Bulletin of the Geological Survey of Japan, vol. 44(5), p. 283-349

Modern sedimentation in the shelf to basin areas around Southwest Japan, with special reference to the relationship between sedimentation and oceanographic conditions

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IKEHARA Ken (1993) Modern sedimentation in the shelf to basin areas around Southwest Japan, with special reference to the relationship between sedimentation and oceanographic conditions. *Bull Geol. Surv. Japan*, vol. 44(5), p.283-349, 48fig., 7tab.

Abstract: Marine sediments have recorded depositional and/or erosional history of the ocean. Many geologists and oceanographers have discussed geomorphological and sedimentological evolutions of the shelves around the Japanese Islands in relation to Quaternary sea-level fluctuations mainly based on the submarine topography and sediment distributions on the shelves. However, few studies have been carried out regarding the factors controlling the sediment distribution. In this study, modern sedimentation around Southwest Japan is discussed on the basis of sedimentological data, such as surface sediment distribution, sediment composition, bedform distribution and morphology, sea bottom photography and seismic record. The purposes of this study are as follows: (1) clarification of the relationship between oceanographic conditions and sedimentation, (2) (re-)evaluation of other factors, such as sea-level changes and tectonic movements, for sediment distribution, and (3) presentation of a key to solve ancient sedimentary processes and environments.

Sedimentological analysis of surface sediments around Southwest Japan shows the close relation between modern sedimentation and oceanographic conditions; that is, waves, tidal and ocean currents, water mass boundaries and water properties strongly affect sediment distribution and composition. Around Southwest Japan, a major factor controlling modern sedimentation on the mid-outer shelves is the ocean current. Effects of wave actions, tidal currents, and gravity currents and movements are found only at the limited areas. The ocean currents and the related water circulations are influential to sediment transport and deposition. Direct effects of the current are found in sand transport on the mid-outer shelves to the upper part of the upper slope and around the knolls or ridges. Indirect effects are recognized in mud

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Keywords : modern sedimentation, sediment transport, Southwest Japan, surface sediments, bedform, ocean current, water mass, sea level change, Pacific Ocean, Sea of Japan.

deposition at the coastal water zones which are formed in relation to the water circulation caused by the ocean currents.

The differences of oceanographic conditions between the Pacific and the Sea of Japan are also reflected on modern sedimentation. Sandy sediments and bedforms are widely distributed on the Pacific bottom but limited on the Sea of Japan bottom, reflecting the difference in strength and mode of bottom currents. Calcium carbonate compensation depth is shallower in the Sea of Japan than in the Pacific, probably reflecting the difference in bottom water properties.

On the other hand, Quaternary sea-level changes are closely related to the formation of sedimentary sand bodies on the shelves. Tectonic movements are also important to the formation of sedimentary basins, in which modern muddy sediments are deposited, and to the filling-up processes of the basins.

1. Introduction

Many studies have been conducted on the bottom sediments around the Japanese Islands and distributional features of surface sediments have been clarified to some extent (e.g. Maritime Safety Agency, 1949). Although more detailed surveys have been carried out in the coastal area (e.g. Hoshino, 1958), only a few sedimentological studies have been made in the deeper areas than on the outer shelves (e.g. Ohshima *et al.*, 1982; Inouchi, 1982). Few studies have also been carried out regarding the factors controlling the sediment distribution (e.g. Hoshino, 1952, 1958; Ikehara, 1988a; Saito, 1989a, b). In the study of modern sediments, the most important and fundamental problem is from where and how the sediments have been derived and what kind of forces controls sediment movements. Spatial distribution of surface sediments is influenced by the vector distribution of currents, because the sediment grain has been transported and deposited reflecting flow velocity (Kimura, 1956; Sundborg, 1956; Ljunggren and Sundborg, 1968). In addition, because surface sediments have been exposed on the sea bottom for a long time, they have recorded the long-term, averaged current conditions near the sea bottom, which are difficult to detect by usual oceanographic measurements. Therefore, sedimentological information is important for understanding not only geological problems such as Quaternary sea-level changes but also modern oceanographic considerations.

The sea around Southwest Japan has the following characteristic oceanographic conditions: the Kuroshio, which is a typical western boundary current and strong ocean current, flows along the Pacific coast. On the contrary, in the Sea of Japan, the Tsushima Current, which is a branch of the Kuroshio, flows gently eastward and the homogeneous Japan Sea Proper Water (JSPW) exists below the Tsushima Current. Thus, the water masses in the Sea of Japan show a stratified structure. Such differences in oceanographic conditions may affect on modern sedimentation. Consequently, clarification of differences in sedimentation between the Kuroshio area and the Tsushima Current area is important for understanding ancient marine sedimentation.

In this paper, I would like to examine the relationship between sedimentation and oceanographic conditions such as currents, waves, sea-water stratification, boundary between the different water masses and sea-water properties around Southwest Japan by using the sedimentological data available at the Geological Survey of Japan and published oceanographic information. The Geological Survey of Japan has conducted the marine geological investigations around the Japanese

Islands by using R/V Hakurei-Maru since 1974 and has stored plenty of sedimentological and geophysical data. I will, at first, briefly describe the sedimentological aspects both on the Pacific side and the Sea of Japan side, examining the relationship between the sedimentation and the oceanographic conditions on each side, and then, compare sedimentational features on both sides.

2. Physiography and oceanography

2-1. Submarine topography

The submarine topography on the Pacific side off Southwest Japan is characterized by the shelf, upper slope from the shelf to the forearc basin (deep sea terrace), forearc basins, knolls constituting the outer ridge, lower slope from the outer ridge to the Nankai Trough and the Nankai Trough (Fig.1). At the southern part of the study area, the outer ridge is poorly developed and the upper slope directly changes to the Ryukyu Trench. The shelf edge in the study area, has a depth of 120-150m. In general, deeper shelf edges have less differences in slope between the shelf and the upper slope. Thus, shallower shelf edges can be recognized easily. The spars are found offshore of the capes extended to the south, such as Cape Muroto-Zaki and Cape Ashizuri-Misaki. The upper slopes dip 2 to 6° and are segmented by many submarine canyons, for example on the western side of Tosa Bay, south of the Bungo Channel and east of Tanegashima Island. The forearc basins are the deep-sea terraces with depths around 1000-2000m. They are divided by the topographic highs which are extended southwards from the spars and bounded by the outer ridges on the south. The forearc basins in the study area are, from west to east, the Hyuga Basin and the Tosa Basin. Further eastwards, the Muroto Trough, the Kumano Basin and the Enshu Basin are distributed. The lower slope shows the stepped topography. Some of these steps are developing trench-slope basins in parallel to the Nankai Trough (Okada, 1989). The Nankai Trough has the maximum water depth deeper than 4800m at the south of the study area. The Trough floor with thicker sediment layer and flatter topography becomes shallower eastwards.

The submarine topography of the Sea of Japan is characterized by N-S and ENE-WSW trending topographic highs, narrow shelf except for the western part, wide marginal terrace with water depths of 200-400m (Iwabuchi, 1968; Iwabuchi and Kato, 1988), slope between the edge of the marginal terrace to the basin or trough, and the basin or trough (Fig.2). Two N-S trending topographic highs are remarkable in the study area. One is a high from the Shimane Peninsula through the Oki Islands to the Oki Spar, and the other from the Mishima Island through the Hachirigase Bank to the Senrigase Bank (Fig.2). The ENE oriented topographic highs are also well developed to the east of the Oki Islands (Fig.2). They are, from south to north, the Echizen Bank Chain, the Wakasa Sea Knoll Chain and the Oki Ridge. Between the highs, topographic depressions are formed. The largest depression is the Oki Trough between the Wakasa Sea Knoll Chain and the Oki Ridge. West of the Oki Islands, buried or semi-buried ridges which have the same direction are observed on the bathymetric or seismic records (Tanahashi and Yamamoto, 1986, 1990).

Except in the Tsushima Strait and the Oki Strait, the shelf is generally narrow. The shelf edge is located at depths of 110-175m (Japanese Association for Quaternary Research, 1987) and is obscured between the Oki Islands and Mishima Island. Small but distinct slope is bounded between the shelf and the marginal terrace in the east of the Oki Islands. The marginal terrace is well-developed from the Mishima Island to offshore of Hokuriku. The slope between the marginal terrace and the basins or trough is 2 to 10°. The basins are bounded by N-S trending topographic highs, as mentioned above. They are, from west to east, the Tsushima

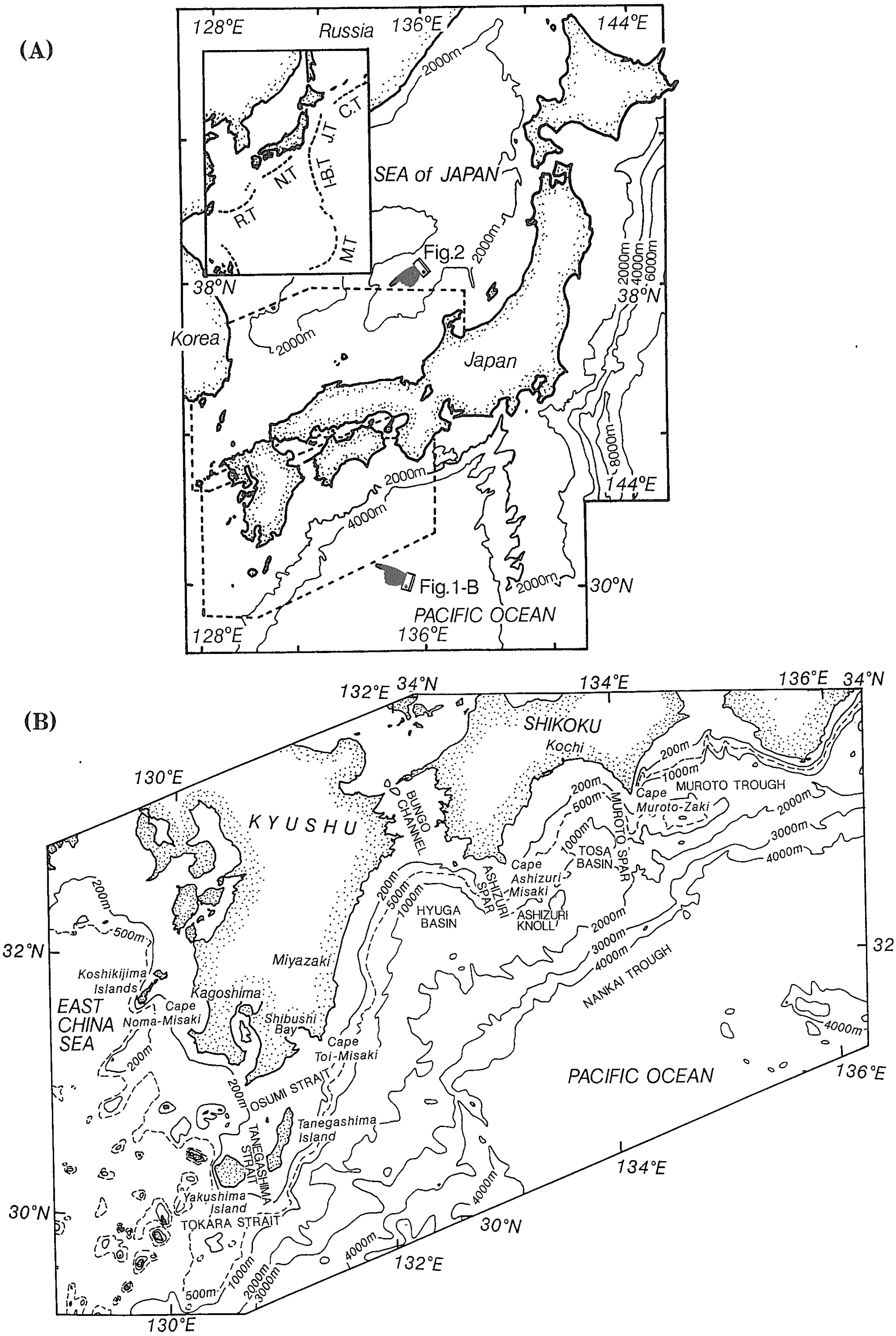


Fig.1 Location of the studied areas (A) and bathymetry of the Pacific off Southwest Japan (B). C.T; Chishima Trench, J.T; Japan Trench, I-B.T; Izu-Bonin Trench, M.T; Mariana Trench, N.T; Nankai Trough, R.T; Ryukyu Trench.

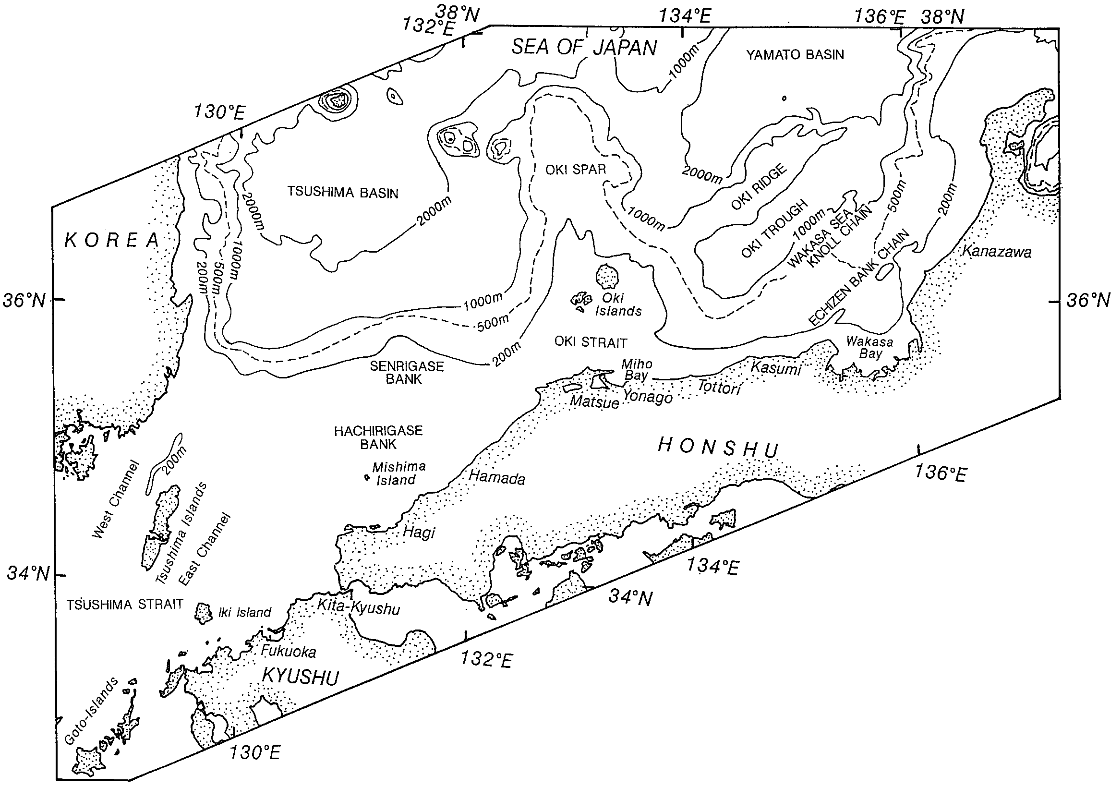


Fig.2 Bathymetry of the Sea of Japan off Southwest Japan.

Basin which opens north- to northeastwards and the Yamato Basin which has an elongated shape with a trend of ENE to WSW and is separated from the Oki Trough with the Oki Ridge. The Oki Trough extends east-northeastwards and is subdivided into two segments (the southwestern and northeastern parts) by small but distinct slope located central part of the Trough (Ikehara *et al.*, 1990a). The southwestern part is gently sloped northeastwards and has small relieves on the sea bottom, while the northeastern part has the flat bottom with a depth around 1750m. The Oki Ridge is the most distinct ridge in the study area and has a terrace of 300m deep.

2-2. Oceanography

The oceanographic conditions are very different between the Pacific side and the Sea of Japan side. On the Pacific side, a strong ocean current, Kuroshio, not only is prevailing along the coast (Nitani, 1972a) but also gives an influence to the whole area (Tamai *et al.*, 1991). On the other hand, most of the water in the Sea of Japan consists of the Japan Sea Proper Water (JSPW), which is homogeneous and shows low temperature, low salinity and high oxygen concentration (Suda, 1932; Nitani, 1972b). In the southern part of the Sea of Japan, the JSPW water mass is covered by the surface water (Asaoka *et al.*, 1985; Murayama *et al.*, 1990) belonging to the Tsushima Warm Current, a branch of the Kuroshio (Nitani, 1972a). Therefore, a distinct stratified structure is formed. A major thermocline between the surface water and the JSPW occurs around the depth of 200m.

The Kuroshio flows along the Pacific coast (Fig.3; Nitani *et al.*, 1979) affecting the behaviors of the shelf water (Miyata *et al.*,

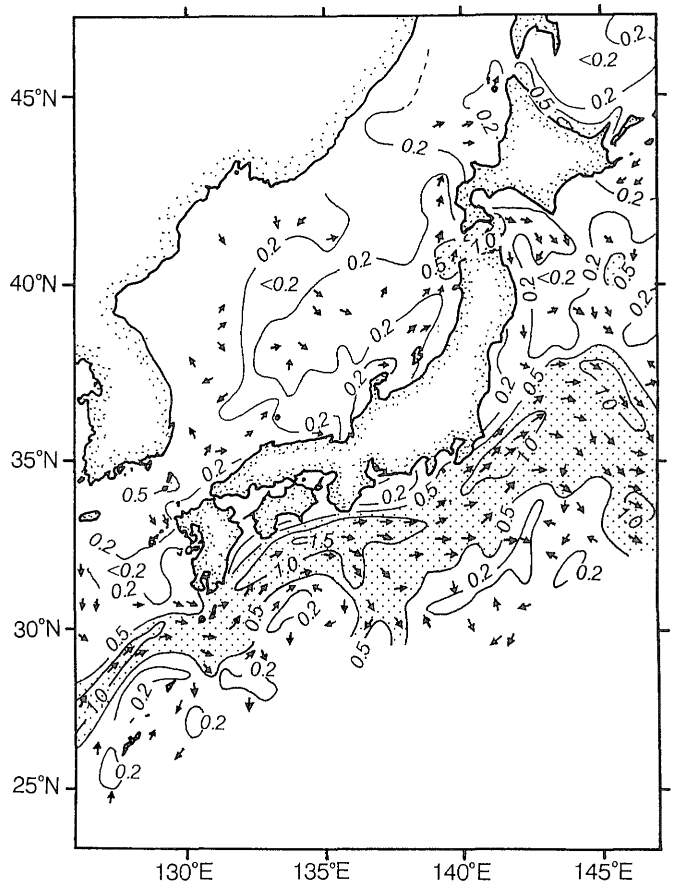


Fig.3 Vector mean velocity of the current around the Japanese Islands (simplified from Nitani *et al*., 1979). Hatched areas show high velocity (faster than 0.5 knots) areas.

1980, 1985; Chaen, 1985; Sakamoto *et al*., 1986; Sakamoto, 1987; Fujimoto, 1987; Tamai *et al*., 1991). The vector mean velocity of the Kuroshio is about 1 knot off Kyushu, 1.5-1.8 knots off Shikoku and Kii Peninsula (Japan Oceanographic Data Center, 1979). The Kuroshio water is characterized by high temperature, high salinity and low oxygen concentration.

The Tsushima Current in the southern Sea of Japan also shows high temperature, high salinity and low oxygen concentration. It flows into the Sea of Japan through the Tsushima Strait, taking eastward flow courses (Figs.3 and 4; Naganuma, 1972; Kawabe , 1986) , but generally shows very complicated flow patterns. According to Suda and Hidaka (1932) and Uda (1934), three branches of the Tsushima Current are recognized. The first branch (the nearshore branch along the Japanese coast) flows eastwards over the Japanese shelf from the East Channel of the Tsushima Strait. The second branch (the offshore branch) flows along the shelf or marginal terrace edge towards east. It appears only in summer time. The third branch (the Eastern Korean Current) splits at the exit of the Tsushima Strait and flows northwards. The third branch exists in all seasons and forms a polar front against the northern cold water mass. The vector mean velocity of

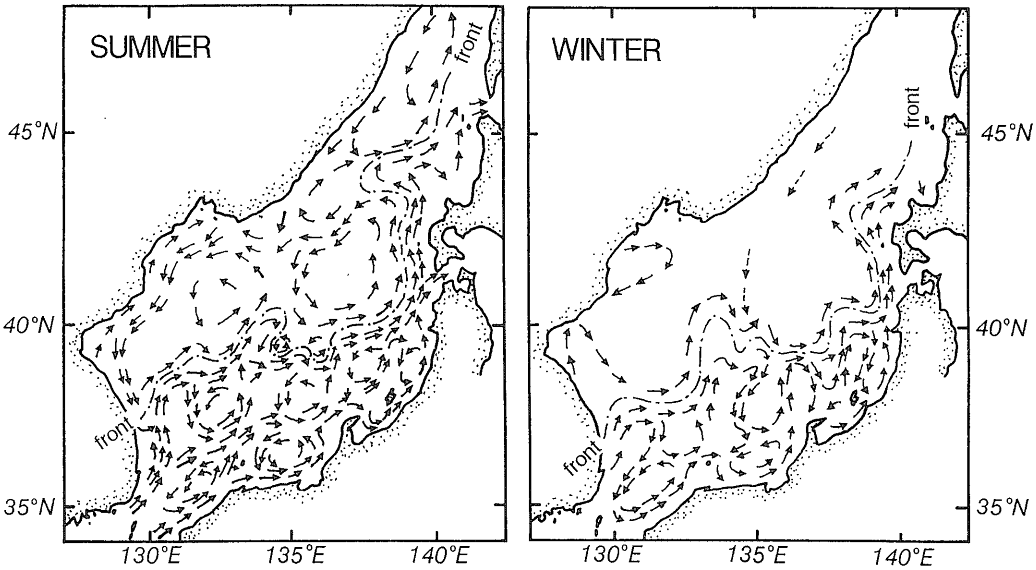


Fig.4 Schematic representation of surface water circulation of the Sea of Japan (after Naganuma, 1972).

the Tsushima Current is small, about 0.1-0.3 knots (Japan Oceanographic Data Center, 1979). Schematic representation of surface currents indicates that many warm and cold water masses are developed among the branches, forming eddies (Naganuma, 1972). A characteristic oceanographic feature in the Sea of Japan is the occurrence of the JSPW (Fig.5) which shows low temperature (0-1°C), rather low salinity (34.0-34.1‰) and high oxygen concentration (5.0 to more than 7.0ml/l) (Suda, 1932; Nitani, 1972b). The JSPW is considered to be originated along the Siberian coast at the time of ice formation in winter (Nitani, 1972b). It is farther subdivided into deep and bottom waters (Gamo and Horibe, 1983; Gamo *et al.*, 1986). The bottom layer deeper than 2000 m has the highest oxygen concentration (Gamo *et al.*, 1986).

