter observed in 1980. In January, a uniform water is formed in the bay. Its density is larger than that of the waters out of the bay, and so a clear density front is formed at the sill. The temperature drops about 2°C in February and the thermosteric anomaly decreases to smaller than 120 cl/ton (larger than 26.86 kg/cm^3 in sigma-t). Such a heavy water has not been found in the previous years. Its density corresponds to those of the waters at depth around 400 m out of the bay.[20)]

Both in 1979 and the first half of 1980, the patterns of seasonal variation in the oceanographic structure shown in Figs. 3 and 4 are similar to that in 1978, although there are small differences.

2. *Seasonal variation of chlorophyll-a, PO_4-P and saturation ratio of dissolved oxygen*

Chlorophyll-a is the most common pigment in phytoplankton[1)] and the observation of chl.-a is thought to be a convenient method to monitor the seasonal variation of phytoplankton activity.

In January 1978 when the oceanographic structure in the bay is uniform, chl.-a and PO_4-P concentrations range within 0.3–0.4 μg/l and 0.6–0.8 μg-at/l respectively, and D.O. is uniformly undersaturated, as shown in Fig. 6. Then, in March, chl.-a in the subsurface layer increases greatly and rapidly to higher than 3.0 μg/l, showing the vernal phytoplankton bloom. According to the increase of

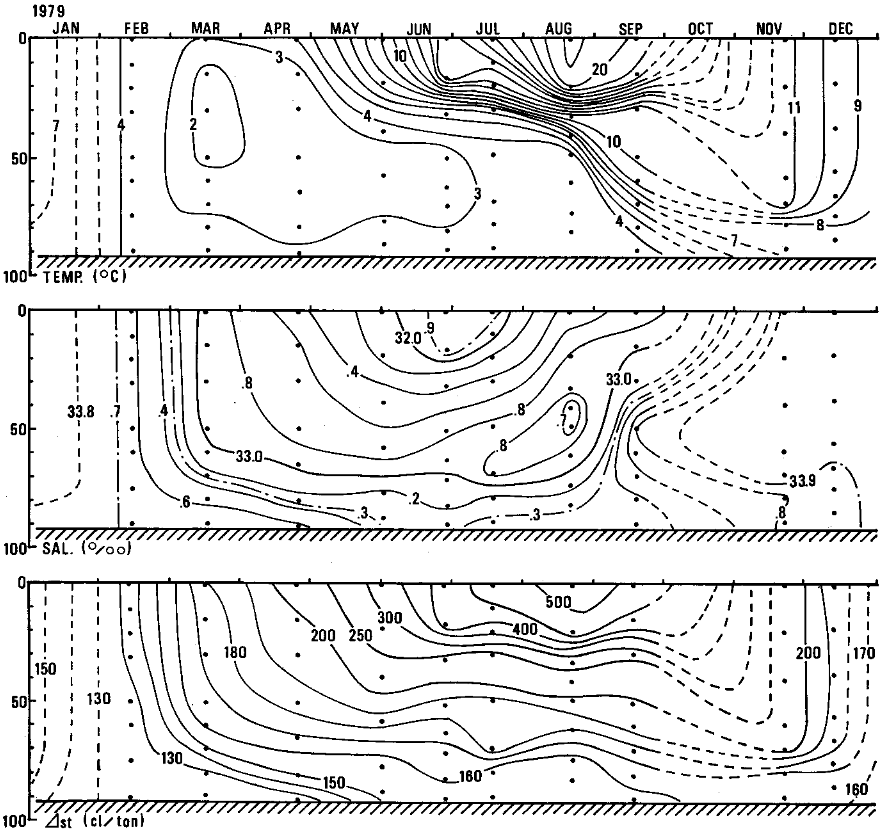

Fig. 3. As in Fig. 2, except in 1979.

chl.-a in this layer, PO_4-P decreases to lower than 0.6 μg-at/l and D.O. becomes supersaturated.

After April, chl.-a rapidly decreases to the level, or lower, prior to the bloom, although the vertical profile has a slight peak at mid-depth. It is noticed here that chl.-a in the basin water increases a little in April. In the upper layer, PO_4-P keeps decreasing and becomes lower than 0.2 μg-at/l in June, and D.O. maintains supersaturated.

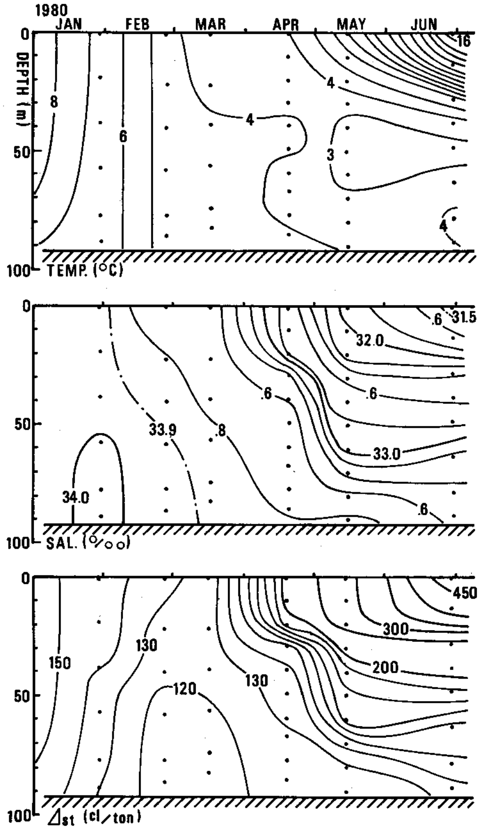

Fig. 4. As in Fig. 2, except in 1980.