3. Methods for sedimentological analysis

The sedimentological and marine geological data, on which this study is based, have been obtained during the survey cruises of R/V Hakurei-Maru by the Geological Survey of Japan. Sediment samples on the Pacific side were collected in the cruises of GH83-2 (June-August, 1983) and GH84-3 (June-August, 1984) and those on the Sea of Japan side were obtained during the cruises of GH85-2 (June-July, 1985), GH86-2 (June-July, 1986) and GH87-2 (June-July, 1987). In addition, seismic records were made available by the cruises of GH83-1 (April-May, 1983) and GH84-1 (April-May, 1984) in the Pacific and GH85-4 (September-October, 1985), GH86-4 (September-October, 1986) and GH87-4 (September-October, 1987) in the Sea of Japan.

The surface sediments were collected by using several instruments, such as a Smith-McIntyre type grab-sampler, a K(Kinoshita)-type grab-samplers newly designed by the Geological Survey of Japan (Kinoshita, 1987), a piston corer with 6.8cm in diameter and 8m in length, two types of gravity corers (one of which is 12cm across, 2-7m long and "rock corer" 5cm across, 2m long), and dredges. For the sedimentological study, the samples collected with grab samplers and corers were used, because dredge samples

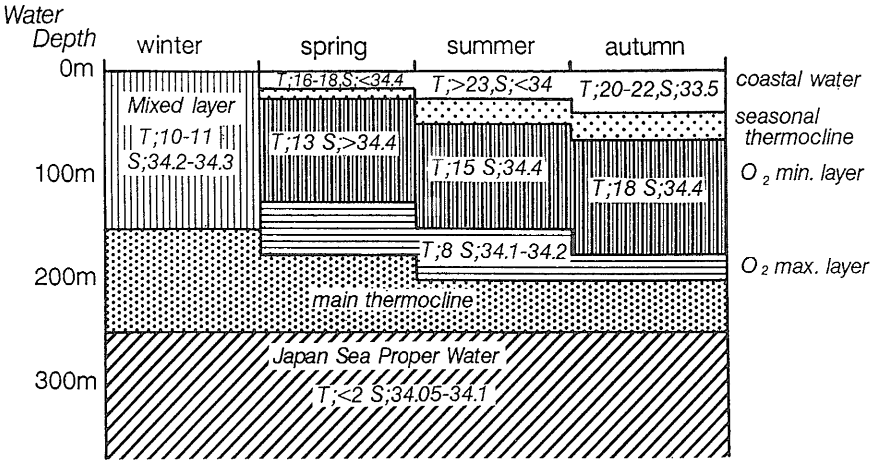


Fig.5 Schematic diagram of oceanographic structure off Wakasa Bay (after Asaoka *et al*., 1985).

were disturbed during samplings.

In the study area, grab samples of 730 and cored samples of 60 from the Pacific and grab samples of 656 and cored samples of 71 from the Sea of Japan were collected during the above mentioned cruises (Fig.6).

Methods for sedimentological analysis are briefly shown in Fig.7. Soft-X radiography and mechanical analysis were conducted for all surface sediments obtained with grab sampler and some of the cored samples. The grain-size distributions of surface sediments were determined by sieve analysis for the sand component and by hydrometer or pipette analysis for the mud component. The sediment cores were observed visually on board and some slices were taken for soft-X radiography. In some core samples, ^{14}C dating was applied to organic matters in the sediments and identification of some tephra layers intercalated in the sediments was carried out.

Sea bottom photography was also conducted. By analyzing the photographs, the distributions of small bedforms, macrobenthos and suspended bottom-water zone were determined.

Larger bottom relieves were distinguished with 12kHz echosounders, 3.5kHz sub-bottom profilers, fish detectors and side-scan sonars. In addition to them, 3.5kHz sub-bottom profilers were used for interpreting sedimentary structures just beneath the bottom.

4. Results

4-1. Surface sediments

4-1-1. Surface sediments on the Pacific bottom off Southwest Japan

Median diameter distribution of surface sediments is shown in Fig.8. Sandy sediments are distributed on the shelf and the upper part of the upper slope. Muddy sediments are found in areas deeper than the middle part of the upper slope. Muddy sand or sandy mud is spread on and around the knolls. Gravelly or rocky bottoms are found on the spars, mid-shelf, upper slope and knolls.

The shelf sediments in the Tosa Bay show the following characteristics: In the eastern part of Tosa Bay, sandy sediments are widely distributed from the nearshore to the offshore (Fig.9; Ikehara and Okamura, 1985; Arita and Kinoshita, 1991). On the other hand, in the western part, muddy sediments cover the inner to mid-shelf, and sandy sediments (offshore sandy sediments of Ikehara, 1988 b) are spread in the area from the shelf edge to the upper part of the upper slope. Muddy sediments occupy gradually deeper parts southwestwards (Fig. 9; Ikehara, 1988 b).

The offshore sandy sediments become finer in grain size and higher in mud content southwestwards (Ikehara and Okamura, 1985; Ikehara, 1988b). Well-sorted very fine sand with little amount of mud (coastal sandy sediments of Ikehara, 1988b) occurs offshore of City of Kochi (Fig.9; Ikehara, 1988b).

In the Bungo Channel, the sediments become finer in grain size with increasing distance from the narrowest part of the Channel (Fig.10; Inouchi, 1982; Ikehara and Kinoshita, 1989). Medium sand is widely distributed in the Channel. Fine sand is spread near the shelf edge and farther southwestwards. The thickness of surface sand layer is around 10m in the Channel and becomes thinner southwards (Fig.11). Coastal area along the Hyuga coast is covered by very fine sand (Fig.8). Fine to very fine sand is widely distributed on the Miyazaki shelf (Fig.8).

On the shelf, east of the Osumi Peninsula, the sediments contain large amounts of pumice grains (Sato *et al.*, 1985) reflecting intense Quaternary volcanic activity in South Kyushu. In the Osumi Strait, the sediments become finer in grain size (Fig. 12; Inouchi, 1982; Ikehara, 1988a, 1989a). The content of heavy minerals also becomes lower toward the same direction (Fig.13; Ikehara *et al.*, 1988a). On the shelf off the north and east coasts of Tanegashima Island, fine sand occurs. In the Tanegashima Strait, coarser sediments are distributed in the central part and the grain size becomes finer both southwards and northwards (Figs.8 and 14). The shelf off the Satsuma Peninsula is covered by slightly finer sediments (very fine sand) (Figs.8 and 14). Muddy sediments on the shelf around South Kyushu occur only in Shibushi Bay (Fig.8).

The surface sediments distributed in the areas deeper than the middle part of the upper slope are fine silt to clay (Fig.8). Thin sand layers are occasionally intercalated in the fine-grained sediments (Honza *et al.*, 1984; Ikehara and Okamura, 1985; Ikehara, 1988b). The Kikai-Akahoya Ash (Ah) of 6300 years B.P. (Machida and Arai, 1978) is intercalated in some sediment cores (Fig.15; Ikehara, 1988b). Sub-bottom depths of ash layers in the lower part of the upper slope and forearc basins provide us with the data of sedimentation rates (about 20cm/1000 years; 3.8-26cm/1000years) during the present interglacial (Ikehara, 1988b).

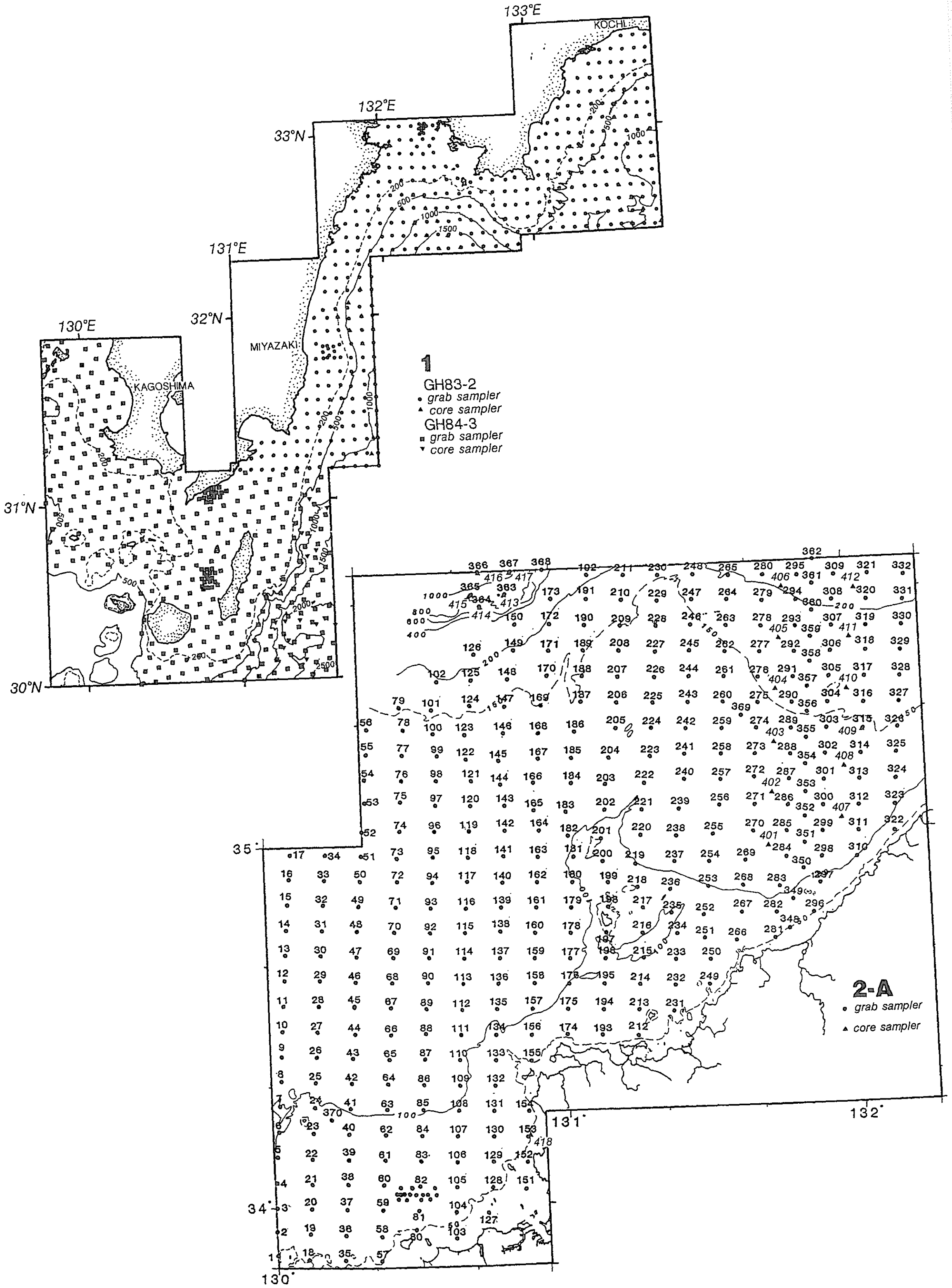
Rocky or gravelly bottom is found on the knolls located around the forearc basins (Okamura *et al.*, 1986). Off Cape Ashizuri-Misaki, the sediments around the knolls are slightly coarser than in the surroundings (Fig.9) and contain much amount of foraminiferal remains (Ikehara, 1988b). These coarser sediment zones are extended eastwards (Ikehara, 1988b).

4-1-2. Surface sediments on the Sea of Japan bottom off Southwest Japan

The median diameter distribution (Fig. 16) in general indicates predominance of muddy sediments throughout the study areas (Ikehara, 1989b, 1991a). Sandy sediments are distributed on the shelf, on the Oki Ridge, a submarine canyon floor and a part of marginal terrace edges.

Sandy sediments are widely distributed on the shelf from the Tsushima Strait to the offshore area of Kita-Kyushu (Fig.17). Generally, the grain size becomes finer eastwards. That is, in the Tsushima Strait, coarse to medium sands are widely developed. Off Fukuoka, medium to fine sand occurs commonly and off Kita-Kyushu, fine sand is most widely distributed.

Around and north of Mishima Island, rocky, gravelly or sandy bottom is found (Fig.16). Between Mishima Island and the Oki Islands, muddy sediments are predominant and sandy sediments are distributed only nearshore and on the banks. In general, the sediment characters are controlled by the basement relief (Fig.18) judging from the seismic records (Tanahashi and Yamamoto, 1990). That is, muddy sediments are deposited where the basement is deeply located and sandy sediments occur where the basement is shallower.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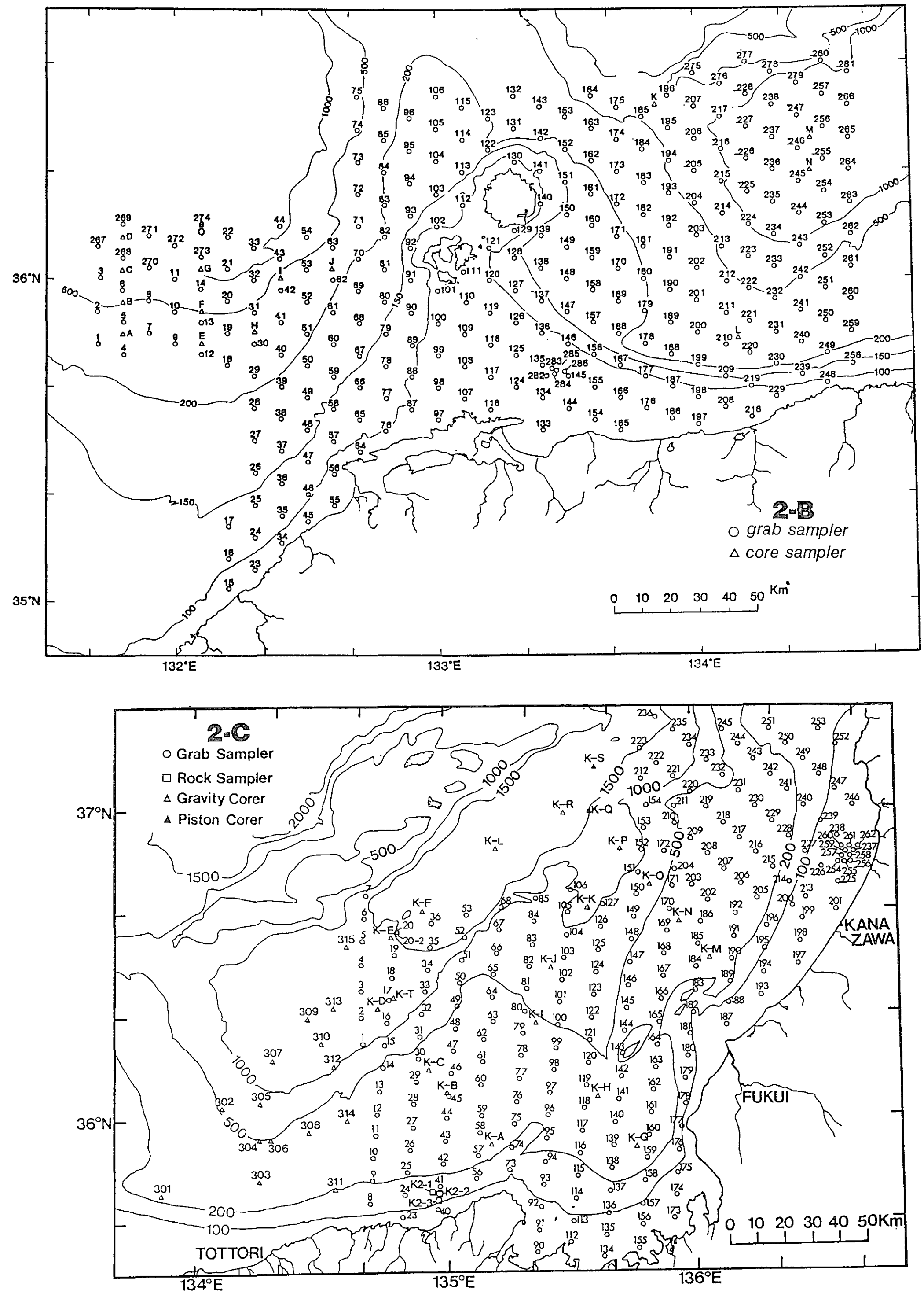


Fig.6 Sampling location. 1; Pacific side (GH83-2& 84-3), 2-A (GH85-2), B(GH86-2) & C(GH87-2); Sea of Japan side.

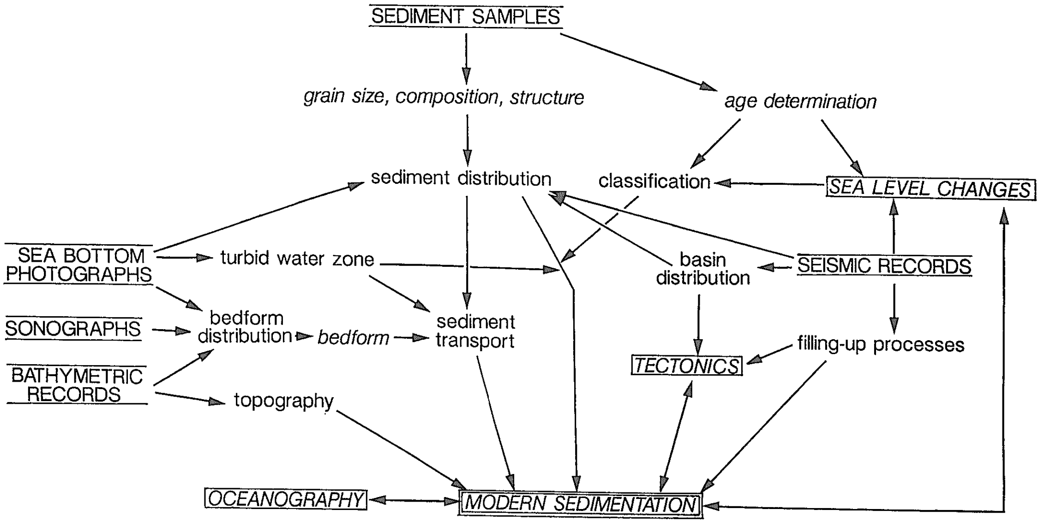


Fig.7 Flow diagram of this study.

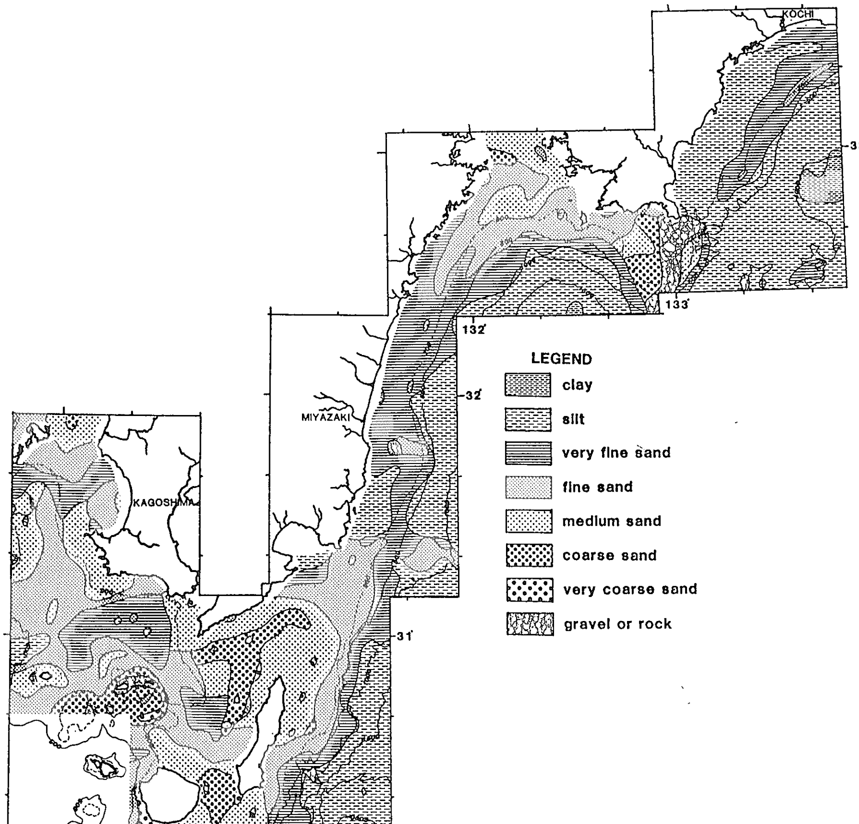


Fig.8 Surface sediment distribution of the Pacific side off Southwest Japan (after Ikehara, 1985).

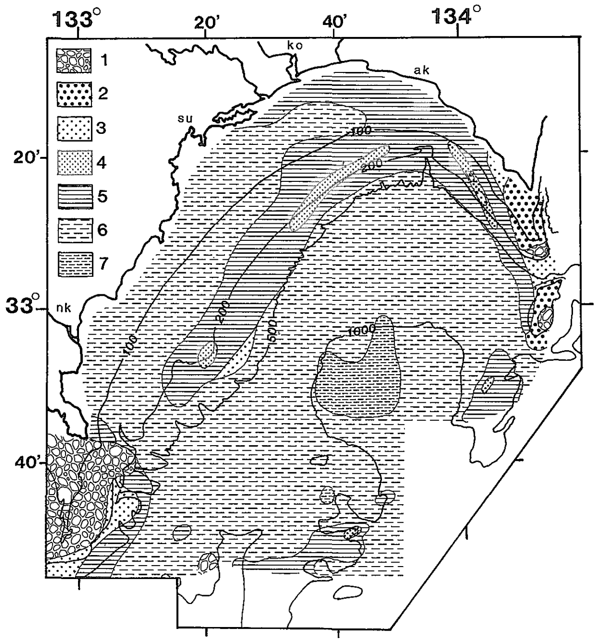


Fig. 9 Median diameter distribution in Tosa Bay (after Ikehara and Okamura, 1985). 1; rocky bottom or gravel, 2; coarse sand, 3; medium sand, 4; fine sand, 5; very fine sand, 6; silt, 7; clay.

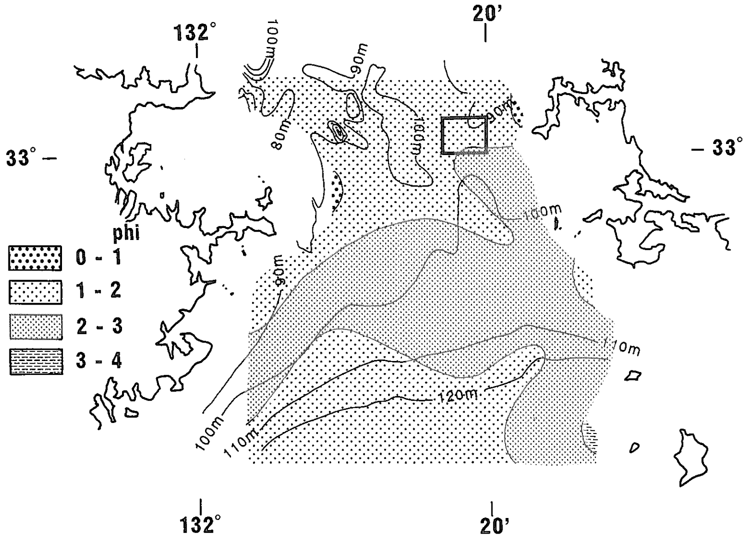


Fig. 10 Median diameter distribution of the south of the Bungo Channel (after Ikehara and Kinoshita, 1989). Box shows the survey area by side-scan sonar.

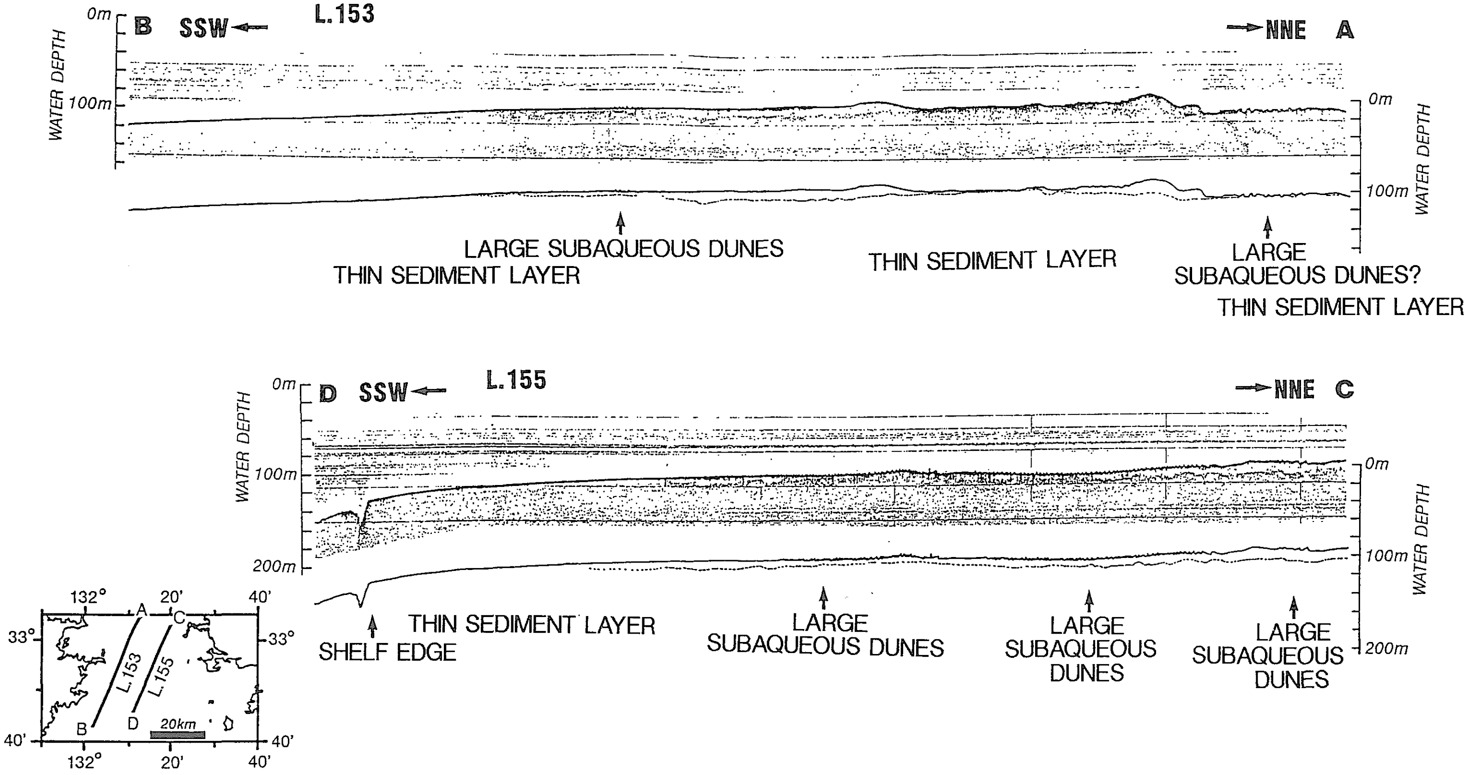


Fig.11 Seismic (3.5kHz) records at the shelf of the south of the Bungo Channel.

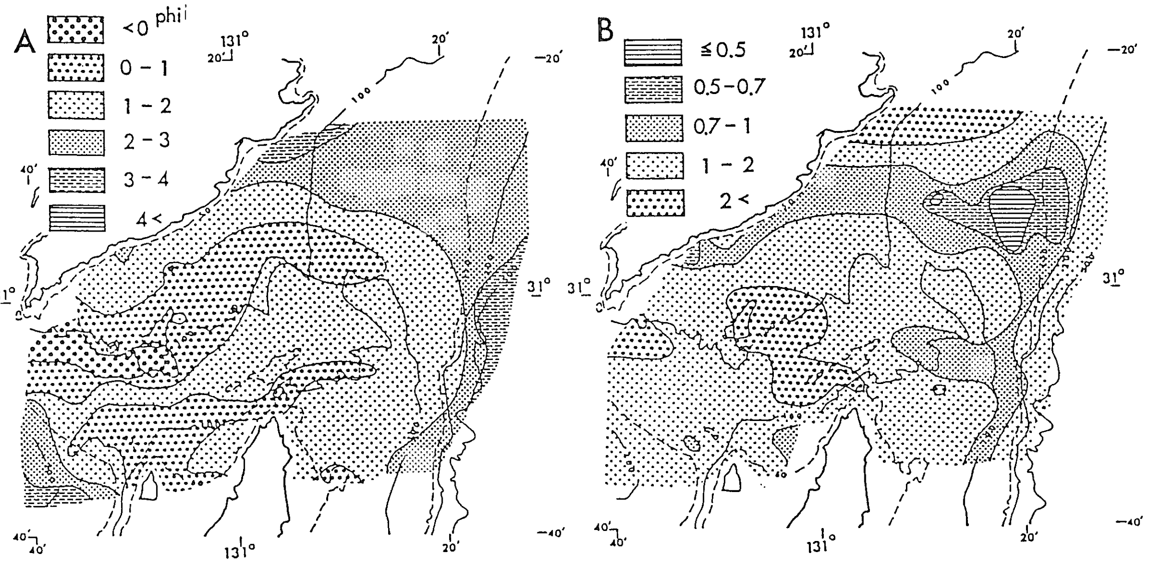
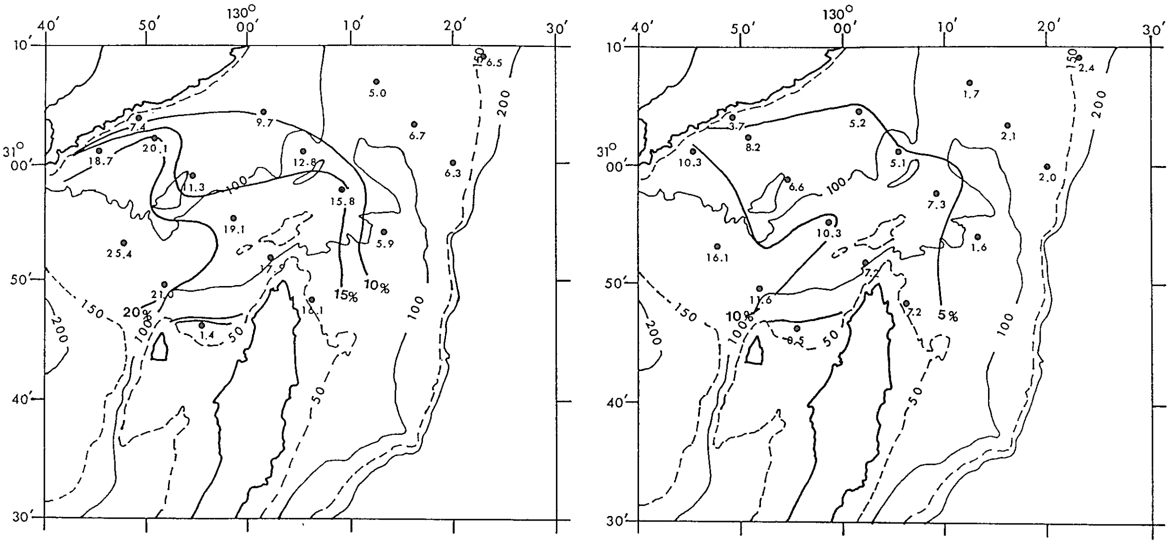


Fig.12 Properties of surface sediments in the Osumi Strait. A; median diameter, B; sorting value (after Ikehara, 1989).



Total Heavy Minerals

Magnetite

Fig.13 Heavy mineral and magnetite contents in the surface sediments of the Osumi Strait (after Ikehara *et al*., 1988a).

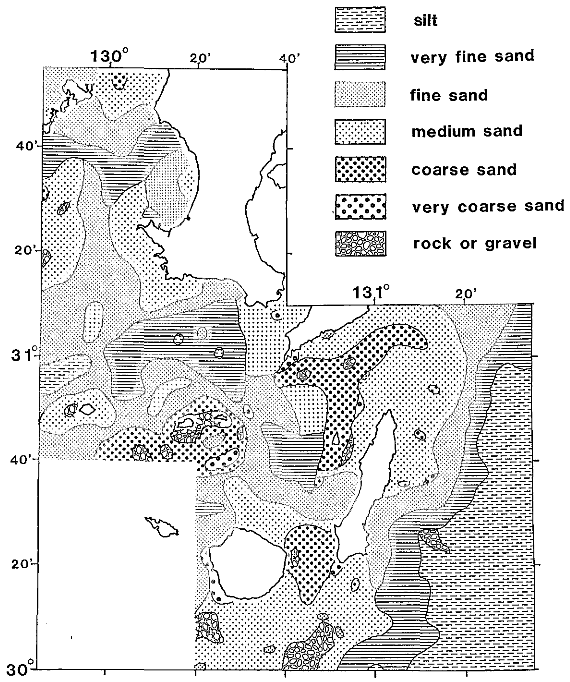


Fig.14 Median diameter distribution at the south of Kyushu (after Ikehara and Kawahata, 1985b)

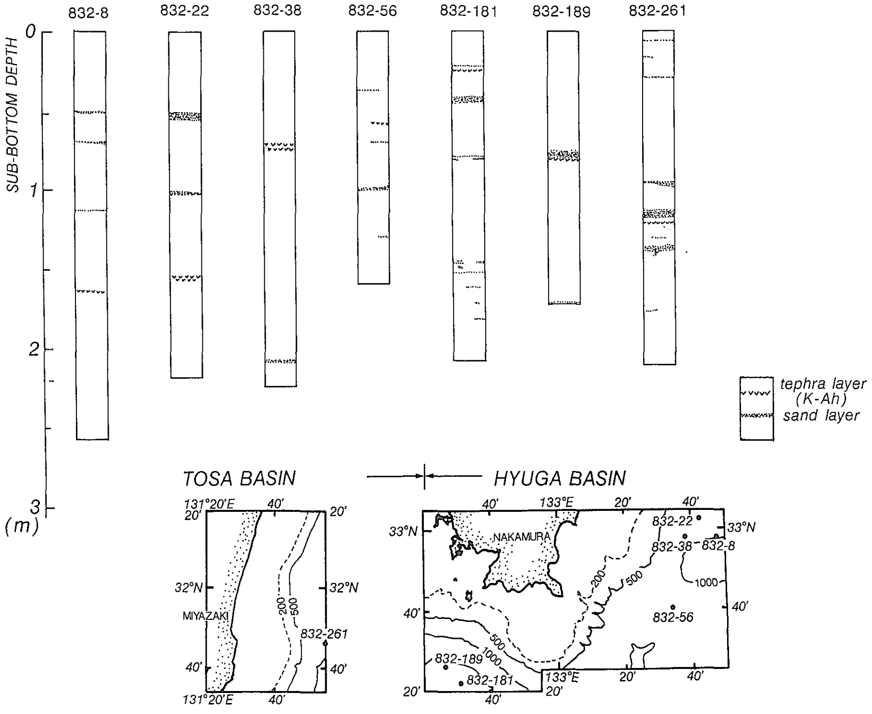


Fig.15 Lithology of the cores collected from forearc basins (Tosa and Hyuga Basins).

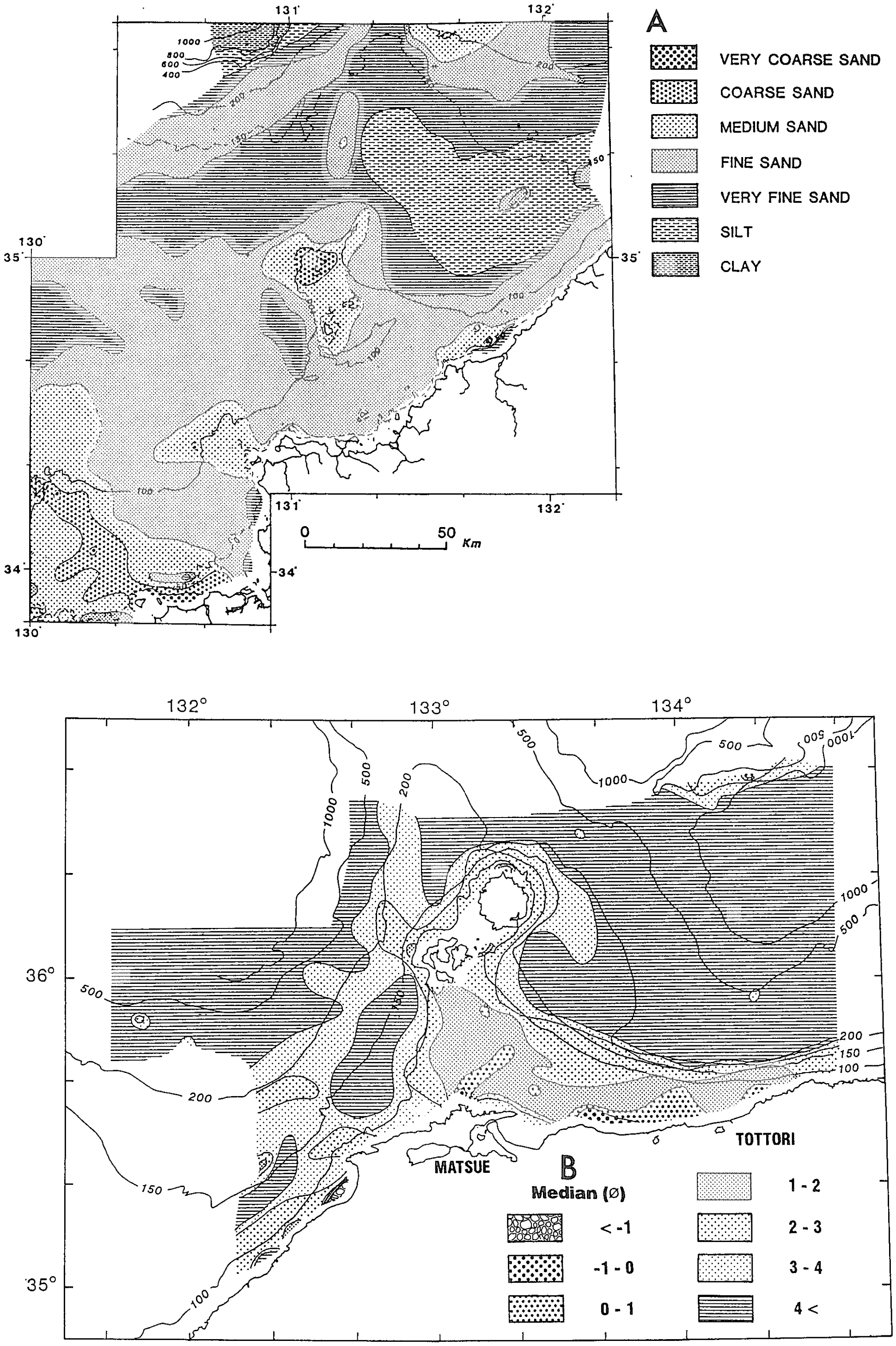


Fig.16 Median diameter distribution in the southern part of Sea of Japan. A; western half (after Ikehara and Kawahata, 1986a), B; eastern half (after Ikehara *et al*., 1987).

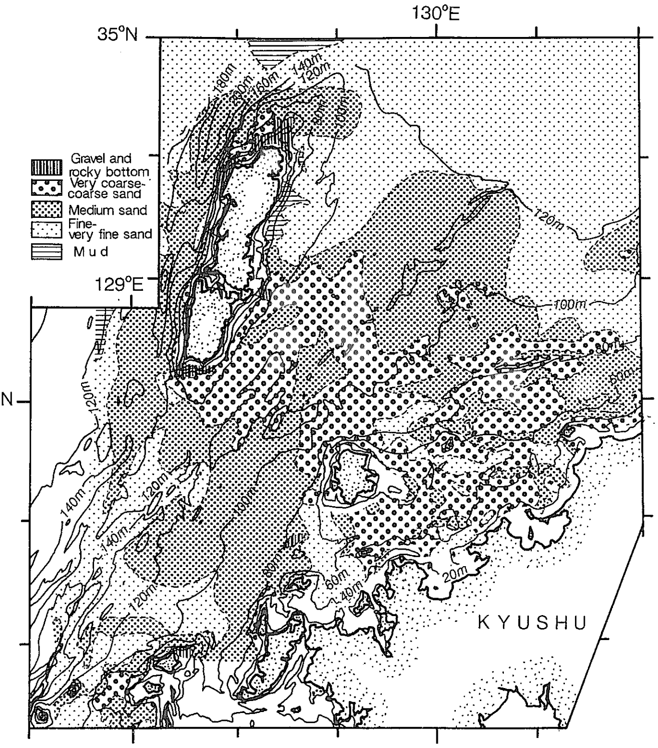


Fig. 17 Sediment distribution in and around the Tsushima Strait (after Ikehara, in press).

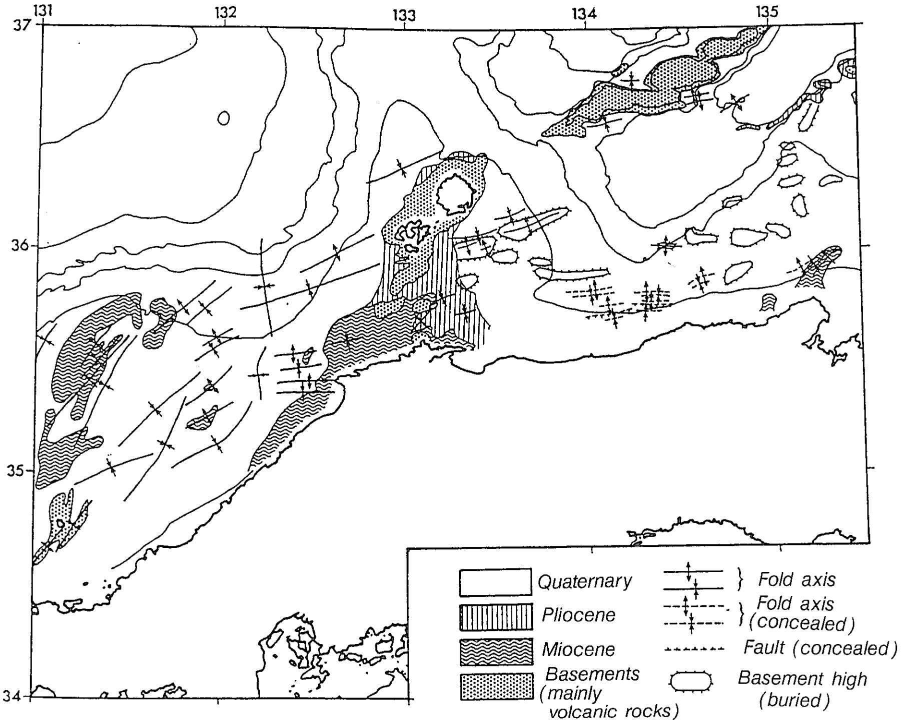


Fig. 18 Submarine geological structures off San'in district (after Tanahashi and Yamamoto, 1990).

In the Oki Strait, coarse sand is distributed. The sediments become finer in grain size eastwards (Ikehara, 1991a, b). Off Tottori, medium sand covers the shelf (Ikehara *et al*., 1990b).

Muddy sediments are widely distributed on the marginal terrace and in the basins or troughs (Fig.16). Off Tottori, the sediments become finer offshore; that is, silt and clayey silt occur on the marginal terrace and silty clay and clay are deposited in the trough (Fig.19). On the other hand, the marginal terrace between Mishima Island and the Oki Islands is partly covered by sandy sediments, and the viscid mud which containing older microfossils of Late Pleistocene age (Tanaka, 1986, 1987), is exposed at the edge of the marginal terrace (Ikehara, in press). As reported by many workers, old elephant fossils assigned to Middle to Late Pleistocene age by fossil assemblage and ^{14}C age determinations (Kamei, 1967; Hosimi and Morioka, 1987; Akiyama *et al*., 1988) were collected from this area (Kamei, 1967; Akagi, 1981; Kamei *et al*., 1986). Rounded pebbles are also obtained just above the viscid mud from this area (Ikehara and Kawahata, 1986a).

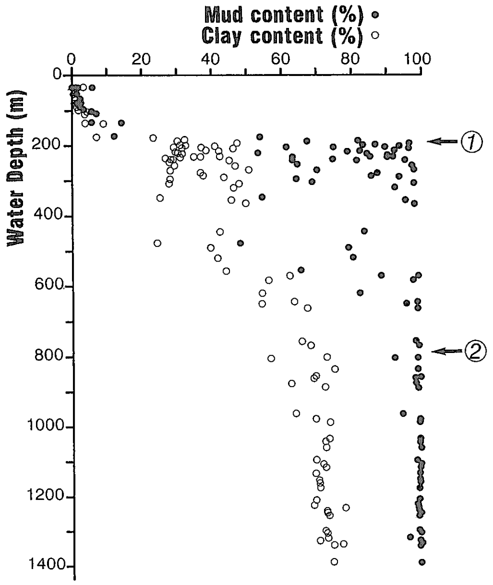


Fig.19 Depth distribution of mud and clay contents off Tottori. Arrows with numbers 1 or 2 show the position of inflection point (after Ikehara, 1991a).

Muddy sediments in the basins or troughs contain 60-70% of clay (Ikehara, 1991a). The sedimentation rates are calculated to be 10-25 cm/1000years during the late Quaternary by using age-known tephra layers (Machida and Arai, 1983; Ikehara *et al*., 1990b, in press; Ikehara, 1991c).

4-2. Bedforms

4-2-1. Bedforms on the Pacific bottom off Southwest Japan

Varieties of bedforms are observed on the sandy bottom of the shelf to the upper part of the upper slope and on the knolls (Fig. 20). These bedforms consists of very large to medium subaqueous dunes, sand ribbons, sand streamers, ripple marks and current lineations. In this study, the nomenclature of transverse bedforms defined by Ashley (1990) is used (Table 1).

Very large subaqueous dunes are those with wavelengths greater than 100m and waveheights more than 5m. Large and medium subaqueous dunes have wavelengths of 10-100m and 5-10m, and waveheights of 0.75-5m and 0.4-0.75m, respectively. Very large subaqueous dunes and some large dunes which have wavelengths more than 30m, are correspondent with sandwaves of McCave (1971) and Ikehara *et al*. (1988b). Smaller large and medium subaqueous dunes are called megaripples by McCave (1971) and Ikehara *et al*. (1988b). Ripple marks are less than 0.6m in wavelength and smaller than 0.06m in waveheight. But in the large subaqueous dune field, bedforms, which are indistinguishable from surrounding dunes in morphology, are counted as large dunes, although they have smaller wavelengths.