On the contrary, in the basin water, PO_4-P begins to increase and D.O. conversely begins to decrease soon after the vernal bloom, and then high PO_4-P concentration and low D.O. saturation ratio are maintained throughout the summer. Those reach the maximum which is higher than 2.2 μg-at/l, and the minimum which is lower than 35%, respectively in September. These changes are attributed to the decomposition of the organic matter sedimented on the bottom and the supply from the sediments.11)

Chl.-a increases in September at mid-depth where the foot of the pycnocline is, but the concentration is much less than that in the vernal bloom. Then it rapidly decreases to about 0.1 μg/l, and is almost uniform from convectional mixing in December. While PO_4-P and D.O. also become uniform from the surface toward the bottom through convectional mixing, PO_4-P increases to higher than 0.6 μg-at/l and D.O. decreases to lower than 94% of saturation without the basin water in December. In the basin water, PO_4-P decreases to about 1.6 μg-at/l and D.O. recovers to about 80%.

Although the observation in January 1979 has not been completed because of severe storms, the water in the bay is thought to become uniform in all factors, considering the results in the other years.

The cyclic seasonal variations stated above are revealed also in 1979 and the first half of 1980 as shown in Figs. 7 and 8, although there are small differences between each other.

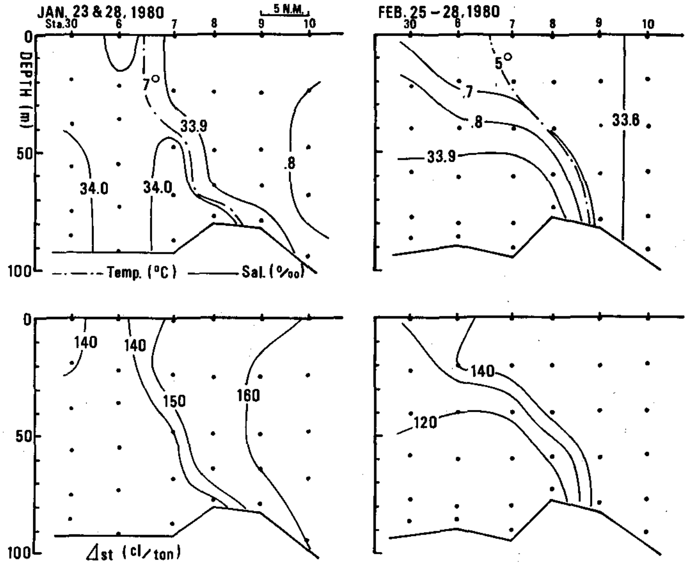

Fig. 5. Typical oceanographic structures in winter observed in January and February 1980.

3. *Seasonal variation of total organic phosphorus*

The concentration of total organic phosphorus (TOP) was detected as the difference of total phosphorus from PO_4-P.

As shown in Fig. 9, in January 1978, TOP concentrations are at the level of 0.1 μg-at/l at all depths and are almost uniform as are the other factors stated in the previous sections. But in March when the vernal phytoplankton bloom occurs, TOP in the waters shallower than 50 m increases corresponding to the increase of chl.-a, and its maximum, which is higher than 0.6 μg-at/l, is reached at the surface. However, such a high concentration disappears in April, and the concentration near the bottom conversely increases to higher than 0.5 μg-at/l.

The vertical TOP sections in March and April 1978 are shown in Fig. 10. The figure indicates more clearly the disappearance of high TOP concentration in the subsurface layer and the increase near the bottom in April.

It can be noticed that, after the vernal bloom, the TOP amount in the water column from 0 to 90 m does not decrease, but rather increases from April through May in contrast to the rapidly decreasing chl.-a amount, as shown in Fig. 9. Especially in 1979, the TOP amount keeps increasing until June. These facts may be attributed to the biological degradation of phyto- and zooplankton, and to the excretion of zooplankton[21] which multiplies after the phytoplankton bloom.[22].

Thereafter, TOP undergoes the summer and fall with a small peak in vertical profile at mid-depth. At the end of November, TOP concentration also becomes uniform in the waters shallower than 70 m. Furthermore the concentration increases in the whole column, and so the amount increases greatly relative to those in the summer and fall.

Although the data on TOP in December 1978 and January 1979 are lacking, the concentration is thought to become uniform through winter as well as the other factors.

Typical TOP sections in winter observed in January and February 1980 are shown in Fig. 11. The TOP concentration in the heavy water in the bay (Fw) is two times higher than that outside of the bay.

Such a seasonal variation of TOP as stated above is observed in 1979 and the first half of 1980, although those are different from each other in detail. Especially the increase of TOP with the development of convectional mixing is commonly observed in both winters.

4. *Seasonal variation of particulate organic phosphorus*

From July through September 1979, the concentration of particulate organic phosphorus (POP) is very low, though it has a slight peak at mid-depth as shown in Fig. 12. Then it also becomes uniform with development of convectional mixing. The POP amount in the water column of 0 to 90 m, in general, decreases during this period and reaches the minimum in December. From January through

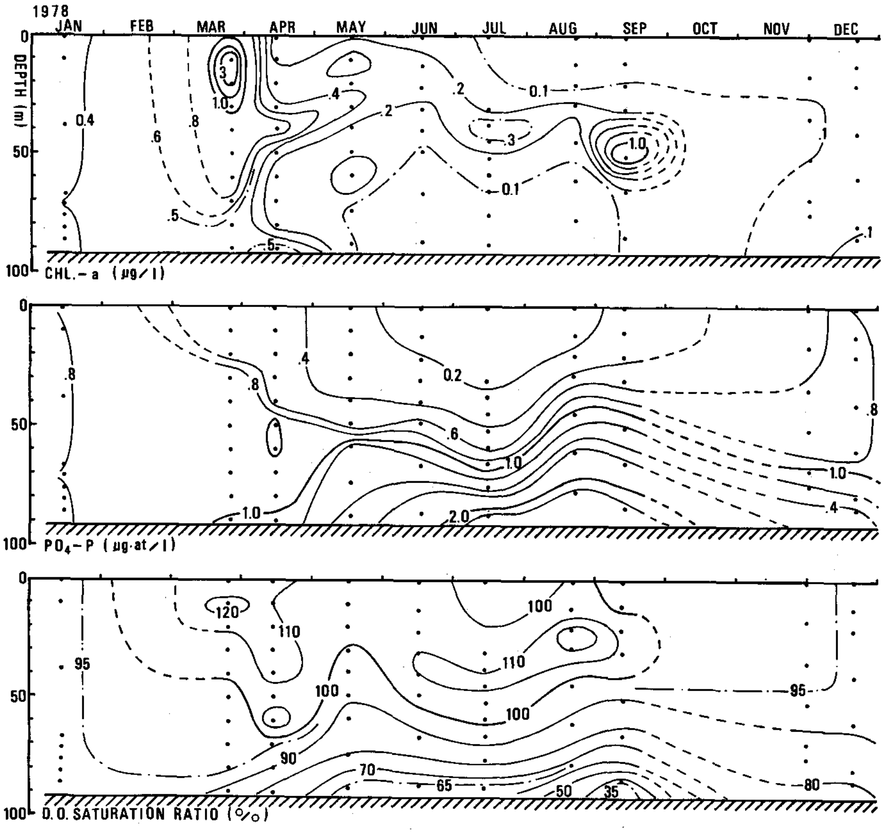

Fig. 6. Seasonal variations of chlorophyll-a (upper), phosphate phosphorus (middle) and saturation ratio of dissolved oxygen (lower) at Sta. 30, in 1978.

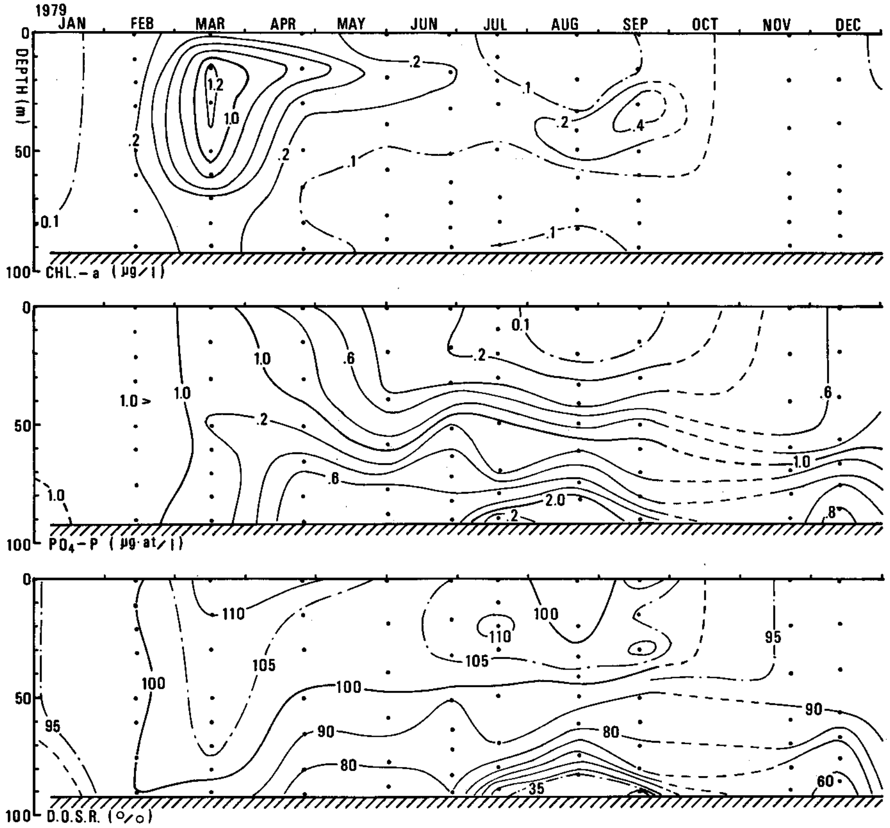

Fig. 7. As in Fig. 6, except in 1979.