Sand streamers and sand ribbons are found on the Muroto Spar (Honza *et al*., 1983) and in the Osumi Strait (Ikehara *et al*., 1988b; Ikehara, 1988a, 1989a). Large

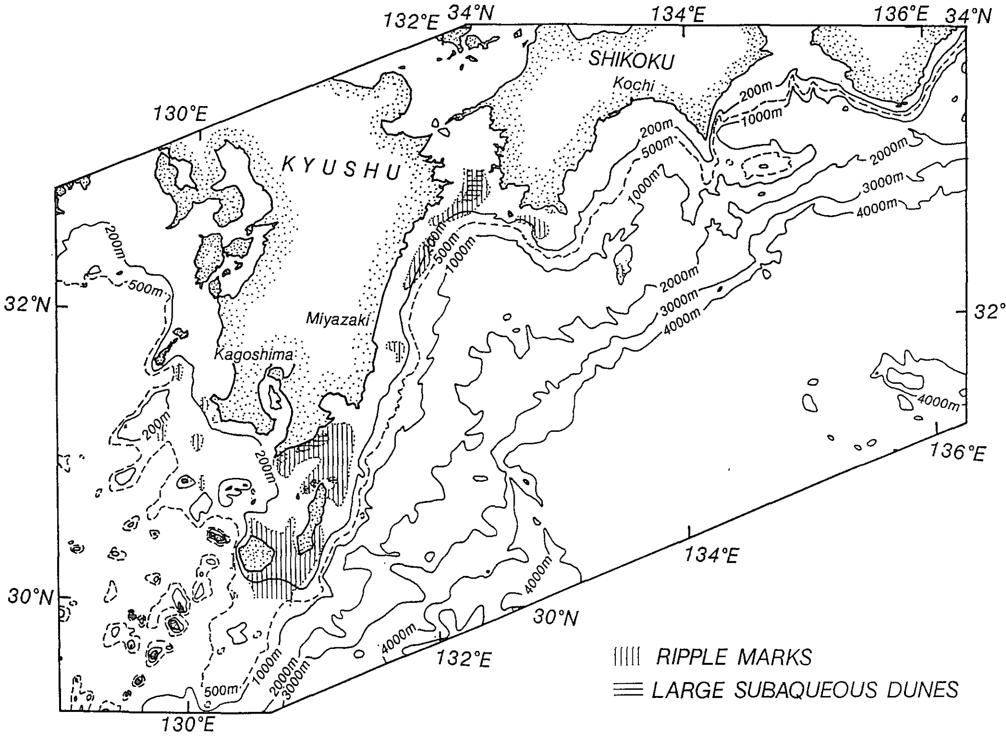


Fig.20 Bedform distribution of the Pacific side off Southwest Japan.

Table 1 Classification of large transverse bedforms (after Ashley, 1990).

SUBAQUEOUS DUNE				
First Order Descriptors (necessary)				
Size: Spacing=	small 0.6-5 m	medium 5-10 m	large 10-100 m	very large >100 m
Height* =	0.075-0.4 m	0.4-0.75 m	0.75-5 m	>5 m
Shape: 2-Dimensional				
3-Dimensional				
Second Order Descriptors (important)				
Superposition: simple or compound (sizes and relative orientation)				
Sediment characteristics (size, sorting)				
Third Order Descriptors (useful)				
Bedform profile (stoss and lee slope lengths and angles)				
Fullbeddedness (fraction of bed covered by bedforms)				
Flow structure (time-velocity characteristics)				
Relative strengths of opposing flows				
Dune behavior-migration history (vertical and horizontal accretion)				

* Height calculated using the equation H=0.0677L0.8098 (Flemming, 1988)

and medium subaqueous dunes are distributed in the Bungo Channel (Mogi, 1977; Inouchi, 1982; Ikehara and Kinoshita, 1989) and in the Osumi Strait (Inouchi, 1981; Ikehara *et al*., 1988b; Ikehara, 1988a, 1989 a). Current (asymmetrical) ripples are observed in the Bungo Channel (Ikehara and Kinoshita, 1989), on the outer shelf off the Hyuga Coast (Honza *et al*., 1984), in the Osumi Strait (Ikehara *et al*., 1988b; Ikehara, 1989a), in the Tanegashima Strait (Ikehara and Kawahata, 1985a), on the outer shelf off the east coast of Tanegashima Island (Ikehara and Kawahata, 1985a), on the lower part of the slope off the south coast of Yakushima Island (Ikehara and Kawahata, 1985a) and on the Ashizuri Knoll (Okamura *et al*., 1986). Wave (symmetrical) ripples occurs only in the Bungo Channel (Ikehara and Kinoshita, 1989). Current lineations, such as obstacle scours and parting lineations, occur in the Osumi Strait (Ikehara *et al*., 1988b) and on the knolls around the Tosa Basin (Ikehara, 1988b).

The bedforms are well-developed in the straits, such as the Osumi Strait and Bungo Channel, where the sea water flows fast enough to move the sandy sediments. In both the straits, the arrangement of bedforms (Fig.21) is essentially same in that, from the upstream to downstream direction, the bedforms change from sand streamers and sand ribbons, through large and medium subaqueous dunes, to ripple marks with decreasing current velocity (Ikehara, 1988 a, 1989a, 1990a; Ikehara and Kinoshita, 1989). At the narrowest part of the straits, erosional scours (cauldrons) are produced by strong currents (Mogi, 1977; Inouchi, 1982, 1990; Ikehara *et al*., 1988b; Ikehara, 1988 a, 1989a; Ikehara and Kinoshita, 1989). This arrangement is almost identical to the tidal arrangement of the bedforms reported by Belderson *et al*. (1982).

4-2-2. Bedforms on the Sea of Japan bottom off Southwest Japan

Bedforms are best developed in and around the Tsushima Strait (Fig.22). Sedimentary sand bodies and large subaqueous dunes are predominantly recognized in this area (Arita, 1976a; Mogi, 1981; Ohshima *et al*., 1982). Large dunes are found only on the sand bodies off Fukuoka. On the Kita-Kyushu shelf, no large subaqueous dune is observed. Ripple marks are observed only at the shelf edge (Ikehara and Kawahata, 1986b; Ikehara, in press), showing the limited occurrence in this area.

Between Mishima Island and the Oki Islands, no obvious records of larger bedforms were available. Only small bottom relief (medium subaqueous dunes?) was observed on the bathymetric records between Mishima Island and Hagi. They were also found in the records obtained by Nihon Telegraph & Telephone CO. (NTT).

In the Oki Strait, large and medium subaqueous dunes and ripple marks were observed (Fig.23; Ikehara, 1991a, b). Vertical profiles of large dunes show asymmetrical forms with steeper slope on the eastern side (Fig.24). The troughs of large dunes are slightly deeper than the surrounding sea floor. Mogi (1973) pointed out that this structure suggests the sea bottom erosion by currents which created the dunes. Some

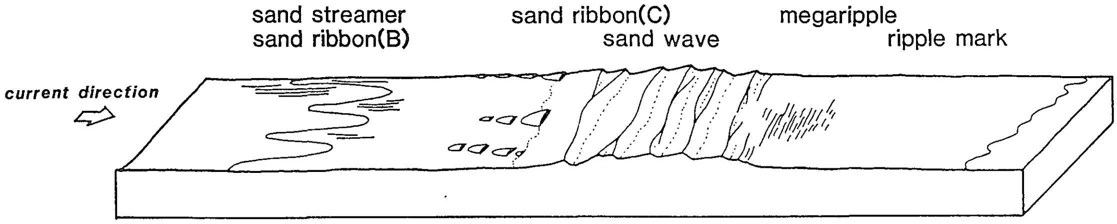


Fig.21 Schematic representation of bedform arrangement.

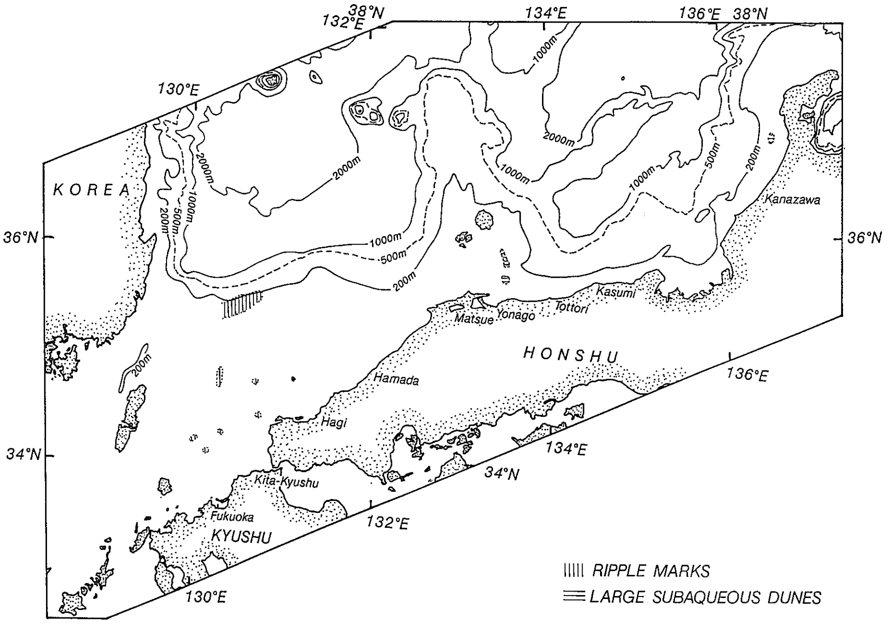


Fig.22 Bedform distribution of the Sea of Japan side off Southwest Japan.

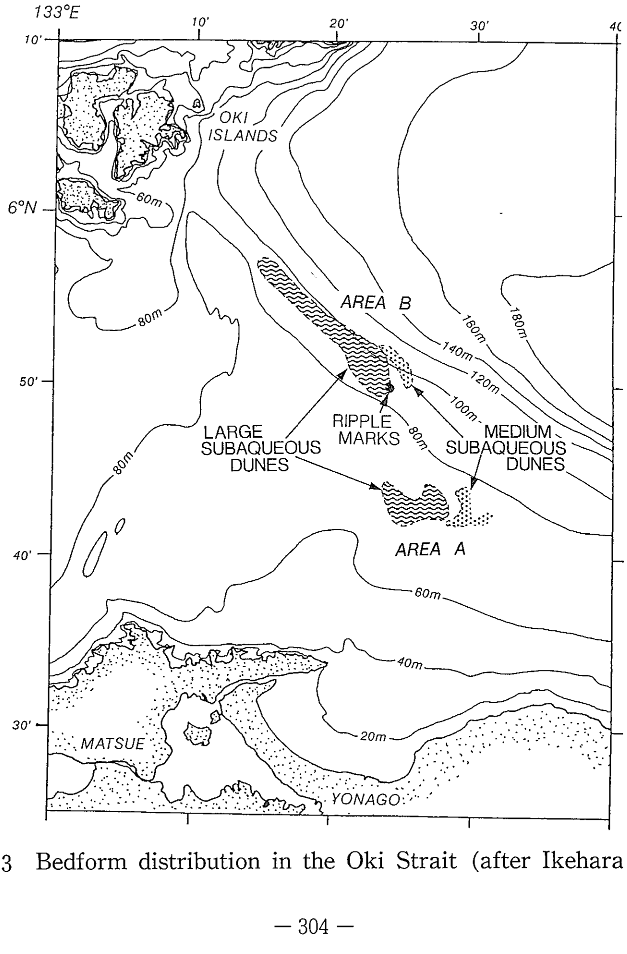


Fig.23 Bedform distribution in the Oki Strait (after Ikehara, 1991b).

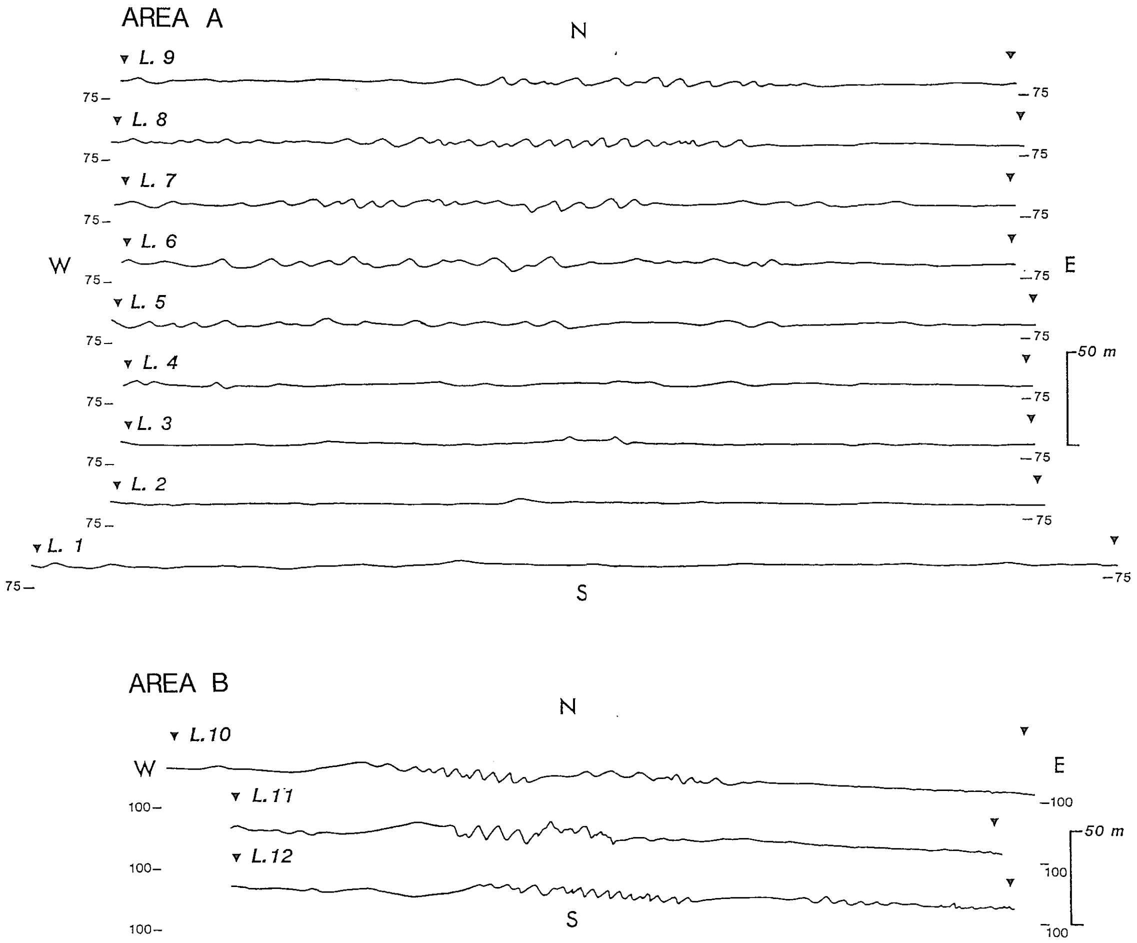


Fig.24 Bathymetric profiles of large subaqueous dune fields in the Oki Strait (after Ikehara, 1991b).

of large dunes have rounded and indistinct crests and others were cut by medium dunes. Medium subaqueous dunes are distributed at the east of large dune field (Fig.23). Some crests of medium dunes are destroyed owing to fishery activities (Fig.25). Ripple marks have straight form in plan and rounded crests and found at only one station in the Strait.

4-3. Acoustic facies

4-3-1. Acoustic facies on the Pacific off Southwest Japan

Blum and Okamura (in press) analyzed acoustic characters of forearc basins off Southwest Japan (Muroto Trough and Tosa Basin). According to them, large parts of the basins show a 2-10m thick, relatively muddy and/or disorganized upper sediment unit overlying a sandier lower unit. This lithologic change was brought about by the Holocene transgression as revealed by dating of cored samples. At present, sandy sediments are limited in their distribution on a narrow coastal area, the fan valley floor in the Tosa Basin, and the proximal fan in the Muroto Trough. The lower unit represents the deposits during the last glacial time. It shows wider distribution of sandy sediments

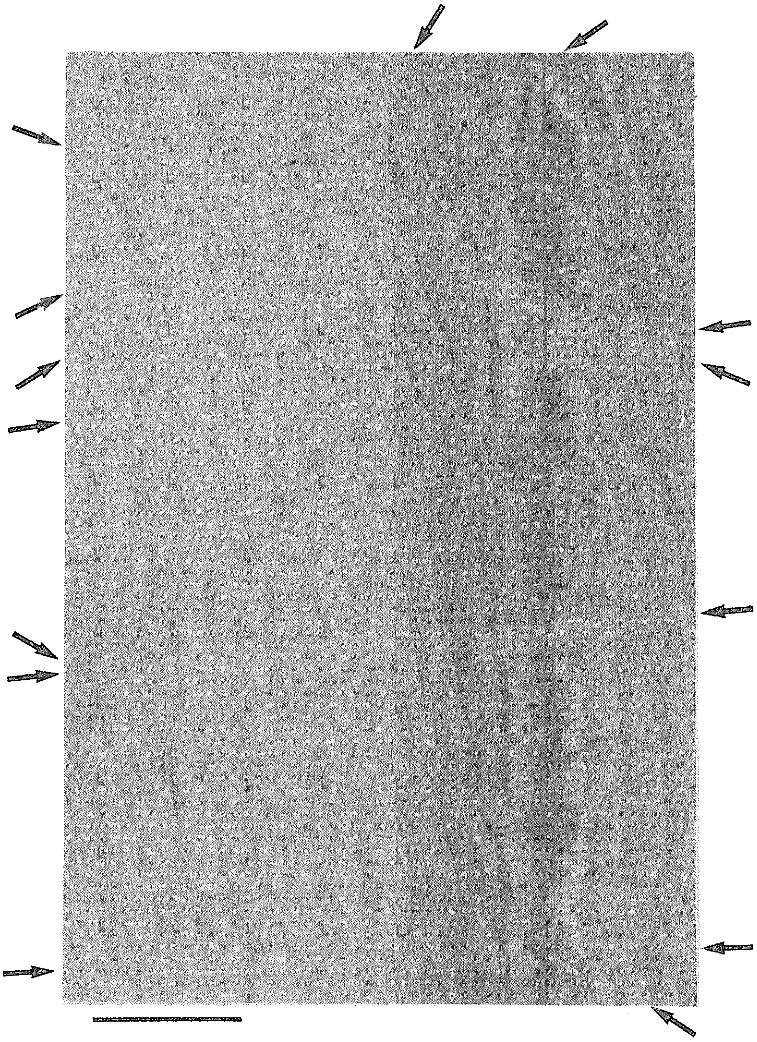


Fig.25 Side-scan sonar record of medium subaqueous dunes in the Oki Strait. Arrows show the lineations made by fishery activities (after Ikehara, 1991b). Top shows north and scale bar is 50m.

as well as larger inputs of coarser particles during the lower sea level. The occurrence of coarser sediments in the deposits of the glacial age is found in the Kumano Trough, another forearc basin (Caddah *et al*., 1991). Lateral facies distribution in the forearc basins is mainly controlled by the presence or absence of canyons, that is, canyon-fan systems are found where the distinct canyon is present, and slope-apron systems are found in the areas of indistinct canyons (Caddah *et al*., 1991; Blum and Okamura, in press). In some areas of the upper slope, erosional gullied-slope canyon systems are recognized (Blum and Okamura, in press).

4-3-2. Acoustic facies on the Sea of Japan off Southwest Japan

3.5kHz sub-bottom profiler records were collected in the southern Sea of Japan. They show poor penetration of sound on the shelf sediments. This means that coarser sediments cover the shelf. The penetration becomes better on the marginal terrace, where muddy sediments are deposited (Fig.26). Small sedimentary basins, the distribution of which is controlled by the basement structure (Ikehara, 1991a), are found on the marginal terrace. The basement is sometimes exposed on the sea bottom and makes banks off Hamada. Surface sediments are thin or absent in the seismic records near the edge of the marginal terrace between the Mishima Island and the Oki Islands (Fig.27). It means that this area is under erosional or non-depositional conditions at present. The escarpments, which have formed in relation to slope failures, are found at the upper part of the slope between the marginal terrace and the basins or troughs (Fig.26). Acoustically chaotic layers as slump or submarine debris-flow deposits (Nardin *et al*., 1979; Damuth, 1980; Chough *et al*., 1985) are well observed at the lower part of the slope (Yamamoto *et al*., 1990; Ikehara *et al*., 1990a, b; Yamamoto, 1991). Also, in the trough, such layers are commonly recognized on the air-gun seismic records (Yamamoto *et al*., 1990). No distinct submarine canyons in the studied slope area are found. Slope and base-of-slope systems (slope failures; line source) are more important for burying processes of the trough and basins than canyon-fan-basin floor systems (point source).

5. Factors controlling surface sediment distribution

The forces which are effected to the sediment movements are waves, tidal and ocean currents (Saito, 1989c) and gravity movements (e.g., slides and gravity currents). On the mid-outer shelf on the Pacific side off Southwest Japan, the ocean currents are predominantly effective to the sea bottom rather than waves and tidal currents (Ikehara, 1988a, 1990b). On the other hand, on the Sea of Japan side, ocean current or surface water circulations (eddies) are influential to the bottom only at selected areas. Sediment distributions are thought to be also effected by Quaternary sea level changes and tectonic movements (e.g., Arita, 1976b, 1982; Kinoshita, 1988). In this chapter, surface sediment distributions will be checked from the viewpoint of the factors mentioned above.

5-1. Oceanographic conditions

5-1-1. Ocean currents

The ocean currents work directly on the sea floor in some areas but indirectly in other areas. In the Kuroshio region, direct effects of the ocean currents to the bottom erosion and/or sediment transportations are recognized in the Tokara Strait, in the Osumi Strait (Ikehara, 1988a, 1989a; Ikehara *et al*., 1988b), on the Ashizuri Spar (Ikehara, 1988b), around the Muroto Spar (Okamura *et al*., 1985), on and around the Ashizuri Knoll (Okamura *et al*., 1986; Ikehara, 1988b), and on the outer ridge south of the Muroto Spar (Okamura *et al.*, 1986). On the other hand, in the Tsushima Current region, these are found at the shelf edge off Kita-Kyushu, in the Oki Strait (Yokota *et al.*, 1990; Ikehara, 1991a, b), on the western Oki Ridge (Ikehara *et al*., 1990b; Ikehara, 1991a, c), and off the east coast of the Oki Islands (Yokota *et al*., 1990; Ikehara, 1991a). Also, sea water movements related to the ocean currents are very effective to modern mud deposition on the western shelf of Tosa Bay (Ikehara, 1985, 1988b) and nearshore areas along the Hyuga coast and the Nichinan coast.

The effects of the ocean currents in each area will be described below.