February 1980 when the convectional mixing has reached the bottom, POP concentration increases gradually, and so the POP amount in February is multiplied by about ten times the minimum. Thereafter the POP amount reaches the maximum which is fifteen times as much as the minimum, in accord with the vernal bloom. While the POP amount still maintains high since the vernal bloom till May, the high POP concentrations are found in the shallow waters. In May, another high POP concentration appears above the bottom. Thereafter the concentra tion and the amount rapidly decrease to the levels similar to those in the previous summer.

In the waters collected by the near-bottom water sampler at 0, 3, 5, 10, 20, 30, 50 and 75 cm above the bottom, a grey-green fluffy aggregate and dark green porous parcel of particles were observed. The former was often found in the waters within 10–75 cm above the bottom. The latter was found in the waters within 0–5 cm which contained 1–2 g of silt per 500 ml of sea water.

The amounts of POM in the samples collected within 0–5 cm above the bottom were markedly large relative to the amounts within 10–75 cm. The absorbancies in photometry were out of the scale, and so the samples had to be measured through dilution by 10–100 fold. But the authors made an error in the analytical process. So we cannot present quantitatively the amounts within 0–5 cm, though, it is certain that POM in large quantity accumulates in this layer.

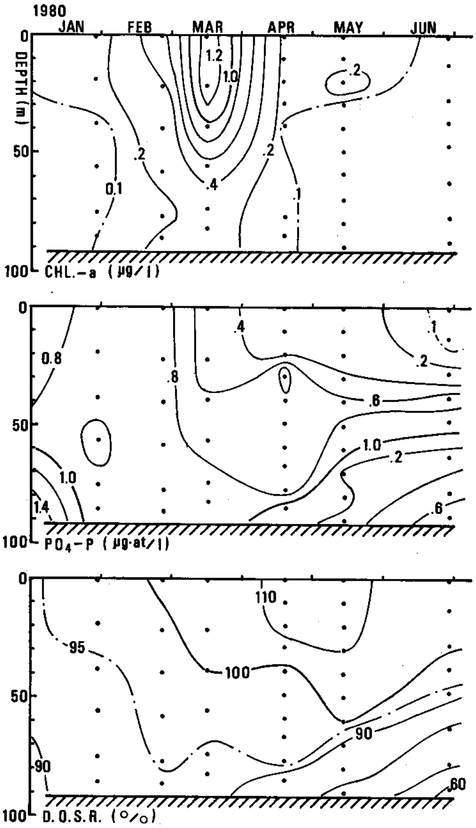

Fig. 8. As in Fig.6, except in 1980.

The POP amount within 10–75 cm above the bottom does not reveal a clear seasonal variation as shown in Fig. 12. The POP concentrations within 10–75 cm are, in general, in the same order as the concentration in 0–90 m column, and the POP amounts in this layer in most months are very small from the summer through the winter in contrast with the large amounts of the samples within 0–5 cm. However, a large amount is observed in June, which is much more than that in 0–90 m column in the vernal bloom.

This is considered to be because the authors have collected the POM which has accumulated above the bottom after the vernal bloom and is removed easily by the movement of waters, as is referred to in the next section.

As stated above, POP in the bay increases rapidly as the vernal phytoplankton bloom occurs, and the amount and concentration above the bottom increase two or three months after the bloom. Furthermore much of POM is accumulated on the surface of the sediments. It is also noticed that POP increases in January when convectional mixing develops at the bottom.

5. *Visual examination of the Nuta and other samples*

The samples of the Nuta were collected from March 9 to May 6, 1981, off Oshima Peninsula where the water depths range from 50 to 120 m.

The majority of the samples were amorphous and mucous organic aggregates of grey-green or light brown (Fig. 13–A, B, D and F), some of which contain fragments of seaweeds and terrestrial plants (D). The black sample (E) changed its color to grey-green like the other ones during the preservation with formalin. The sample in Fig. 9–C is a mucous aggregation of organic parcels, and in spite of the conspicuous difference in appearance, the constitutions are similar to those of the others.

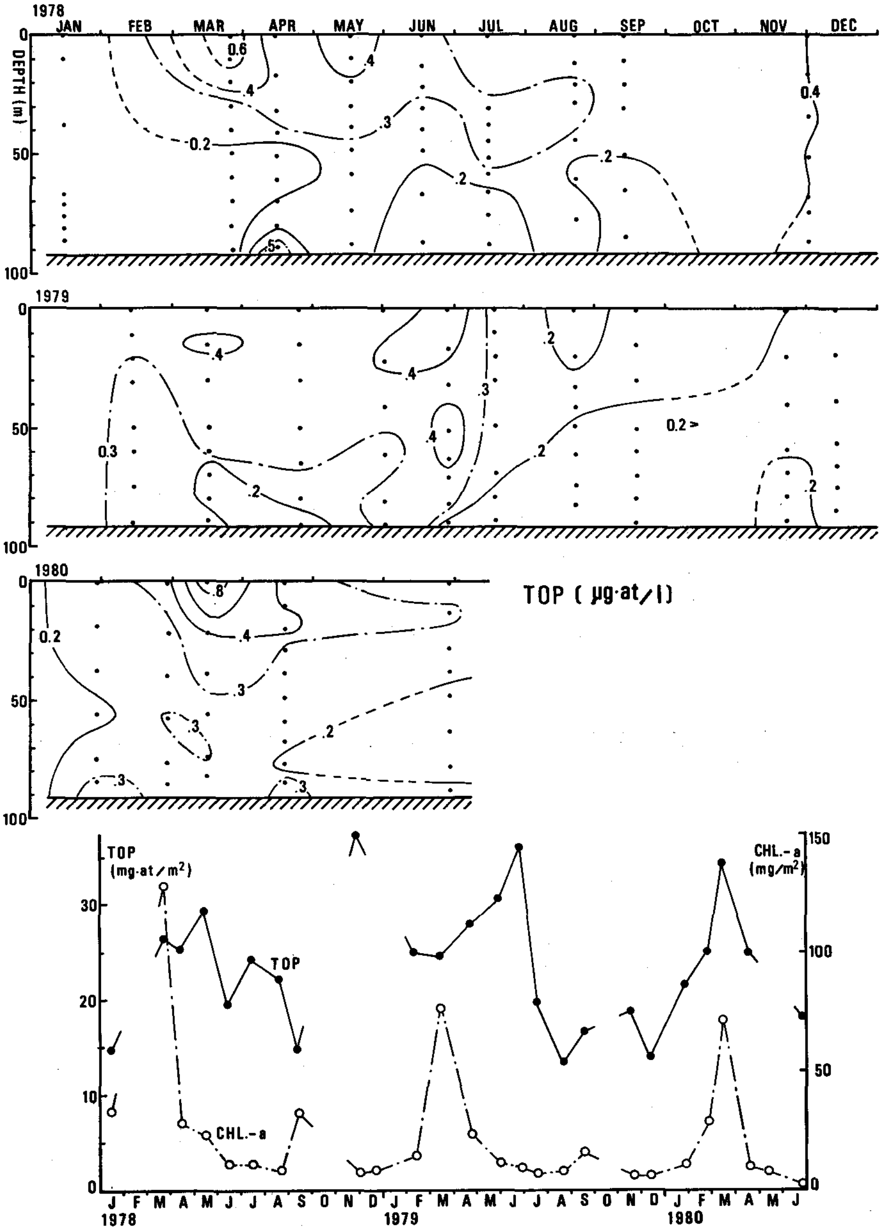

Fig. 9. Seasonal variations of total organic phosphorus (upper), and of the amounts of total organic phosphorus and chl.-a in the water column from 0 to 90 m beneath a unit surface (lower) at Sta. 30, from 1978 through 1980.

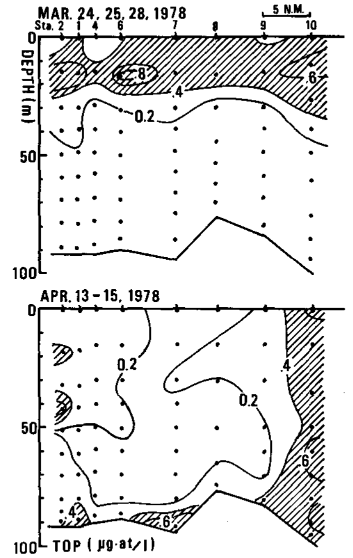

Fig. 10. Vertical distributions of total organic phosphorus in March and April 1978, along the section shown in Fig. 1.

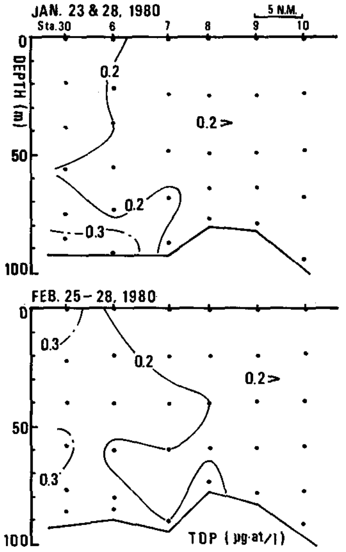

Fig. 11. Vertical distributions of total organic phosphorus in January and February 1980, along the section shown in Fig. 1.