A) The Pacific Ocean off Southwest Japan

A-a) Northern part of the Tokara Strait

The Kuroshio flows from the East China Sea to the Pacific Ocean through the Tokara Strait (Fig.3; Nitani, 1972a; Japan Oceanographic Data Center, 1979; Kawabe, 1986; Ishii *et al*., 1991; Kaneko *et al*., 1991). On the slope south of Yakushima Island, which is located at the northernmost part of the Tokara Strait, rock exposures and ripple marks are common (Figs. 8 and 20; Ikehara and Kawahata, 1985a, b). Sandy sediments and rocky bottom are distributed throughout the Strait judging from the navigational chart

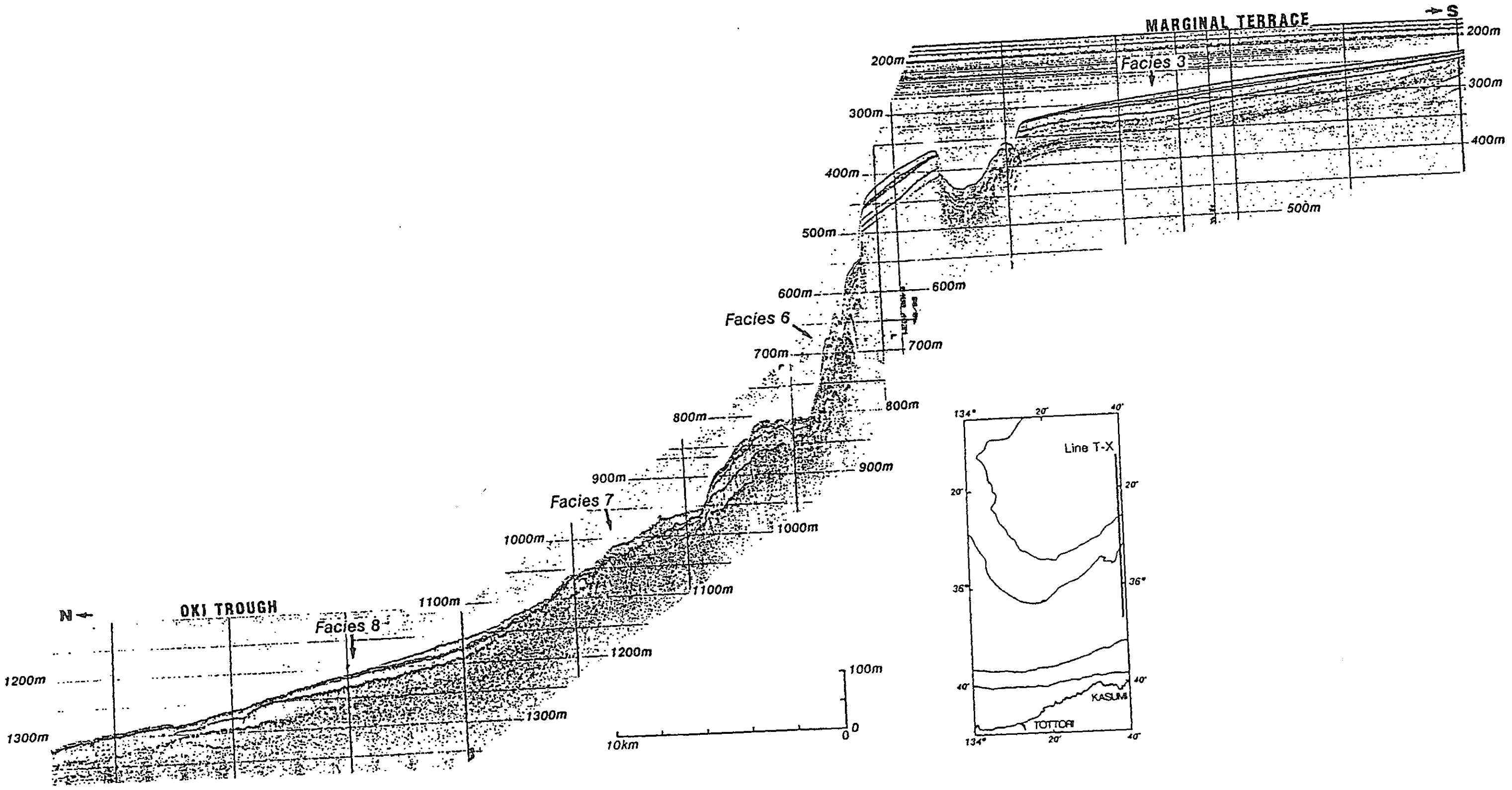


Fig.26 Typical example of 3.5kHz seismic record off Tottori (after Ikehara *et al.*, 1990b).

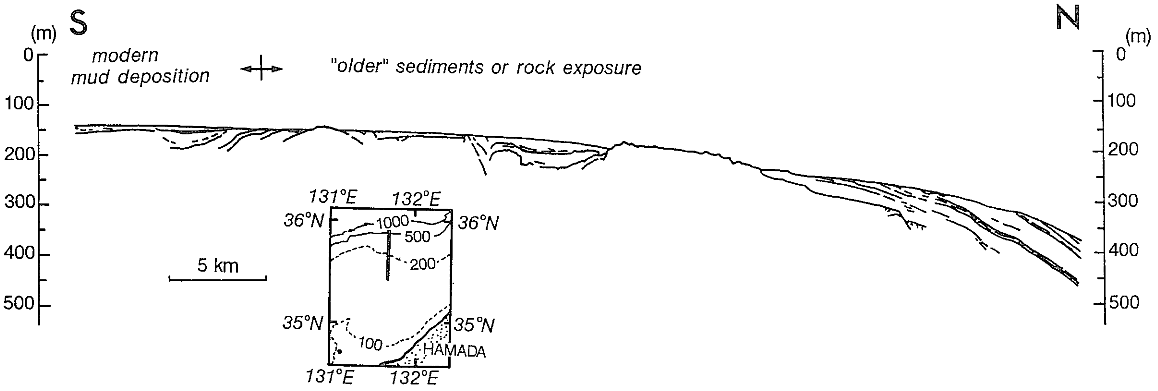


Fig.27 3.5kHz seismic record at the north of Mishima Island (after Ikehara, in press).

descriptions (Fig.28). Heavy mineral (orthopyroxine) concentration in surface sediments occurs southwest of Yakushima Island. The direction of sediment transport inferred from ripple mark morphology is east- to east-northeastwards (Ikehara and Kawahata, 1985a). This direction is harmonious with the downstream direction of the Kuroshio. It is known that the current velocity near the sea bottom at the Tokara Strait is not zero (Ishii *et al.*, 1991; Kaneko *et al.*, 1991). Therefore, bottom erosion, sediment transport and ripple formation is now occurred by the Kuroshio.

A-b) Surrounding area of Tanegashima Island and the Osumi Strait

On the shelf and upper part of the slope, ripple marks are widely developed around Tanegashima and Yakushima Island and in the Osumi Strait (Figs.20 and 29; Ikehara and Kawahata, 1985a; Ikehara, 1988a). These ripple marks are produced by the Kuroshio because the current direction inferred from ripple marks is concordant with that of the Kuroshio.

The current branching from the Kuroshio flows into the Tanegashima Strait between Tanegashima and Yakushima Island. It further flows into the Osumi Strait, judging from distributions of ripple marks and sediment grain size as well as biotite concentration in surface sediments. Recently, Ichikawa (1990) pointed out the importance of this Kuroshio branch in the Osumi Strait. The Osumi Branch Current which is branching from the Tsushima Current off the west coast of the Koshikijima Islands, flows southeastwards into the Osumi Strait (Nitani, 1972a). No record of the Osumi Branch Current has been obtained from the sediments before its entrance to the Osumi Strait. In the Osumi Strait, these two combined currents control sediment transport and deposition (Ikehara *et al.*, 1988a, b; Ikehara, 1988a, 1989a). That is, surface sediments tend to become finer in grain size, better sorted and lighter in specific gravity from southwest to east-northeast. Morphology of bedforms indicates the same direction of bottom currents (Fig.30). The bedforms also show a systematic change in the same direction. It is interpreted that these changes are caused by a downstream decrease in the current velocity. Therefore, sedimentation in the Osumi Strait is controlled by the ocean current related to the Kuroshio (Fig.31).

Inouchi (1981) considered that the surface sediments of the Osumi Strait were transported and attained their present distribution during the maximum Würm stage, when the current velocity was much stronger. Ikehara (1988a), on the other hand, showed that the distribution of both surface sediments and bedforms was controlled by modern ocean current, because the bedform arrangement in

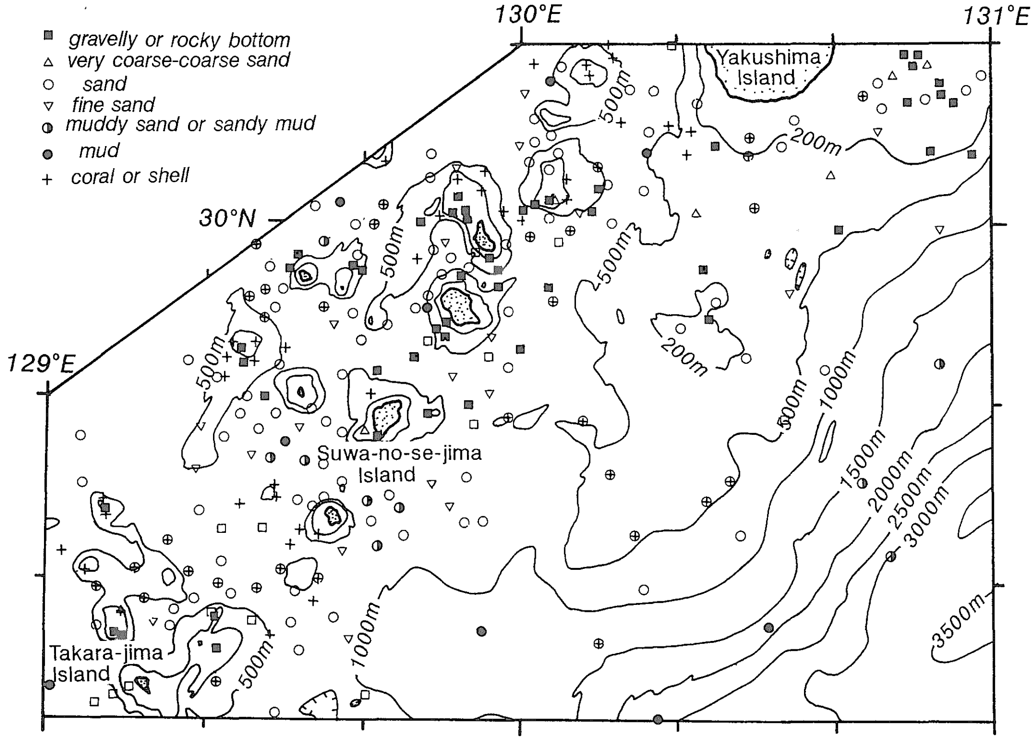


Fig.28 Sediment distribution around the Tokara Strait.

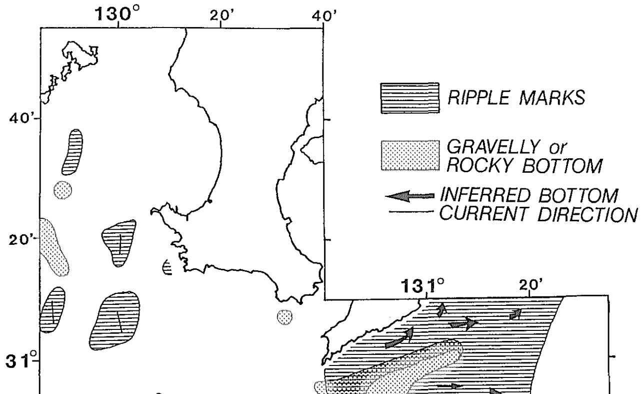


Fig.29 Sea bottom features at the south of Kyushu (after Ikehara and Kawahata, 1985a).

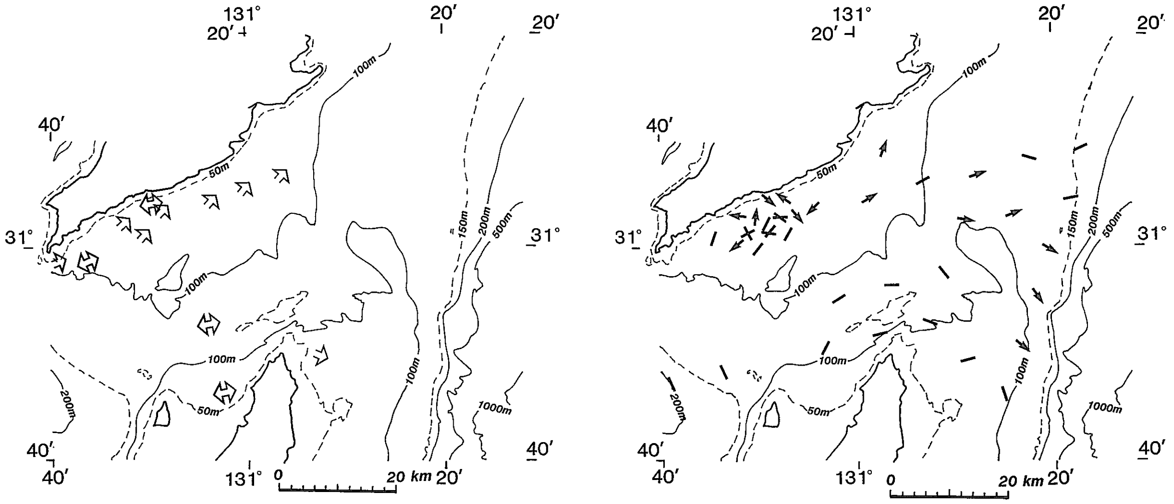


Fig. 30 Direction of sediment transport in the Osumi Strait. A; estimation from sand streamers, sand ribbons and subaqueous dunes, B; estimation from ripple marks (after Ikehara *et al.*, 1988b).

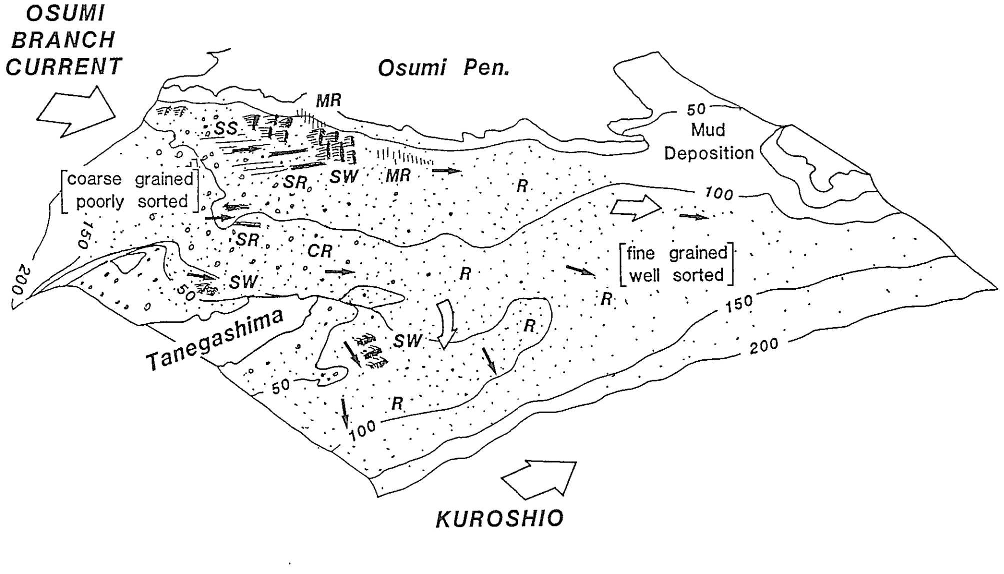


Fig. 31 Schematic representation of sedimentation in the Osumi Strait. SS; sand streamers, SR; sand ribbons, SW; large subaqueous dunes, MR; medium subaqueous dunes, R; ripple marks, CR; small current lineations, solid arrows; sediment transport direction, open arrows; direction of ocean currents (after Ikehara, 1988).

the Strait is the same as that formed by modern tidal currents on the European shelves (Belderson *et al.*, 1982) and sandstreamers which are not resistant to changes in hydraulic conditions (Werner and Newton, 1975) occur in harmony with modern oceanography in the Strait.

Bedforms are primarily controlled by the interaction between hydraulic conditions of the flows such as current velocity and flow depth and sediment properties (Rubin and McCulloch, 1980). The ranges of flow velocity necessary to create bedforms, are inferred from experimental and field observation data (Simons *et al.*, 1965; Southard, 1971, 1975; Rubin and McCulloch, 1980). Depth-mean velocities ($\hat{U}$) are inferred from the bedform and sediment properties of an ancient subaqueous dune field (Allen and Homewood, 1984). Depth-mean velocities are estimated from:

$$\hat{U}=(U_*/k)\ln(h/ez_0)$$

in which U_* is friction velocity, k von Karman's constant, h flow depth and z_0 roughness length. In this calculation, k is 0.4, z_0 is 0.4 mm for flat beds, 6mm for rippled beds and 10mm for duned beds. U_* is calculated from the experimental data for any grain size. In the case of the Osumi Strait, the grain size used for calculation of U_* is 0.35mm (1.5phi) in dune field, because large subaqueous dunes are developed in areas of medium sand. The friction velocity necessary to form ripple marks is 0.016m/sec, according to Miller *et al*. (1977, fig.3); the transition from ripple marks to dunes is 0.037m/sec, based on Vanoni (1974, fig.7), and the transition from dunes to upper-plane bed is 0.059m/sec, according to Allen (1972). The flow depth is unknown in the Osumi Strait; thus, the water depth of the duned field (90m) is used instead of the flow depth. As the results, the depth-mean velocity necessary to form ripple marks is 0.45m/sec, the transition from ripples to dunes is 0.8m/sec, and the transition from dunes to upper-plane bed is 1.20m/sec. Consequently, the depth-mean velocity necessary to produce subaqueous dunes is about 80-120cm/sec.

The relationship between depth and depth-mean velocity is indicated by flume and field observations in San Francisco Bay by Rubin and McCulloch (1980). In the case of medium sand (0.35-0.60mm) and a depth of 90m, the velocity necessary to form ripples is about 0.45m/sec, the transition from ripples to dunes is about 0.80m/sec, and the transition from dunes to upper-plane bed is 1.90m/sec. The former two estimates agree with those from calculation. Although there is a difference of the velocity for the transition from dunes to upper-plane bed, it is inferred that the velocity necessary to produce subaqueous dunes is over 0.80m/sec in the Osumi Strait.

Observations from 1955 to 1974 (Maritime Safety Agency, 1971, 1977) indicated that surface current velocity of over 2 knots (about 1.00m/sec) occurred once every 4 to 5 year, and reached 2 knots about once every 2 year. Although it cannot be said with great accuracy whether there is a difference between the surface current velocity and the depth-mean velocity, it is probable that large subaqueous dunes are activated at the time of strong flow at least once every two or three year. These strong flows may be originated from the Kuroshio fluctuation. On the other hand, under normal conditions, current velocity is about 0.6-1.5 knots (about 0.30-0.75m/sec), so processes forming only ripple marks are active at those times.

A-c) The inner shelf along the coast of Kyushu

Indirect effects of the Kuroshio are well recognized on modern mud deposition. Muddy sediments in Shibushi Bay and near-shore areas off Kyushu are characteristic of the inner side of the water-mass boundaries between the coastal water and the shelf or oceanic water. Muddy sediments occurs where the Osumi Branch Current does not approach the Shibushi Bay (Fig.32). The quiet water conditions are made off the Nichinan coast where finer sediments are distributed, because Cape Toi-Misaki plays as a topographic barrier preventing the in-

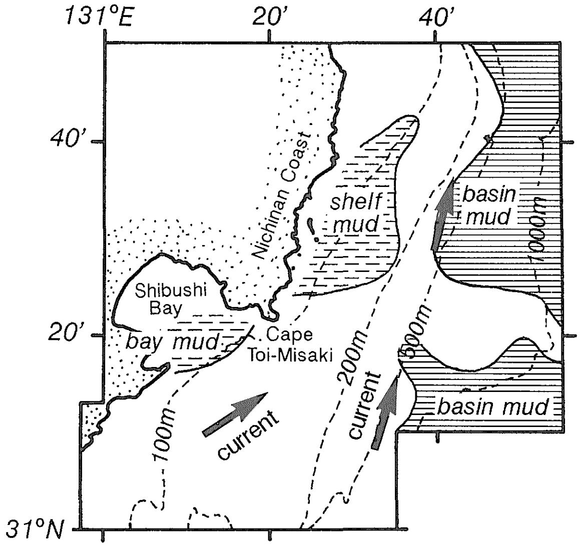


Fig.32 Mud deposition off south Kyushu.

trusion of the Osumi Branch Current from the south, but the Kuroshio itself flows along the shelf edge (Fig.32). In the near-shore area along the Hyuga coast, muddy sediments are deposited. It seems that the combined flow of tidal currents and water circulation caused by the Kuroshio on and near the shelf edge (Yanagi *et al.*, 1986) restricts mud deposition (Fig.33). Therefore, modern mud deposition occurs where the water circulation is weak because of no or little influence of the Kuroshio.

A-d) The outer shelf at the south of the Bungo Channel

The distribution area of sandy sediments and ripple marks tends to become deeper in water depth southwestwards on the outer shelf and the upper part of the upper slope from the south of the Bungo Channel to offshore of the Hyuga coast (Fig.8). In this area, the southwestward bottom current, which is formed in relation to the fluctuation of the Kuroshio path, occurs (Yanagi *et al.*, 1986). The geographical grain-size distribution indicates that the sediments have been transported southwestwards. This is well co-incident with the flow direction of the bottom current. As most of sandy sediments distributed in the Bungo Channel were derived from the narrowest part of the Channel (Hayasui Strait) and from some scour holes by the tidal currents (Inouchi, 1982, 1990; Ikehara, 1990a; Yanagi, 1990a), sandy sediments on the mid-outer shelf, which were initially transported by tidal currents, are removed by the currents closely related to the Kuroshio motions.

A-e) Ashizuri Spar

The Ashizuri Spar has a terrace with water depth around 150m. Very coarse sediments such as very coarse sand and gravels as well as rocky bottoms are occasionally found on the Spar (Fig.8; Ikehara, 1988b). These facts show that the terrace is of erosional origin. Calcareous nannofossils of older age are found in the slope sediments just east of the Spar (Tanaka, personal communications). Because of no other exposures of older sediments in this area, it is thought that eroded materials from the Spar are transported eastwards. This direction is concordant with that of the Kuroshio.

A-f) On and around the Ashizuri Knoll and other sea knolls of the outer ridge

Sediment transport by the Kuroshio on and around the outer ridge is inferred from the occurrence of ripple marks and their movements on the slope of the Ashizuri Knoll (Okamura *et al.*, 1986), the occurrence of current lineations (Ikehara, 1990b) and the

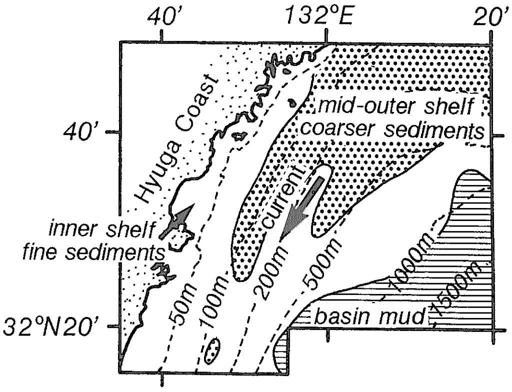


Fig.33 Deposition of fine-grained sediments off Hyuga coast.

distribution of coarser sediments and volcanic glass shards in bottom sediments (Ikehara, 1988b). As the strong upwellings and bottom currents are concordant with the Kuroshio direction (Okamura *et al*., 1986), these sediment distributions and bedforms are considered to be caused by local acceleration of bottom current velocities because of the presence of the topographic highs (topographic effects).