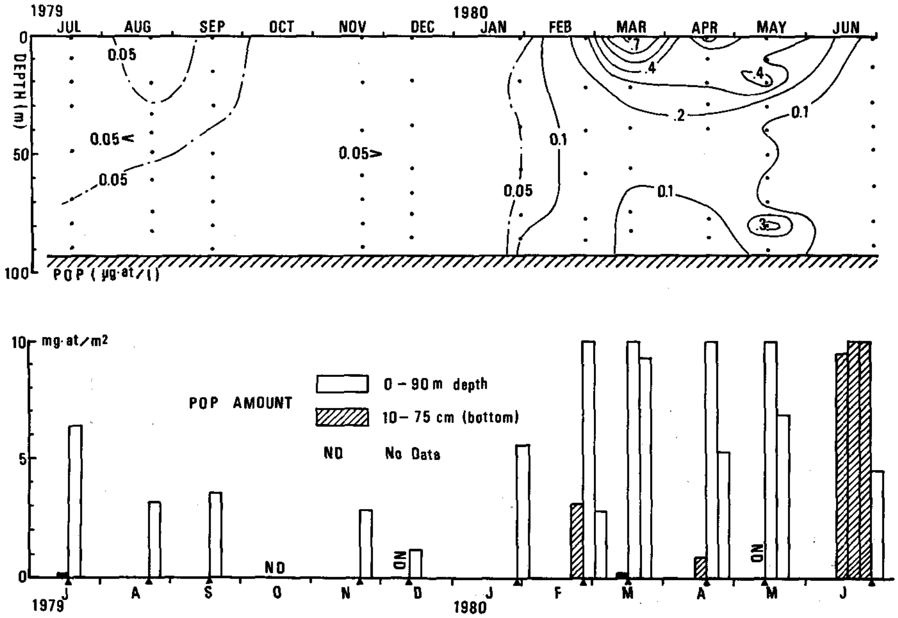

Fig. 12. Seasonal variations of the concentration of particulate organic phosphorus (POP) and the amounts of POP in the water columns beneath a unit surface, within 0–90 m depth and 10–75 cm above the bottom.

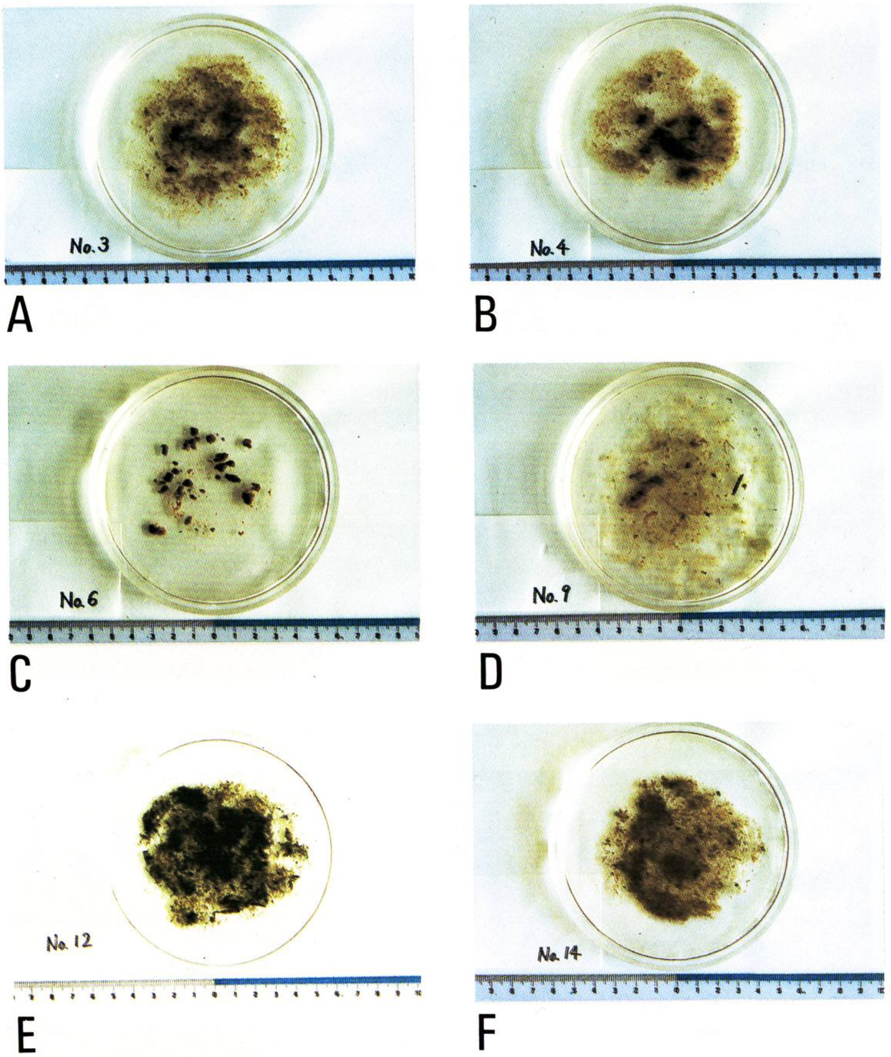

Fig. 13. Photographs of the samples of the "Nuta".

Micrographs of the Nuta are shown in Fig. 14 (A to D). The figure shows that the Nuta consist of phytoplankton cells, fragments and clumps of indistinguishably small particles. The assemblage which seems to be constituted of phytoplankton cells, as shown in Fig. 14-A, is destroyed by water flush into phytoplankton cells, fragments of plankton and others. Most of the phytoplankton found in the Nuta are diatoms (*Biddulphia aurita*, *Thalassiosira* spp., *Coscinodiscus* spp., etc.) and those are the dominant species in the vernal bloom.9).