A-g) Western shelf of Tosa Bay

Muddy sediments are widely deposited on the inner to mid-shelf of western Tosa Bay (Fig.9; Ikehara, 1985, 1988b). The boundary between muddy shelf sediments and sandy offshore sediments tends to become deeper in water depth southwestwards and may be coincident with that between the coastal water and the Kuroshio water (Ikehara, 1985, 1988b). There is a possibility that this sediment distribution is caused by tectonic movements. The geological structure of Tosa Bay (Okamura *et al*., 1987), however, is not concordant with the sediment distribution pattern, but it is most probably caused by sedimentological processes (Ikehara, 1988b). Sandy sediments on the outer shelf to the upper part of the upper slope tend to become finer in grain size and indicate the southwestward sediment transport (Ikehara, 1988b). The southwestward flows in western Tosa Bay were observed in the oceanographic measurements (Maritime Safety Agency, 1971, 1977; Miyata *et al*., 1985; Sakamoto *et al*., 1986; Hanaoka *et al*., 1986; Sakamoto, 1987; Fujimoto, 1987) and were estimated from the simulation of the water circulation in Tosa Bay (Awaji *et al*., 1987). Such flow behaviors are closely related to the Kuroshio (Miyata *et al*., 1985; Sakamoto *et al*., 1986; Awaji *et al*., 1987; Sakamoto, 1987; Fujimoto, 1987). Therefore, deposition of muddy sediments takes place where the southwest flows related to the Kuroshio movements are nil or small (Ikehara 1988b).

A-h) On and around the Muroto Spar

Older calcareous nannofossils, which were derived from the outcrops exposed on the western slope of the Muroto Spar, are found in the slope and basin sediments (Okamura *et al*., 1985). Okamura *et al*. (1985) considered that the erosion was exerted by the Kuroshio because the Spar is located just beneath the Kuroshio path. The reworked nannofossil remains tend to decrease in number westwards along the upper slope (Okamura *et al*., 1985), and westward flows are also inferred along the upper slope. This is well concordant with the above mentioned water circulation in Tosa Bay and the sedimentation pattern in western Tosa Bay.

B) The Sea of Japan off Southwest Japan

B-a) In and around the Tsushima Strait

Sediment grain size becomes finer from the central part of the Tsushima Strait northeastwards (Fig.17). For example, in the East Channel, the coarsest sediments (coarse to very coarse sand) are distributed in the central part. The grain size becomes finer northeastwards and the fine to very fine sand is widely distributed around the exit of the East Channel. This northeastward sediment transport is confirmed by the fact that sediment grains become finer with decreasing flow velocity and this trend is in harmony with the direction of sediment transport (Kimura, 1956; Ikehara, 1988a).

The NE-SW trend of submarine linear sand ridges (more than 10m in waveheight), which are arranged in parallel to the current direction (Mogi, 1981) also shows the same direction of sediment transport. Katsura and Nagano (1982) reported the distribution of large subaqueous dunes near the shelf edge of the northwestern Goto Islands, southwest of the Tsushima Strait. Based on their profiles, sediments are transported northeastwards.

It is considered that the area of mud deposition off the east coast of the Tsushima Islands (Fig.17) may be coincident with a hydrographically stacked zone between the northeastward current from the East Channel and the east to east-northeastward current from the West Channel (Ikehara, in press).

Muddy sediments on the northern side of the West Channel are deposited in the area of the Korean Coastal Water. They are derived from Korea.

These sediment and bedform data indicate that the bottom sediments have been affected by the Tsushima Current flowing northeast to east-northeastward in and around the Tsushima Strait.

B-b) On the shelf edge of the north of City of Kita-Kyushu

Well-sorted sandy sediments with low mud content and ripple marks are found along the shelf edge off Kita-Kyushu at water depths of around 120-200m (Fig.34). According to Ikehara (in press), this fact indicates the existence of bottom currents capable of transporting sandy sediments and preventing mud deposition. Surface sediments become finer in grain size, greater in mud content and more poorly sorted northeastwards. This is the direction of decreasing in current velocity as well as that of sediment transport. Plan morphologies of ripple marks show relatively complicated flow patterns dominated by eastward to northeastward flow, that is almost parallel to the direction of shelf edge and also to that of the second branch of the Tsushima Current (Naganuma, 1972; Kawabe, 1986).

The current velocity near the bottom can be inferred from sedimentological data. As ripple marks are forming and subaqueous dunes are not found on the fine sand bed at the shelf edge off Kita-Kyushu, it is estimated that the current velocity necessary to form ripple marks is about 0.25m/sec and the transition from ripples to dunes is about 0.70m/sec at 1m above the sea bottom, according to Rubin and McCulloch (1980, fig. 8). Therefore, it is inferred that the bottom currents have the velocity between 0.25-0.70 m/sec at 1m above the sea bottom.

B-c) On and around the edge of the marginal terrace north of Hamada

At the edge of the marginal terrace between Mishima Island and the Oki Islands, semiconsolidated muddy sediments are exposed at water depths around 200-500m (Fig.35; Ikehara, in press). They are sometimes covered by thin very fine sand with rounded granules. Older and reworked foraminiferal species are found in the very fine sand (Oda and Ikehara, 1987; Nomura and Ikehara, 1987). Calcareous nannofossil assemblages in semiconsolidated mud are different from those in modern mud deposited on both the inner marginal terrace and the outer basin. They contain cold-water species and reworked older fossils indicating the Cretaceous age (Tanaka, 1986, 1987). Pollen fossils in a semiconsolidated mud collected at Station 862-63 (location shown in Fig. 35) with a water depth of 311m indicate a colder climate (glacial period). That is, it has a high percentage of subarctic flora containing Haploxyon-type Pinus with five needled leaves and a low percentage of temperate broad-leaved trees (Table 2). In this area, uplifting and exposure of older basement is met with in the sub-bottom profiler records (Fig.27), and rocky bottoms are observed north of Mishima Island. In addition, teeth of older elephants (*Palaeoloxodon naumanni* Makiyama), indicating the Pleistocene age (about 30000-40000 years B.P.; Hosimi and Morioka, 1987; Akiyama *et al.*, 1988), have been collected from this area (Kamei, 1967; Akagi, 1981; Kamei *et al.*, 1986). These facts show that the sedimentation rate in this area is very small. The occurrence of current lineations found on the sea bottom around the rocky area, indicates the presence of bottom current (Ikehara, in press). Therefore, it is considered that this area is now under non-depositional or erosional condition by the effects of bottom currents.

As this area is just beneath the second branch of the Tsushima Current, non-deposition or erosion is caused by the influence of the second branch of the Current. However, the second branch is not a permanent flow but is present only in the summer time (Kawabe, 1982). Therefore, bottom currents here are difficult to transport sandy sediments and to prevent mud deposition throughout the

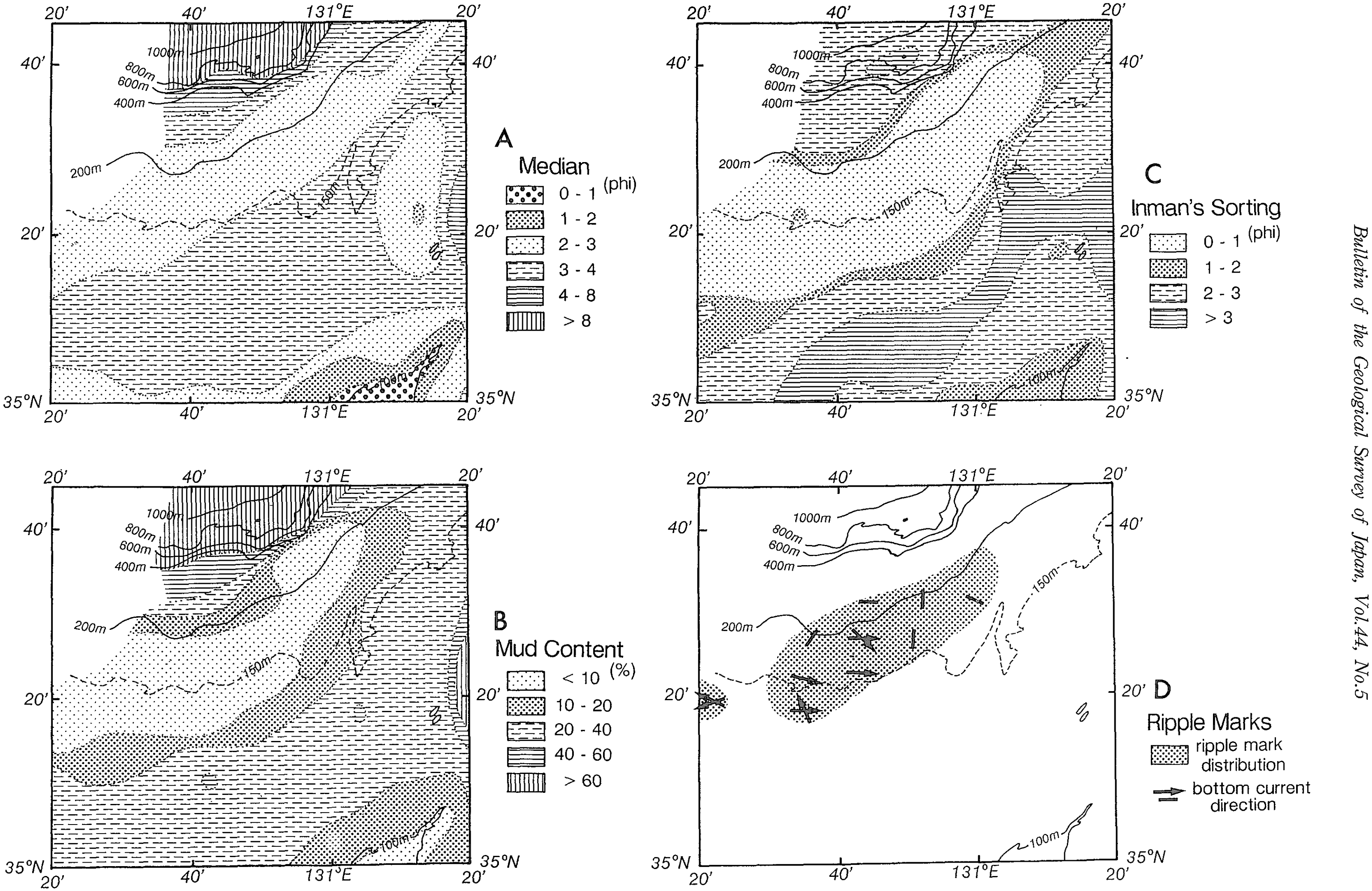


Fig.34 Sediment properties and ripple marks at the shelf edge of the north of Kita-Kyushu (after Ikehara, in press).

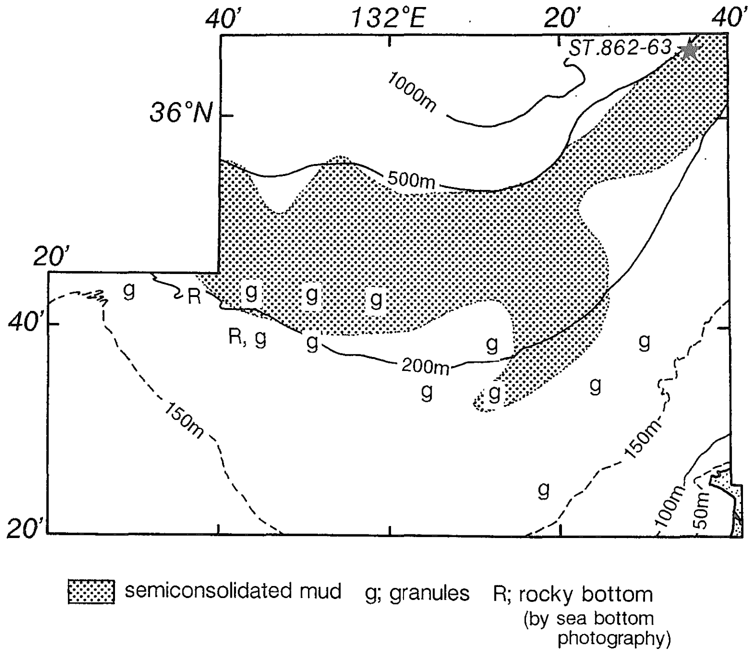


Fig.35 Distribution of semiconsolidated mud off Hamada (after Ikehara, in press).

Table 2 Composition of pollen and spores contained in the semiconsolidated mud at station 862-63 (after Ikehara, in press).

Arboreal Pollen (AP)			Nonareboreal Pollen (NAP)		
Taxa	Counts	Percentage	Taxa	Counts	Percentage
Picea	18	5.6	Typha	2	0.6
Abies	38	11.9	Umbelliferae	2	0.6
Pinus	72	22.6	Chenopodiaceae	2	0.6
Tsuga	67	21.0	Rosaceae	1	0.3
Cryptomeria	1	0.3	Caryophyllaceae	2	0.6
Larix	1	0.3	Artemisia	11	3.4
Cupressaceae	1	0.3	Liliaceae	1	0.3
Fagus	1	0.3	Poligonium	1	0.3
Carpinus	5	1.6	Carduoideae	1	0.3
Castanea	1	0.3	Cyperaceae	2	0.6
Quercus	31	9.7	Gramineae	4	1.3
Celtis	1	0.3	Lycopodiaceae	2	0.6
Betula	13	4.1	Tricolporate	5	1.6
Alnus	10	3.1	Trilete type	1	0.3
Carya	2	0.6	Monolete type	20	6.3
AP Total	262	82.1	NAP Total	57	17.9

year. Another possibility to make bottom currents is the surface water circulations (eddies) (Fig.4; Naganuma, 1972) formed among the branches of the Tsushima Current. Although there are no data to decide the initial force inducing the bottom currents at present, the Tsushima Current itself or the current-induced water circulation may make the bottom current and control modern sedimentation (Ikehara, in press).

B-d) In the Oki Strait and on the shelf off Tottori

Large subaqueous dunes produced by the eastward flows (Fig.24; Ikehara, 1991a, b) are found in the Oki Strait. The sediments become finer in grain size eastwards (Fig. 16; Ikehara, 1991a). The sediment provinces inferred from heavy mineral compositions in the Oki Strait are same as those on the mid-outer shelf off Tottori and different from those on the inner shelf (Fig.36; Yokota *et al.*, 1990). Therefore, it seems that the sediments have been transported eastwards (Yokota *et al.*, 1990; Ikehara, 1991a, b). The inferred direction of sediment transport is concordant with the current direction in the Oki Strait (Japan Oceanographic Data Center, 1979) which is in parallel with the flowing direction of the first branch of the Tsushima Current (Naganuma, 1972; Kawabe, 1986). Because of no evidence for westward sediment transport in the Strait, these bedforms were formed by unidirectional flows such as ocean currents rather than bidirectional tidal currents.

The present current velocity observed in the Strait (Minami *et al.*, 1984), however, is only about 0.6-0.8knots and is insufficient to move the sandy sediments. The bedforms in the Oki Strait lack the rippled sand sheet (Ikehara, 1991a, b), as compared with those formed under modern oceanographic conditions in European (Belderson *et al.*, 1982) and Japanese shelves (Osumi Strait; Ikehara, 1988 a). This means that the currents are not strong enough to form any bedform at present. However, older bedforms abundantly found in the Oki Strait were produced by stronger currents than present during a period of sea-level rise after the last glacial maximum. According to the submarine topographic analysis by Ohshima (1990), the Oki Islands were separated from the Honshu at the sea level 60 m below the present. As active large dunes are observed at water depths of 10-40m on the European tidal shelves (Berné *et al.*, 1989; van Alphen and Damoiseaux, 1989) and large dunes are found at water depths of 70-100m in the Oki Strait, these bedforms are considered to have been formed at the sea level about 30-60m below the present (Ikehara, 1991 b).

B-e) On the marginal terrace east of the Oki Islands

Coarse sediments are spread southeast on the marginal terrace off the Oki Islands (Fig. 16; Ikehara *et al.*, 1990b; Ikehara, 1991a). High concentration of biotite in the surface sediments (Fig.36; Yokota *et al.*, 1990) and

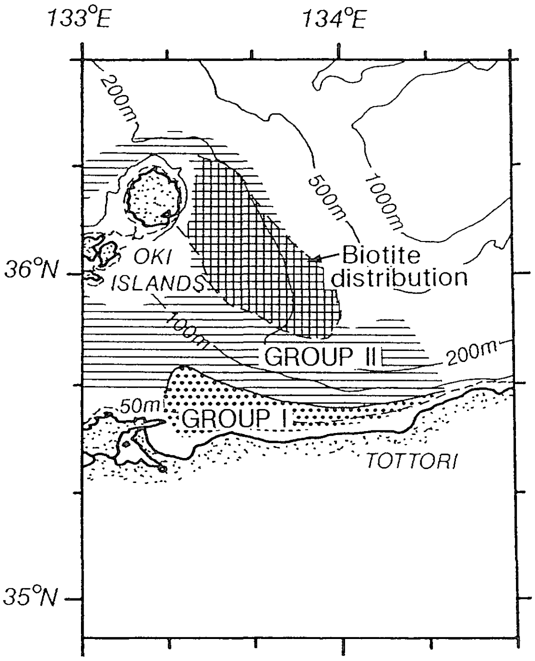


Fig.36 Province of heavy mineral and biotite distribution of surface sediments off Tottori (modified from Yokota *et al.*, 1990). Group I; hypersthene, oxyhornblende, brown hornblende, and Group II; green hornblende, clinopyroxene, olivine.

turbid bottom water zone (Ikehara *et al.*, 1990b) is also found there. These facts mean that the sediments have been transported southeastwards. Because higher temperature of bottom water which is similar in water properties to the surface water (the Tsushima Current Water) rather than the JSPW is recognized in the same place (Ikehara and Katayama, 1987), surface water circulations may affect sedimentation in this area.

B-f) On the western Oki Ridge

Sedimentation rate on the flat of the western Oki Ridge is estimated to be very low, judging from the sub-bottom depth (18 cm just beneath the sea bottom) of Aira-Tn Ash (21000-22000 years B.P.; Machida and Arai, 1976 or 24500 years B.P., Matsumoto *et al.*, 1987) at Station 862-196 (Fig.37; Ikehara *et al.*, 1990b; Ikehara, 1991a, c). On the marginal terrace which has almost the same water depth and in the Oki Trough just near the station, Aira-Tn Ash is intercalated in muddy sediments at the sub-bottom depth of about 200cm (Machida, 1988; Ikehara *et al.*, 1990b; Ikehara, 1991c). This means that some actions to prevent mud deposition are working on the Ridge. The surface sediments containing bubble-wall type volcanic glass shards are distributed on the western Oki Ridge to the Oki Trough (Ikehara *et al.*, 1990 b; Ikehara, 1991a, c). The trend of glass distribution is as same as off the east coast of the Oki Islands. Therefore, the sea bottom is influenced by the surface water circulations which are induced by the Tsushima Current motions at the water depth around 500m. As the Tsushima Current has flowed into the Sea of Japan since 8000-10000 years B.P. (Oba, 1987; Oba *et al.*, 1991), it is thought that the sea bottom was eroded to a considerable extent immediately after the inflow.

5-1-2. Wave actions

The wave actions are one of the important factors to the shelf sedimentation (e.g. Saito, 1989c). In the nearshore areas both on the Pacific and the Sea of Japan shelves, the wave actions give influences to the sea bottom (Ikehara, 1988b, 1991b).

At the central part of Tosa Bay, well-sorted fine sand occurs at the nearshore off Kochi (Fig.9; Ikehara, 1988b). In this area, high concentration of suspended particles makes turbid bottom water as observed by sea-bottom photography. This probably means that present wave actions are strong enough to remove the bottom sediments in this area. Using offshore wave data measured off Kochi (Sugawara *et al.*, 1986) and the equation to calculate the critical depth for sand to move in the wave direction (Sato *et al.*, 1963), the depth beyond which fine sand is unable to be moved by the fairweather wave, is estimated to be less than 7m and that by the storm wave is to be 40-90m. It supports that present wave actions are able to agitate sandy sediments in this area. As on the inner shelf off Miyazaki, the similar critical depth is calculated to be less than 7m and 50-100m, respectively, and well-sorted very fine sand occurs at this depth, the wave actions are also influential to the bottom sediments here.

On the Sea of Japan shelf, the wave effects are reported from the nearshore off Tottori (Ikehara *et al.*, 1990b; Ikehara, 1991 a). Coastal sediments off Tottori, which consist of well to moderately sorted sandy sediments (medium to coarse sand) or moderately to poorly sorted gravelly sand with a little amount of mud (Ikehara *et al.*, 1990b) are distributed in zones shallower than 50-60m depth (Ikehara, 1991a). Off Tottori, well-sorted medium sand with a little amount of mud occurs (Fig.16). According to offshore wave data at Tottori (Sugawara *et al.*, 1986) and the above-mentioned equation, the critical depth of the fairweather wave base is inferred to be less than 8m, and that of the storm wave base is to be 40-50m. The water depth of the storm wave base is almost the same as that of coastal sediments. It is thought that gravelly or rocky bottom recognized in the coastal area off Daisen Volcano and offshore areas between Tottori and Kasumi (Fig.16), is formed by wave erosion, consider ing the critical depth data for bedrock abrasion showing the maximum water depth

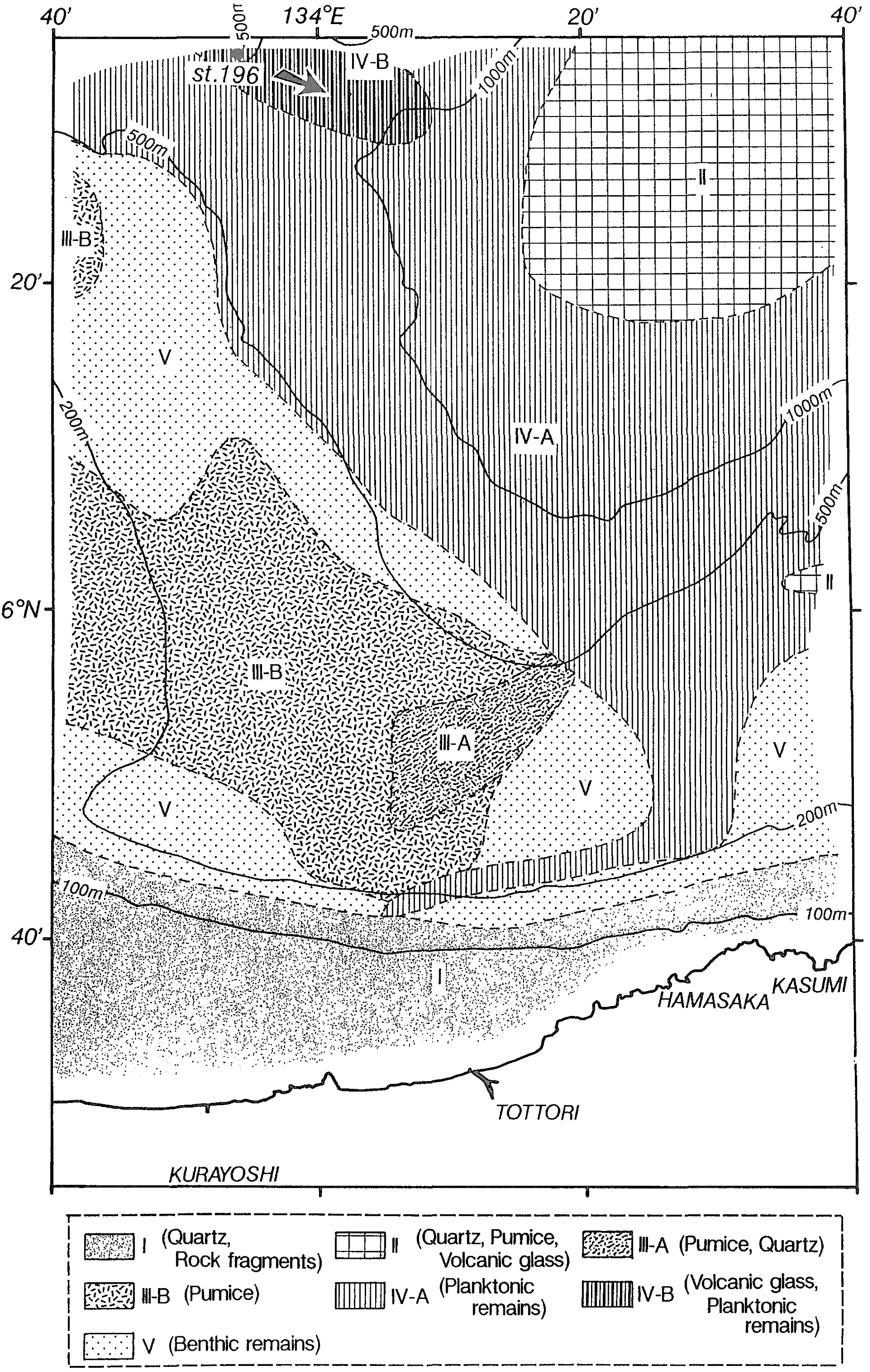


Fig.37 Province of coarse fraction of surface sediments off Tottori (after Ikehara, 1991c).

beyond which no abrasion can take place (40m near Niijima Island: Sunamura, 1986; 50m near Iceland: Sunamura, 1990). Therefore, it is considered that the coastal sediments off Tottori is effected at present by wave actions.

The critical water depths as inferred above in the study area are almost the same as in Sendai Bay (50-60m; Saito, 1989a; Saito *et al.*, 1989), Akita Bay (50-70m; Saito, 1989 d), and near Niijima Island (40m; Sunamura, 1986). The coincidence of critical depths suggests that present storm waves are influenced to the nearshore bottom as deep as around 50 m throughout the Japanese Islands.

5-1-3. Tidal currents

Tidal effects to the sea bottom are recognized in the Bungo Channel. Tidally controlled sediment movements and bedform formation have been reported by many workers (Mogi, 1977; Inouchi, 1982, 1990; Ikehara *et al.*, 1988c; Ikehara and Kinoshita, 1989; Yanagi, 1990a). That is, the oceanographic data in the Bungo Channel and morphological changes of bedforms (Ikehara and Kinoshita, 1989) indicate that the sediment transport is controlled by the tidal currents (Fig. 38). These currents eroded the sea bottom and have produced erosional scours at the narrowest part (Hayasui Strait) and around the promontories or islands (Inouchi, 1982, 1990; Ikehara, 1990a) where tidal currents are locally accelerated by the topographic effects. Sand grains produced by the sea bottom erosion are transported either southwards or northwards reflecting change of dominant flow directions and are deposited as current velocity decreases. Sedimentary sand bodies and large subaqueous dunes are formed where medium sand is deposited, and tidal currents are distorted and formed eddies due to the bottom relief of erosional scours (Ikehara, 1990a). In the southern Bungo Channel, medium sand is distributed in the north and fine sand occurs in the southern part. It means that sandy sediments are transported tidally southwards.

Bedform migrations are associated with sediment transport (Harms *et al.*, 1975; Reineck and Singh, 1980). If sandy sediments in the Bungo Channel are moved the bedforms and their morphology would change accordingly. The dominant factors determining the nature of these changes would be the degree and direction of sediment transport, which are influenced by the velocity and direction of tidal currents. Because the velocity necessary to produce larger bedforms is greater than that of smaller ones (Simons *et al.*, 1965; Rubin and McCulloch, 1980), all these bedforms could be moved and their morphology is changed in areas where the tidal currents are strong enough to reform the largest bedform. On the other hand, if the tidal currents are not strong, it is possible that only some bedforms will be moved by the current. Therefore, bedforms, which are smaller and easily formed by low velocity currents, would be sensitive to velocity and direction of currents.

In the southern Bungo Channel, only two smaller bedforms have undergone morphological changes over three years. Profiles of the ripple marks have changed in accordance with changes in direction of tidal currents (ebb-flood change) (Table 3). Medium subaqueous dunes also changed their plan patterns during a three-year period (Fig.39), demonstrating that they moved during at least a few years. On the other hand, large subaqueous dunes did not change their plan morphology nor their distribution in three years (Fig.40). The spacing and branching patterns of dunes' crest lines are coincident with the records obtained in these two cases. This means that large dunes have not moved laterally during this time span. Water depth in the dune field was almost same in both the cases. This means that upward-growth of dunes was none or very low. Therefore, the activity of large subaqueous dunes in the southern Bungo Channel may be nil or very low during the period of the order of a few years, under present conditions.

Mogi (1981) pointed out that ancient tidal effects to the sediments were clearly shown in the Tsushima Strait by finding of linear sand

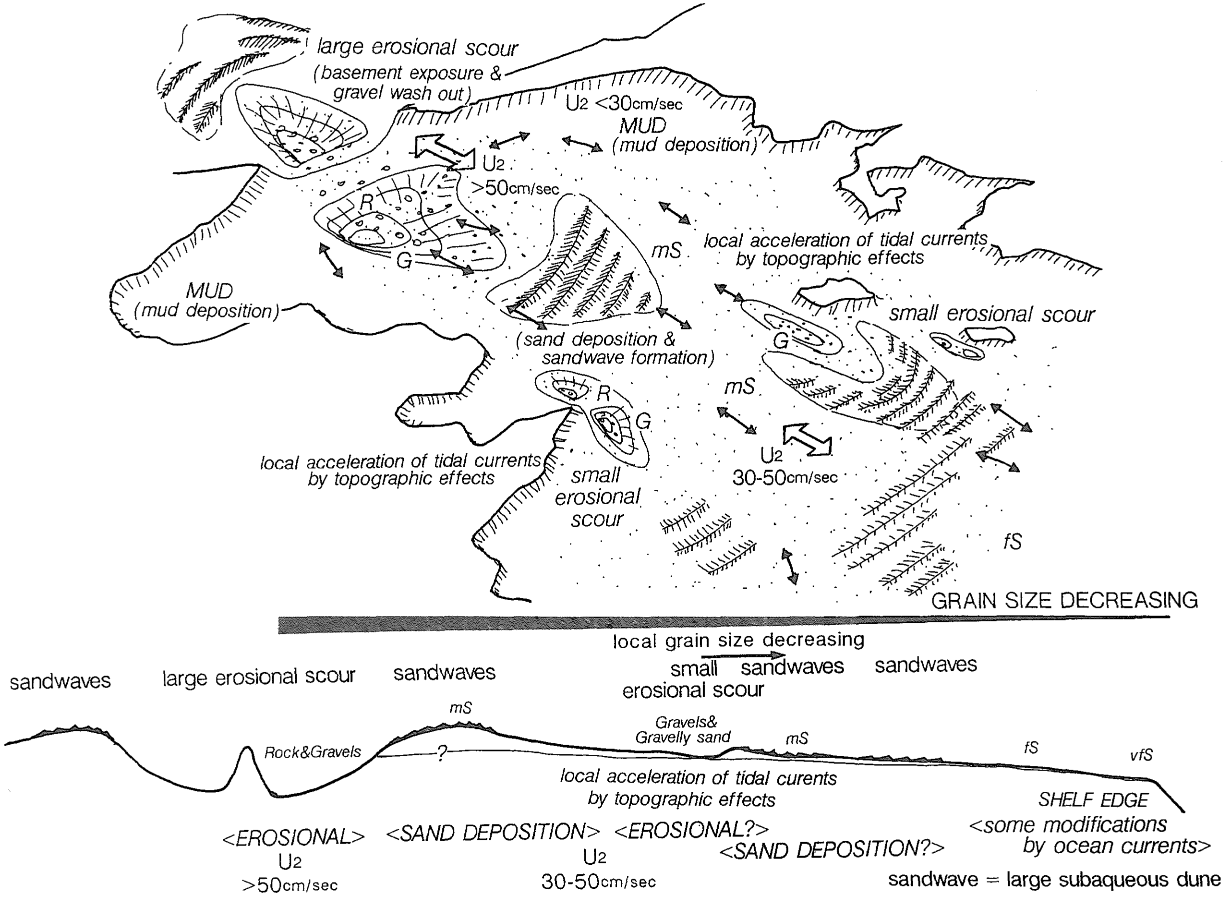


Fig.38 Schematic diagram of sedimentation in the Bungo Channel.

Table 3 Direction of sediment transport inferred from ripple mark morphology (after Ikehara and Kinoshita, 1989).

STATION NO.	POSITION		DATE	TIME	OCCURRENCE OF RIPPLES	DIRECTION OF SEDIMENT TRANSPORT	DIRECTION OF TIDAL CURRENT
	LAT. (N)	LON. (E)					
392	33-00.1	132-20.1	23, JULY	12:09	○	S	S
393	33-01.5	132-20.2	1983	12:31	○	S	S
394	33-03.0	132-20.1		12:51	×	—	S
395	33-02.3	132-19.1		13:15	×	—	S
396	33-00.8	132-19.0		13:33	○	S	S
397	33-00.0	132-18.2		13:57	○	S	S
398	33-00.9	132-17.5		14:17	○	N	slack
399	33-00.0	132-16.5		14:34	○	N	N
400	33-01.6	132-16.5		14:54	○	N	N
401	33-03.0	132-16.5		15:11	○	N or S(symmetrical)	N
402	33-03.2	132-18.4		15:32	×	—	N
403	33-01.6	132-18.4		15:54	×	—	N

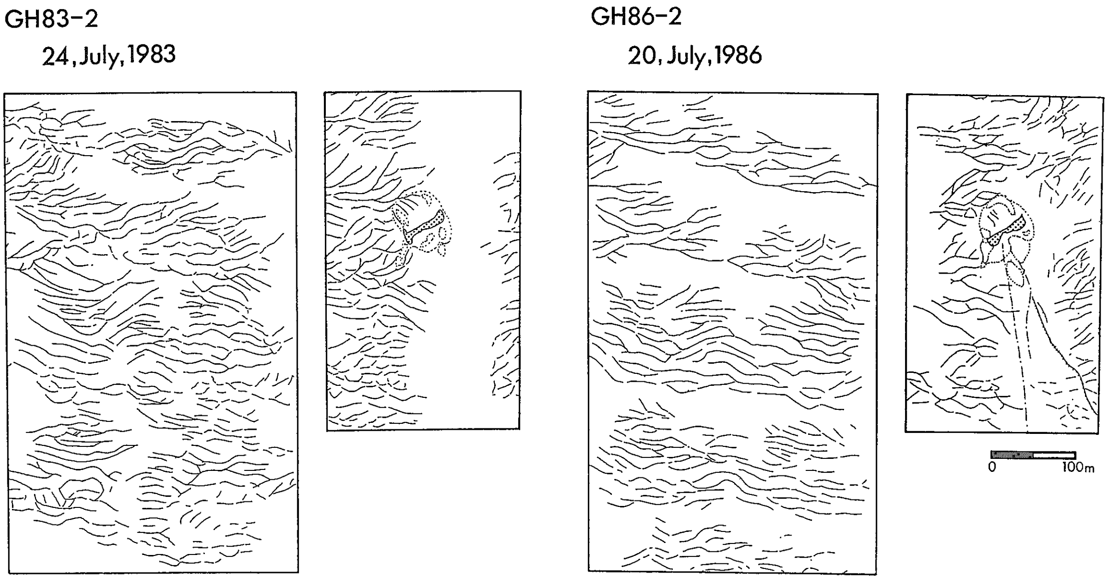


Fig. 39 Morphological change of medium subaqueous dunes in the southern Bungo Channel (after Ikehara and Kinoshita, 1989).

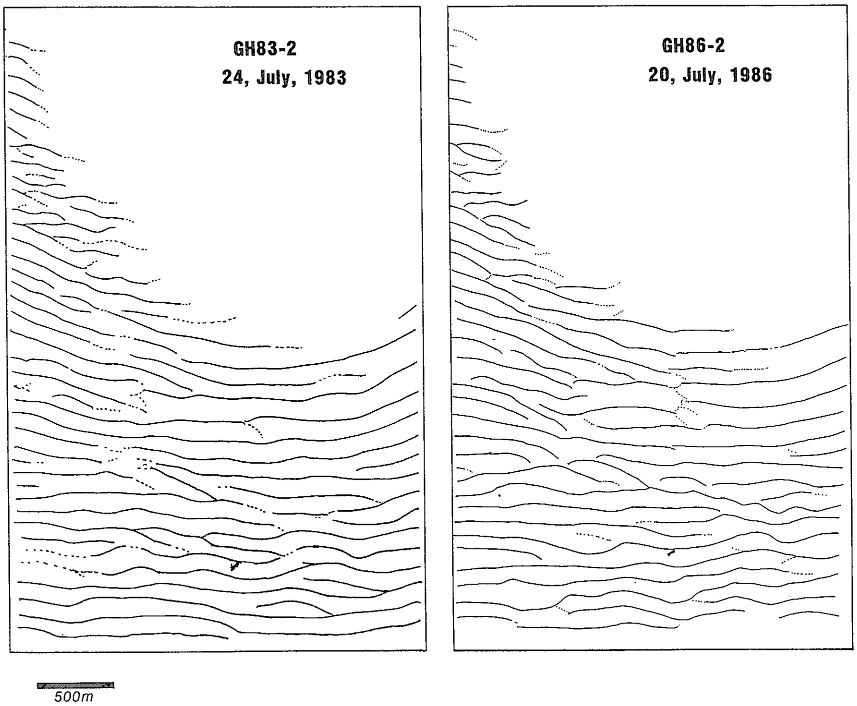


Fig.40 Morphological change of large subaqueous dunes in the southern Bungo Channel.

ridges. These structures, showing current-parallel directions, were formed during the lower sea level stage, judging from the relationship between the wavelength and water depth of active ridges under present conditions. As mentioned earlier, because sediment distribution on a large scale shows northwestward transport of sediments, the ocean currents are thought to be dominant in the Strait. However, as the tidal currents also superimpose the ocean currents, there is a possibility that tidal currents are much more important in a part of the Strait.

5-2. Other conditions

5-2-1. Sea-level changes

Many submarine terraces are found on the shelves. These terraces are considered to have been formed at some stages during the transgression after the last glacial maximum (e.g. Sato and Mogi, 1982; Ohshima *et al.*, 1982). As the nearshore sandy sediments could be deposited on each terrace, the water depth may have controlled surface sediment distribution. For example, at the north of Kyushu coast, depth-controlled sediment distribution is well recognized (Fig.17). This means that surface sediments have not been transported enough to rearrange their distribution by any forces in this area. On the other hand, in the straits such as the Tsushima Strait, where surface sediments, which are considered to be relict sediments as mentioned later, have been transported and rearranged by the currents, the distribution of surface sediments is controlled by current velocity rather than water depth.

Quaternary sea-level fluctuation is strongly related to the formation of sedimentary sand bodies on the shelves. Most of sand bodies, superimposing subaqueous dunes, were formed during the transgression after the last glacial maximum. The formation of sand bodies in the coastal and shallow marine environments is controlled by sufficient supply of sand, by the force to trans port and rearrange sandy sediments, and by the presence of the space to accommodate sand bodies. Because the inflow of oceanic water to marginal seas and the location of current path are controlled by the sea-level changes, these changes in the marginal seas would be influential to sedimentation in the straits around the Japanese Islands.

For example, in the Osumi Strait, the duned sand bodies occur on the submarine terrace of 80-100m deep, which was formed during a stage of sea-level rising after the last glacial time (Ikehara, 1992). Because present bedforms in the Strait (Ikehara, 1988a, 1989 a) show no or little growth of sand bodies, they had been formed before the formation of present oceanographic conditions. Paleoceanography in the East China Sea at the last glacial maximum indicates the coastal water development along the "paleoshoreline" (Fig.41). This means the absence of not only the Tsushima Current but also the Osumi Branch Current, which is branched from the Tsushima Current off the west coast of Kyushu. As the Tsushima Current has flowed into the sea area off the west coast of Kyushu (Oyama, 1985; Tanimura, 1985) and into the Sea of Japan (Oba, 1987) since 8000-10000 years B.P., the Osumi Branch Current has also flowed into the Osumi Strait since this time. Sandy sediments deposited in the coastal areas during the glacial time and shaped by bottom erosion, have been transported and rearranged by the current. Owing to low activity of larger bedforms in the Osumi Strait as mentioned earlier, the duned sand bodies had been formed during the transgression after the last glacial maximum (Ikehara, 1992).

Also in the Bungo Channel, the duned sand bodies are thought to have been formed during the transgression. Large subaqueous dunes in the Bungo Channel maintained their morphology over the period of three years (Ikehara and Kinoshita, 1989). Therefore, sand bodies superimposed on large dunes did not grow under present conditions. They occur on the terrace at a depth around 90m (Fig. 11).

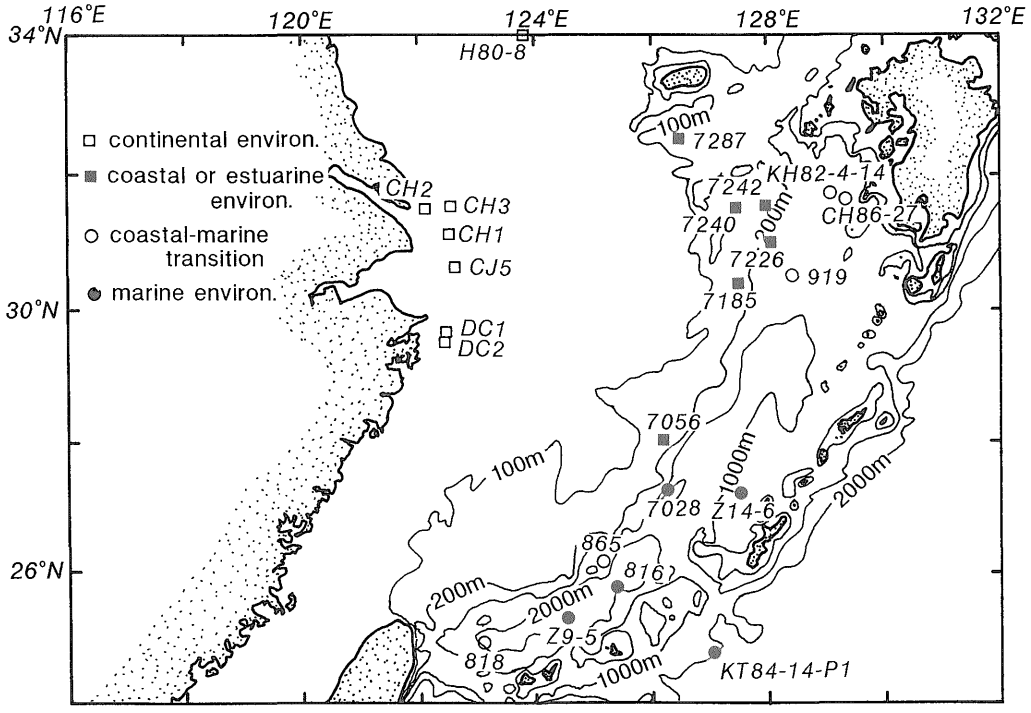


Fig.41 Paleooceanographic conditions in the East China Sea at the last glacial maximum (after Ikehara, 1992).

Stacked prograding wedges recognizable on the seismic records at the upper slope south of the Channel are located the subsidence area during the Quaternary (Okamura, 1989, 1990). The fact indicates that the terrace was formed during the last glacial time. Tidal prism defined as an exchange volume of water through a channel is controlled by tidal range and surface area of the bay (Shigemura, 1980). The throat area of the Hayasui Strait did not change so largely that tidal currents through the Strait became faster with sea level rising. Therefore, tidally generated bedforms and sand bodies were formed subsequent to the inflow of sea water into the Suonada Sea. Some data on seismic records (Anma *et al*., 1992) indicate that the duned sand body around the Oobatake Strait, Yamaguchi Prefecture, was built up on the Pleistocene muddy sediments. These data indicate that sand bodies were formed during the transgression following the last glacial maximum.

This is the case for bedforms on other shelves around the Japanese Islands (Table 4), judging from repeated bedform observations, bedform arrangement, and modern physical oceanographic conditions, and seismic profiles of sand bodies.

5-2-2. Tectonic movements

Depth distribution of surface sediments may be influenced by tectonic movements (Arita, 1982; Kinoshita, 1988). If sediments were originally distributed in parallel to the depth contours, tectonic movements (tilting) can make a contour-oblique distribution of sediments. In this case, the distribution must become deeper toward the tilting direction. Though the contour-oblique distribution is found on the western shelf of Tosa Bay, tectonic movements judged from seismic records (Okamura *et al*., 1986) are not concordant with the trend of sediment distribution. Therefore, tectonic influence for surface sediment distribution is not clear around Southwest Japan.

In spite of that, tectonic movements have formed the sedimentary basins in which modern muddy sediments are deposited. On the marginal terrace off the Tottori area, for example, small sedimentary basins are recognized from the sub-bottom profiler records (Ikehara, 1991a; Katayama *et al*., 1993; Fig. 42). In general, each sediment layer found in seismic records (Fig.43) becomes thicker offshorewards reflecting the northward tilting (Yamamoto *et al*., 1990). The sediment layers, which are deposited from homogeneously suspended water mass, become thicker with increasing water depth (Inouchi, 1988). In this area, however, tectonic movements probably construct basinward thickened sedimentary layers. This is inferred from the fact that the thickness distributions of each sedimentary layer are more concordant with the geological structures such as depths of the acoustic basement (Yamamoto *et al*., 1990) and with isopack of Tottori-oki Group (late Pleistocene-Quaternary in age; Yamamoto, 1992) rather than the water depth. It is interesting to point out that all the sedimentary units deposited after the Miocene are thicken offshorewards (Yamamoto *et al*., 1990) and the thickness of sedimentary layers seems to be controlled by tectonic movements since the Miocene (Yamamoto *et al*., 1990). In the present environments, most of terrigenous materials, especially coarser particles than silt are trapped in basins on the marginal terrace and only clay is transported to deeper troughs.