Fig. 14-E is the micrograph of the organic aggregate which has been collected in

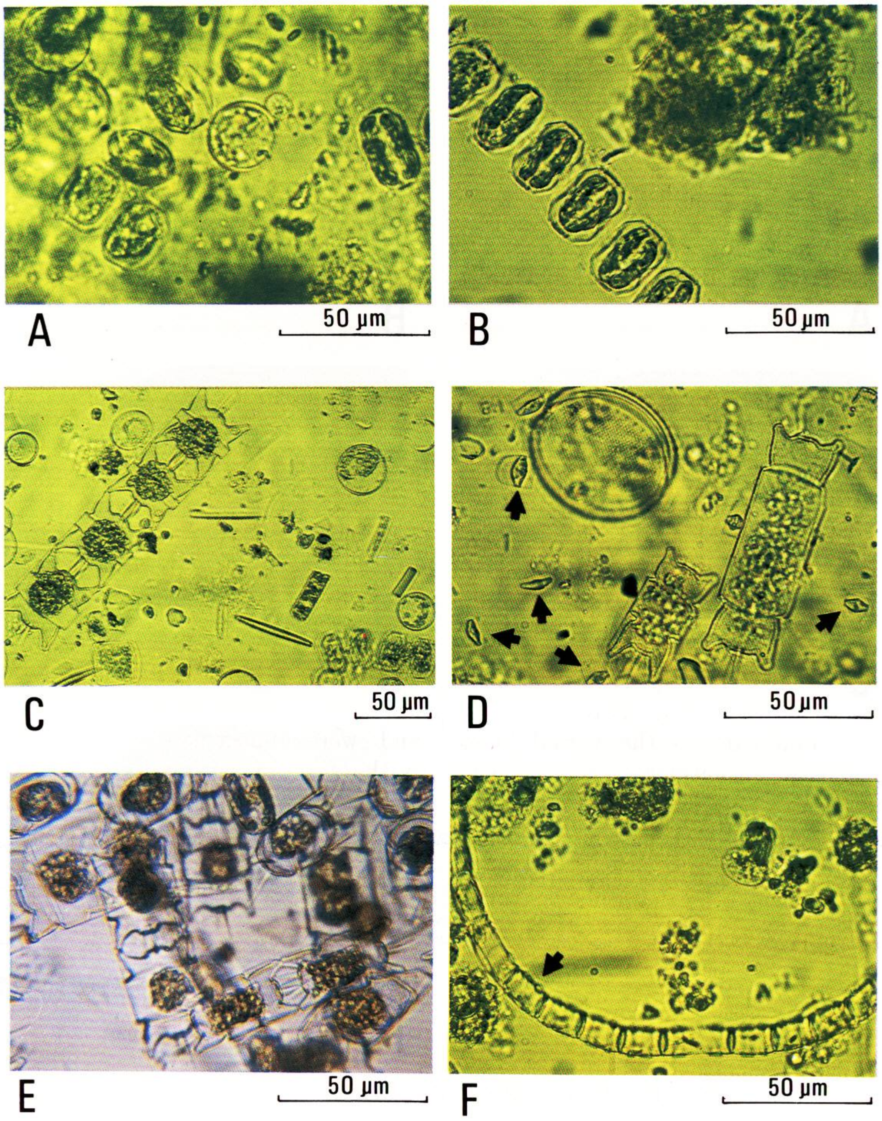

Fig. 14. Micrographs of the Nuta (A-D), suspended organic matter collected with a larva net (E) and gravity core sampler (F). The arrows indicate the resting spores.

large quantity with a larva net hauled at about 40 m depth in April 1978. This aggregate consists of the diatom, *Biddulphia aurita*, which occupies 90% or more in cell number.

During the sampling period of the Nuta, the suspended materials in the waters on the sediment were collected with gravity core sampler at Sta. 30. The suspended materials were grey-green small particles or fluffy aggregations of organic matter. An example of the micrograph of these suspended materials is shown in Fig. 14-F. In those samples, the phytoplankton cells as found in the Nuta are also observed, but the amount of amorphous aggregate of unidentifiable materials is relatively more than those in the Nuta.

The phytoplankton cells shown in Fig. 14 are seen to be undefiled and to have not undergone biodegradation. So the cells are thought to have sunk fast after the production.

In the samples of the Nuta and others, resting spores are frequently found, most of which are thought to be of *Cheatoceros* spp. also dominating in the vernal bloom. These are indicated by the arrows in Fig. 14.

Discussion

In Funka Bay, the phytoplankton bloom occured in March every year when the Oyashio Water (O&Oi) entered the bay. Then, one to three months after the bloom, the concentrations or amounts of chl.-a, TOP and POP above the bottom increased, although those variations were not always coincidental. Furthermore PO_4-P concentration and D.O. saturation ratio above the bottom began to increase or decrease respectively, immediately after the bloom. This is attributed to the fast sinking of POM produced in and after the bloom to the bottom, and decomposition as was previousely indicated.11) Yanada and Maita23) estimated that 22% (phosphorus) to 40% (carbon) of POM produced since March to September sunk to the layer deeper than 70 m.

The Nuta collected with submersible gillnets were clarified to be amorphous aggregates of phytoplankton, small organic particles including fragments of plankton and resting spores. Most of the phytoplankton in the Nuta were the diatoms dominant in the vernal bloom, and were almost undefiled. So those aggregates are considered to have sunk to the bottom without biodegradation soon after the bloom.

Tsujita24) reported large organic matters found in the surface layer of the southern waters of Japan, which were also called "Nuta" there. Those were constituted of phytoplankton in gelatinous matrix of cytoplasm of zooplankton, or in the matrix of small phytoplankton cells. The Nuta in this study seem to be a form of large organic parcel in the waters before adhesion like those reported by Tsujita.

Because the Nuta were collected with gillnets of large mesh size (7–8 cm), the amount of the organic parcel is estimated to be much more than that which actually adhered to the nets.

The positions where the Nuta have been collected are located near the coast of Oshima Peninsula and along the valley stretching from the inside of the bay, where the basin water passes after flowing out of the bay intermittently.10) Hence, the Nuta are thought to have been transferred by the outflowing basin water to the place where they were collected. Those which have been formed outside of the bay verify that the same phenomena occurs in the shallow waters outside of the bay as well as in the bay.

The waters in the bay were stratified weakly during March to April, compared with the strong stratification in summer. Such a structure and formation of mucous aggregation of phytoplankton may possibly contribute to the fast sinking of the POM produced in the vernal bloom.

According to the experimental study,(25) the velocity of heterotrophic uptake of POM increases exponentially with temperature, and it increases approximately eight times for each 10°C rise in temperature. Therefore the cold basin water which is maintained lower than 5°C throughout the summer is considered to contribute to the preservation of the organic materials accumulated on the bottom. On the contrary, the temperature in the surface layer becomes higher than 20°C in summer, and so the POM produced in this layer is decomposed actively.(25),(26) Actually, the concentration and amount of POP in the summer were small in spite of the high primary productivity.(25) This implies that the high primary productivity in summer may not contribute largely to the net production of POM.

In winter when the convectional mixing developed and the waters in the bay became homogeneous, the concentration and amount of POP increased greatly, and TOP in the bay became two times larger than that outside of the bay. According to Maita and Yanada,(25) the primary productivity in this season is very low, and so the increase of organic phosphorus is scarcely thought to be caused by the primary production.

Tsunogai et al.(27) reported the upward flux of particulate matter from the sediment trap experiment, and stated from isotopic studies that the particulate matter was not attributed to the resuspension of old bottom sediment.

Therefore the increase of organic phosphorus in this season is thought to be caused by the resuspension of the POM which has been accumulated and preserved on the surface of the sediment or in the water near the bottom since the vernal bloom. The increase of PO_4-P in this season is considered to be partly because of the decomposition of the resuspended POM as previously suggested,(10) because dissolved oxygen in this season was undersaturated in spite of the large flux of oxygen into the water caused from heavy storm in winter.(28)

The resting spores observed in the Nuta and other samples are also found in the POM suspended in the Winter Funka Bay Water (personal communication from K. Nakata). Those resting spores are thought to have been accumulated on the bottom with other POM including phytoplankton cells from spring, and resuspended by the convection in winter. Because the vernal phytoplankton bloom occurs when the Oyashio Water enters the bay and replaces the Winter Funka Bay Water (Fw), the resting spores suspended in Fw may probably be an inoculum for the next bloom, which indicates the importance of the accumulated POM in reproduction of the phytoplankton as reported by Preston et al.(29)

Funka Bay region is a good fishing ground of Crustacea (crab and Hampback shrimp), benthic fishes (flounder, rockfish, sculpin, etc.) and migrating fishes (Alaska pollack, Pacific cod, sardine, etc.), and is well known as a spawning and nursery area of Alaska pollack. The POM accumulated on the bottom is possibly an important food source for them whether directly or indirectly through harvivorous animals. And the deposition of undefiled phytoplankton cells is a channel of food supply which connects directly the primary production and the benthic community, and also should be added to the channels through detritus(1) and fecal pellet(30),(31),(32) as previously known.

The homogenization of waters through convection in winter, stratification in summer and the resulting preservation of the cold water on the bottom are commontly observed in the neritic zones of the subarctic seas.5),6) Such a common oceanographic structure and the similarity in the annual cycle of plankton community2) imply that the food channel observed in the Funka Bay region as stated above can be expected to exist in the other subarctic neritic zones.

Summary

The behaviour of particulate organic matter (POM) was investigated through chemical observation of particulate organic phosphorus (POP) and microscopic observation of POM on the bottom, in relation to the oceanographic structure and other conditions in Funka Bay. The results of the studies are summarized as following.

1) The homogeneous and heavy Winter Funka Bay Water (Fw) originating from the Tsugaru Warm Water (Tw) remains in the basin as the basin water, being affected by the overlying cold Oyashio Water (O&Oi), from spring until autumn. Therefore the temperature in the basin is kept extremely cold throughout the summer, relative to that in the surface layer.

2) POP in the surface layer greatly increases in accord with the vernal phytoplankton bloom. Two or three months after the bloom, POP above the bottom increases, especially the POP amount within 75 cm above the bottom becomes much more than the amount in the water column of 0–90 m in the vernal bloom. Within 0–5 cm above the bottom, POP in large quantities are observed throughout the year, which seem to correspond to the POP standing stock in the water column of 0–90 m in the vernal bloom.

These indicate that POM produced in the vernal bloom sinks fast to the bottom, and is preserved in the cold basin water.

3) The accumulated POM is significantly important as a source of nutrients and food for the benthic community. Furthermore, much of undefiled phytoplankton cells and resting spores are contained in the POM accumulated on the bottom. The deposition of undefiled phytoplankton cells is a new food channel connecting the primary production and benthic community directly, which should be added to the channels through organic detritus and fecal pellet as is well known. The resting spores found in the POM are considered to become an inoculum for the next phytoplankton bloom.

4) The phenomena similar to those stated above are expected to occur in the neritic zones of the northern North Pacific.

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