Seismic records obtained from the Oki Trough show another effect of tectonic movements for the sedimentation. The occurrence of slope failures between the marginal terrace and the trough is inferred from a remarkable development of acoustically chaotic layers (Yamamoto *et al*., 1990; Ikehara *et al*., 1990a, b; Yamamoto, 1991). These chaotic layers suggest submarine debris flow deposits (Nardin *et al*., 1979; Damuth, 1980; Chough *et al*., 1985; Katayama *et al*., 1988; Ikehara *et al*., 1990a; Ikehara and Katayama, 1992). The triggering mechanism of these slope failures is considered to be differential tectonic movements between the acoustic basements (ridges) and basin areas (Yamamoto *et al*.,

Table 4 Occurrence and modern activity of bedforms around the Japanese Islands. Water depth in meter. SS; sand streamer, SR; sand ribbon, LSD; large subaqueous dune, MSD; medium subaqueous dune, R; ripple mark.

Area	Water Depth	Bedforms	Sand Body	Main Force	Modern Activity
Shelf edge of the East China Sea	140-170	MSD	N	ocean (+storm) current	MSD?
Osumi Strait	70-100	SS,SR,LSD,MSD,R	Y	ocean current	LSD
Hayasaki Channel (Ariake Sea)	40- 50	LSD,MSD	Y	tidal current	LSD
NW of Goto-Islands	120-155	LSD	Y?	ocean current	?
Goto-nada Sea	60- 70	LSD,MSD,R	Y	tidal current?	MSD?
Tsushima Strait	100-120	LSD,MSD	Y	ocean (+tidal) current	?
Bungo Channel	70- 90	LSD,MSD,R	Y	tidal current	MSD
Kanmon Channel	8- 20	LSD	Y	tidal current	LSD
Bisan-seto Channel	40- 50	LSD,R	Y	tidal current	LSD
Akashi Channel	20- 30	LSD	Y	tidal current	LSD
Oki Strait	60-100	LSD,MSD,(R)	N	ocean current	R?
W of Noto Peninsula	50	LSD,MSD,R	Y	storm current?	MSD?
Off Udo Hill (Suruga Bay)	10- 30	MSD,R	N	storm current	MSD
NE of Hachinohe	40-100	LSD,MSD	N?	ocean current? & storm current?	?
Tsugaru Strait	60	LSD,MSD,R	Y	ocean (+tidal) current	LSD?

SS;sand streamer, SR;sand ribbon, LSD;large subaqueous dune, MSD;medium subaqueous dune, R;ripple: Sand Body; N;absent, Y;present

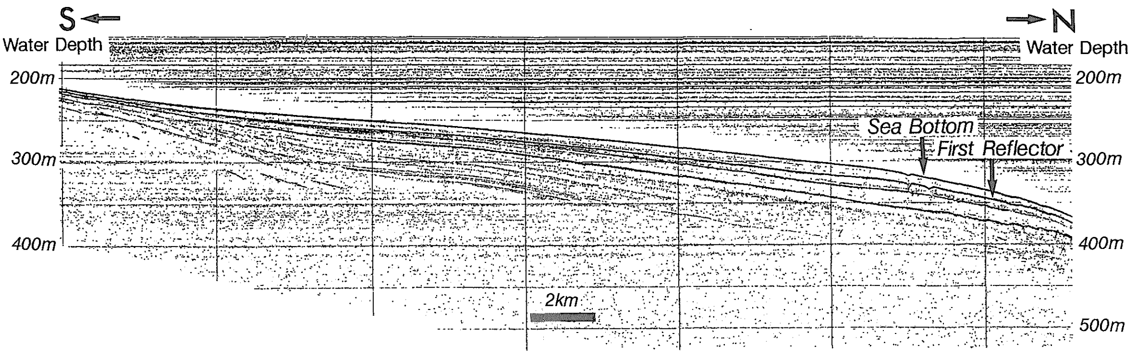


Fig.42 Typical example of seismic (3.5kHz) record on the marginal terrace off Tottori. Note the sedimentary layer between the sea bottom and first reflector becomes thicker northward (after Ikehara, 1991a).

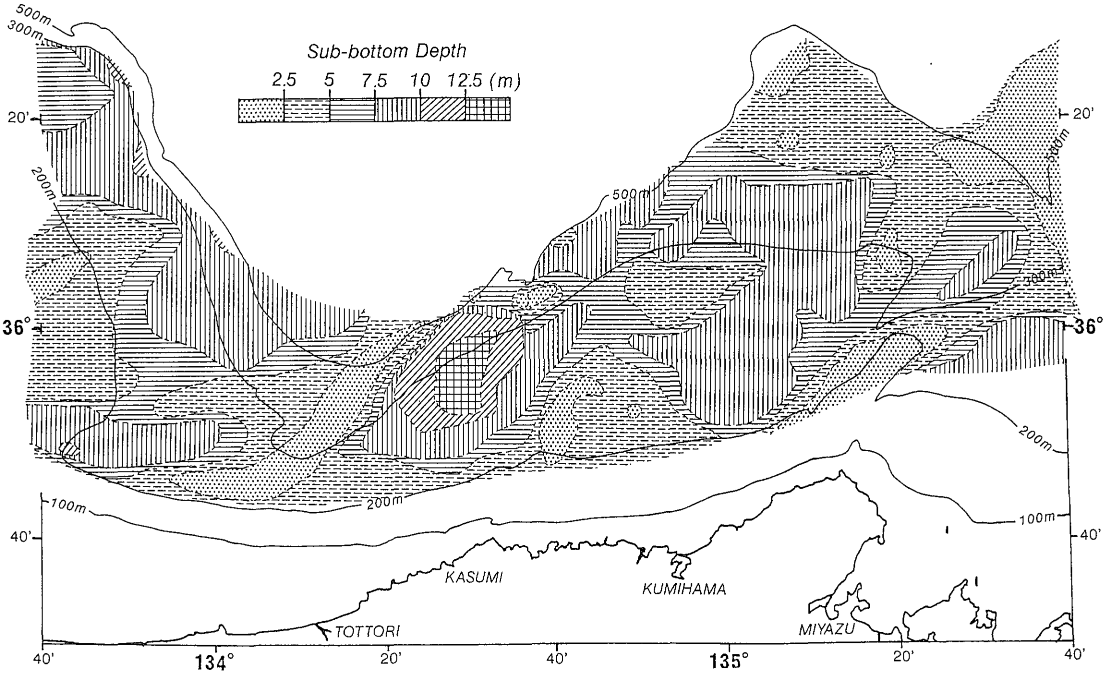


Fig.43 Sub-bottom depth contour of the first reflector on the marginal terrace of the eastern San'in district (after Ikehara, 1991a).

1990; Ikehara *et al*., 1990a). Therefore, tectonic movements are closely related to the filling-up processes of the trough.

6. Some sedimentological aspects of surface sediments around Southwest Japan

6-1. Classification of the shelf sediments

Emery (1952) classified the shelf sediments into the following five groups: 1. authigenic; glauconite, phosphorite and others, 2. biogenic; foraminiferal tests, shell fragments and others, 3. residual; residues of bottom erosion by water movements, 4. relic; the sediments which were formed under different environments from present, 5. clastic; the sediments which are forming under present environments. Emery (1968) added another group, volcanic which are supplied by volcanic activities, and asserted that about 70% of the shelf sediments in the world is relic sediments which were formed during the last glacial period. Based on the idea of coastal erosion and sediment movements in the coastal area during the sea level rising (Bruun, 1962), the shelf sediments are subdivided into three groups (Harms *et al*., 1982; Johnson and Baldwin, 1986; Saito, 1989c). That is, 1. modern sediments; the sediments deposited under the same environments as present, 2. palimpsest; the sediments which are or were removed and replaced to adapt to new environments, 3. relic sediments; the sediments which were formed under different environments from present. Furthermore, Johnson and Baldwin (1986) added the concept of forces which are worked to the sediments and classified the shelf into six groups as follows: 1. storm-dominant shelf which is covered by palimpsest or relic sediments, 2. tidal-dominant shelf which is covered by palimpsest, 3. storm-dominant shelf which is covered by modern sediments, 4. storm-dominant shelf which is covered by palimpsest or modern sediments, 5. storm-dominant shelf which is covered by modern sediments and on which the sediments tend to become finer in grain size offshoreward, 6. ocean current-dominant shelf which is covered by palimpsest or modern sediments. Saito (1989c) added a new group, tidal-dominant shelf which is covered by palimpsest or modern sediments, as division 7.

Taking these classifications into account, the shelf sediments and shelf itself around the Southwest Japan are divided into several groups (Tables 5 and 6). At first, based on Emery's concept, sandy sediments distributed in the coastal area or inner shelf correspond to the clastic sediments which are derived from rivers and nearby coasts. On the other hand, mid-outer shelf sediments are not directly supplied from the land at present, because finer sediments are distributed in the inner shelves, such as Tosa Bay, Shibushi Bay, Miho Bay and coastal areas off Hyuga and Nichinan coasts (Ikehara, 1985, 1988b, 1991a). Heavy mineral compositions of the mid-outer shelf sediments are different from those of coastal sediments on the Tottori shelf (Yokota *et al*., 1990). Iron-coated quartz grains and manganese-replaced or very poorly preserved foraminiferal tests are contained in the offshore sandy sediments of Tosa Bay (Ikehara, 1988b) and mid-outer shelf sandy sediments off Tottori (Ikehara *et al*., 1990a; Ikehara, 1991a). Thus, the sandy sediments on the mid-outer shelf and upper part of the upper slope is considered to be relic sediments. This is supported by ^{14}C age determination of molluscan shells collected from the mid-outer shelf by Ohshima *et al.* (1978) and this study (Table 7). Residual sediments are found around the rocky bottoms on the Ashizuri Spar, off Aoshima, off the north coast of Mishima Island, around the Shimane Peninsula and the Oki Islands, at the coastal area off the Daisen Volcano, and offshore between Tottori and Kasumi. Biogenic sediments occur on the topographic highs such as the Ashizuri Spar, which are washed by the currents.

Next, introducing the concept of forces, most of shelf sediments are influenced and more or less removed by present ocean currents, as discussed earlier. Therefore, at least some of them are modern sediments and the shelf covered by them correspond to the division 6 of Johnson and Baldwin

Table 5 Shelf sediment classification around Southwest Japan. (Emery's classification)

Classification	Occurrence around SW Japan
AUTHIGENIC	shelf edge of Tosa Bay
BIOGENIC	topographic highs (on the spars and knolls)
RESIDUAL	rocky bottom
RELIC	mid-outer shelf
CLASTIC	coastal and inner shelf
VOLCANIC	around the south Kyushu

Table 6 Shelf sediment classification around Southwest Japan. (Johnson and Baldwin's classification)

Classification		Occurrence around SW Japan
Force	Sediments	
Storm	Palimpsest or relic	none
Tidal current	Palimpsest	around Iki Island ?
Storm	Modern	inner shelf (coastal sandy sediments)
Storm	Palimpsest or modern	none
Storm	Modern (graded shelf)	inner shelf (coastal sandy sediments)
Ocen current	Palimpsest or modern	mid-outer shelves
Tidal current	Palimpsest or modern	Bungo Channel

Table 7 ^{14}C age determinations of shells collected from the studied area. *; data from Ohshima *et al*. (1978)

Sample No.	Latitude(N)	Longitude(E)	Water depth(m)	Age(yr.B.P.)
832-3	33-20.5	133-47.1	140	4,170±210
832-18	33-20.48	133-43.01	127	6,840±260
832-175	32-49.0	132-31.0	130	7,060±280
832-251	32-30.63	131-55.02	177	13,960±230
832-402	33-03.2	132-18.4	95	>39,000
843-286	31-33.43	129-56.19	272	19,800±900
PO-62 *	30-59.7	131-00.5	99	4,300±330
PO-63 *	31-00.0	131-08.2	100	7,570±480

* data from Ohshima et al.(1978)

(1986) and Saito (1989c). As tidal currents are prevailing and remove the sediments in the Bungo Channel (Inouchi, 1982, 1990; Ikehara and Kinoshita, 1989; Yanagi, 1990a), the sediments are modern ones or palimpsest, and the shelf belongs to the division 7. On the other hand, Mogi (1981) indicated that the sediments in the Tsushima Strait are moved but sand ridges are not formed under present conditions. As mentioned in the earlier chapter, the sediments may partly be moved by the tidal currents. Therefore, the Tsushima Strait may correspond to the division 2. As sandy coastal sediments are highly influenced by present wave actions and are derived from nearby land, the shelf corresponds to the division 3 or 5.

The McCave's classification of shelf (McCave, 1972) based on sediment distribution indicates that the shelves of western Tosa Bay and coastal areas off the Hyuga and Nichinan coasts correspond to the nearshore mud-belt and mid-shelf mud-belt. No other type of mud is distributed on the shelf in the study area.

6-2. Sedimentation model for the ocean current-controlled shelf to basin area

As mentioned earlier, the effects of the ocean currents are found in both of the Pacific and the Sea of Japan, although the degree of the effects to the bottom is different in each of the areas. The ocean current is very important factor to modern sediment movements and deposition on the Pacific side, while in the Sea of Japan it is influential to modern mud deposition but not to the sand transport except in and around the Tsushima Strait and on the shelf and marginal terrace edge off Kita-Kyushu and Hamada. Schematic representation of ocean current-controlled sedimentation on the Pacific side is shown in Fig. 44. Although the sedimentation model on the shelf is basically same as that proposed by Flemming (1978, 1980), the ocean current is important not only to direct transport of sediments on the shelf but also to sand supply to the upper slope and to modern mud deposition. Although the turbidity current is also important mechanism to sediment supply to the lower part of upper slope and basins, the

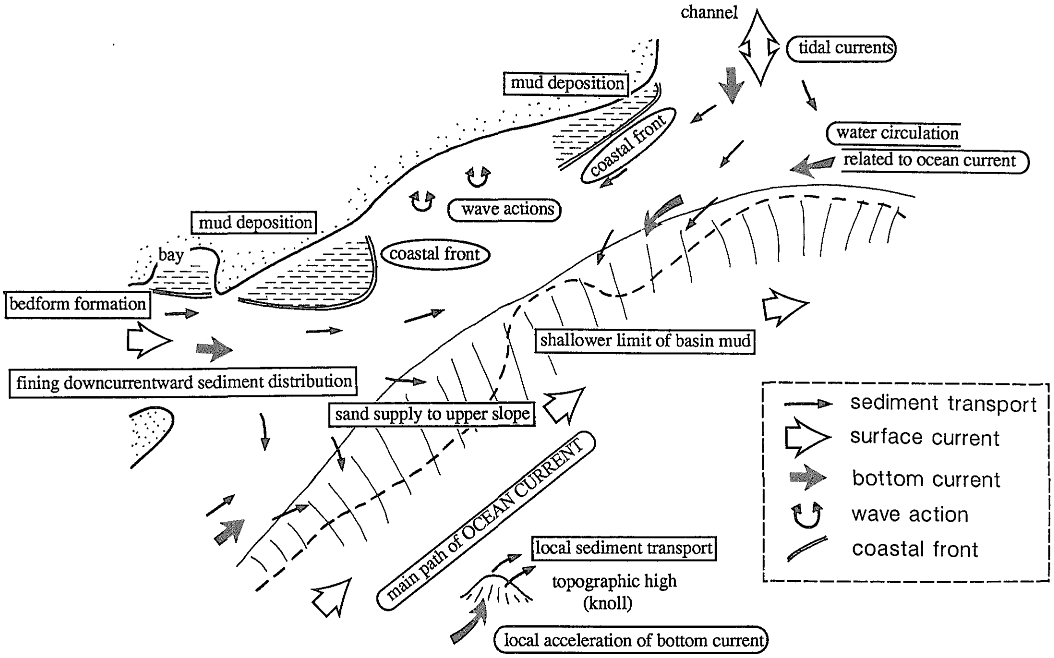


Fig.44 Schematic representation of the effects of ocean current to the sedimentation.

ocean currents are more important to the formation of sandy mud or muddy sand from the shelf edge to the upper part of the slope. As water circulation at the shelf edge were highly controlled by behavior of the Kuroshio (e.g. Sakamoto, 1987; Fujimoto, 1987), sand supply to upper slope is thought to be uncontinuous events. Because of high activities of benthos at upper to lower part of upper slope, for example in Tosa Bay (Ikehara, 1988b), supplied sandy sediments might be bioturbated quickly. This process is a possibity to form muddy sand or sandy mud in slope sediments. Also in the basin area, the ocean current is influential to the sedimentation where the current is locally accelerated by the topographic effects such as around the knolls or spars.

6-3. Importance of the water mass boundary to modern mud deposition

As pointed out by Hoshino (1952, 1958) and Ikehara (1985), the geographical boundary between two water masses (Siome in Japanese) controls mud distribution. Recently, Oki (1989, 1991) showed modern mud deposition and high surface productivity at the water mass boundary in spite of high energy field as in the strait. However, the effects of vertical boundary between two water masses, for example a thermocline, have not been discussed. The southern part of the Sea of Japan has a typical stratification of water masses (Fig.5; Uda, 1934; Nitani, 1972b; Asaoka *et al.*, 1985; Murayama *et al.*, 1990). Here, the effects of boundary of water masses, both geographical and vertical, will be discussed.

The geographical boundaries in the study area are formed among the coastal, shelf and oceanic water masses. Generally speaking, terrigenous muddy sediments are deposited in the territory of the coastal or shelf water. A typical example is found in the western Tosa Bay. Muddy sediments, which are composed of silt and very fine sand, occur on the landward of the boundary between low salinity shelf water and high salinity oceanic (Kuroshio) water (Fig. 45; Ikehara, 1988b). Dispersal patterns of river-driven materials can be inferred from the geographical distribution of sediment compositions such as plant debris and sediment grain size (Ikehara, 1988b). That is, the debris supplied from the Niyodo River are transported southwestwards and those from the Shimanto River are carried northeastwards and southwestwards (Ikehara, 1988b). These inferred directions of sediment transports are almost concordant with the water circulation pattern on the shelf of Tosa Bay (Miyata *et al.*, 1985; Sakamoto, 1987; Fujimoto, 1987). It is thought that fine terrigenous materials are transported with the shelf water circulation and are deposited in the shelf water zone which is relatively more quiet than offshore area. In the case of western Tosa Bay, a projection of Cape Ashizuri-Misaki and the Ashizuri Spar prevents the direct invasion of the Kuroshio to the western shelf. The topographic barrier may be important for developing the shelf water zone. Near the boundary, the current is convergent and down-current is formed (Yanagi, 1990b). Therefore, most of terrigenous materials transported by shelf water circulations cannot disperse offshoreward over the boundary but are deposited immediately. The development of the coastal or shelf water zone is classified into three types as, schematically shown in Fig.46. One of them is formed in relation to the path of the ocean currents, such as Shibushi Bay and Miho Bay. In this type, the water mass boundary is formed near the mouth of the bay, and the distribution of muddy sediments is limited by the path of the ocean current. Another one is formed in relation to the shelf water circulations induced by the main ocean current motions, as in the case of Tosa Bay. Although the last one is not found in the study area, the coastal water is developed by a large input of river water as on the shelf off Niigata.

As mentioned above, modern mud deposition on the shelf is controlled by the geographical distribution of the water masses and their boundaries.

The Japan Sea Proper Water (JSPW) exists below the water depth of around 200m

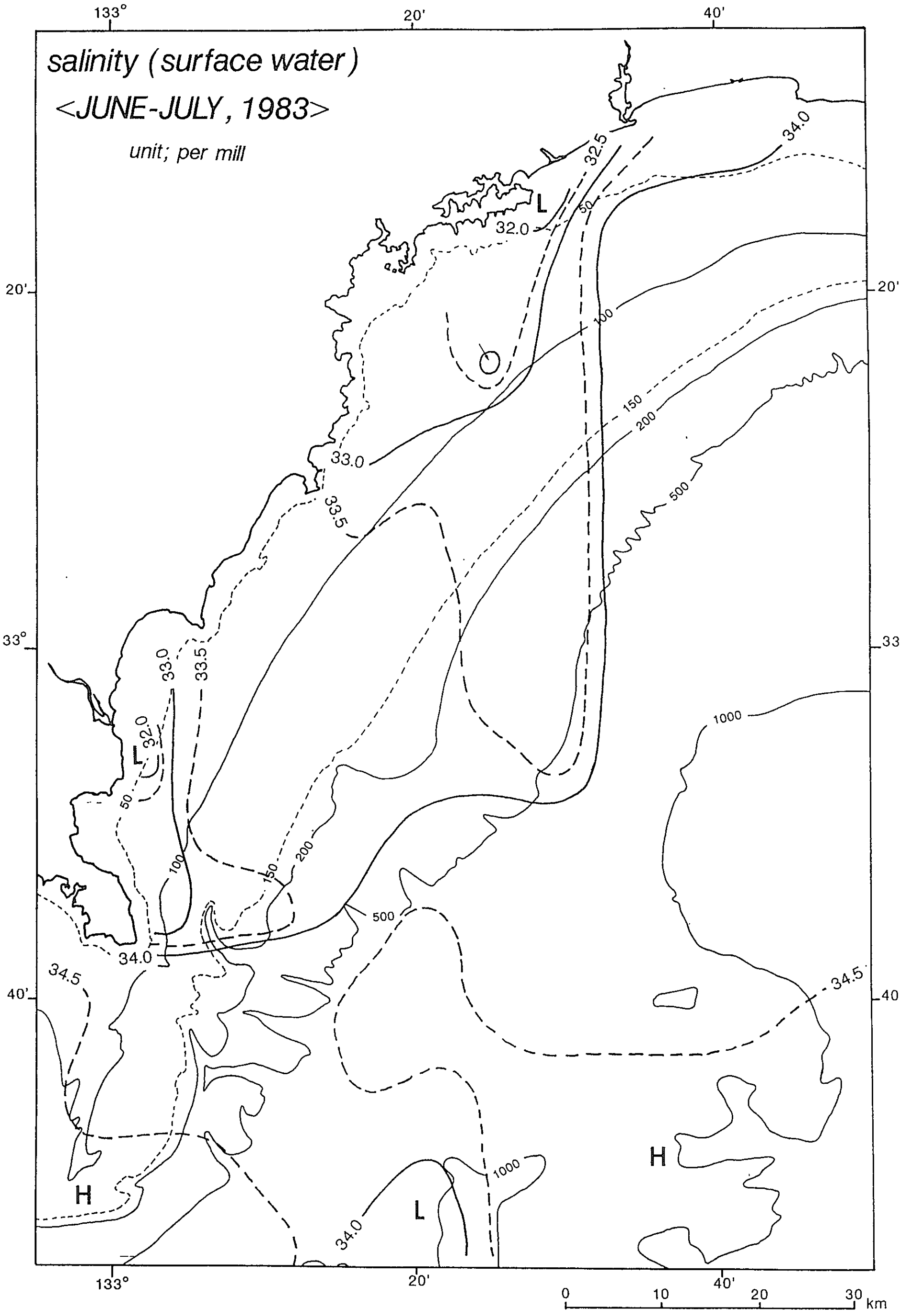


Fig.45 Salinity distribution in Tosa Bay (after Ikehara, 1988b).

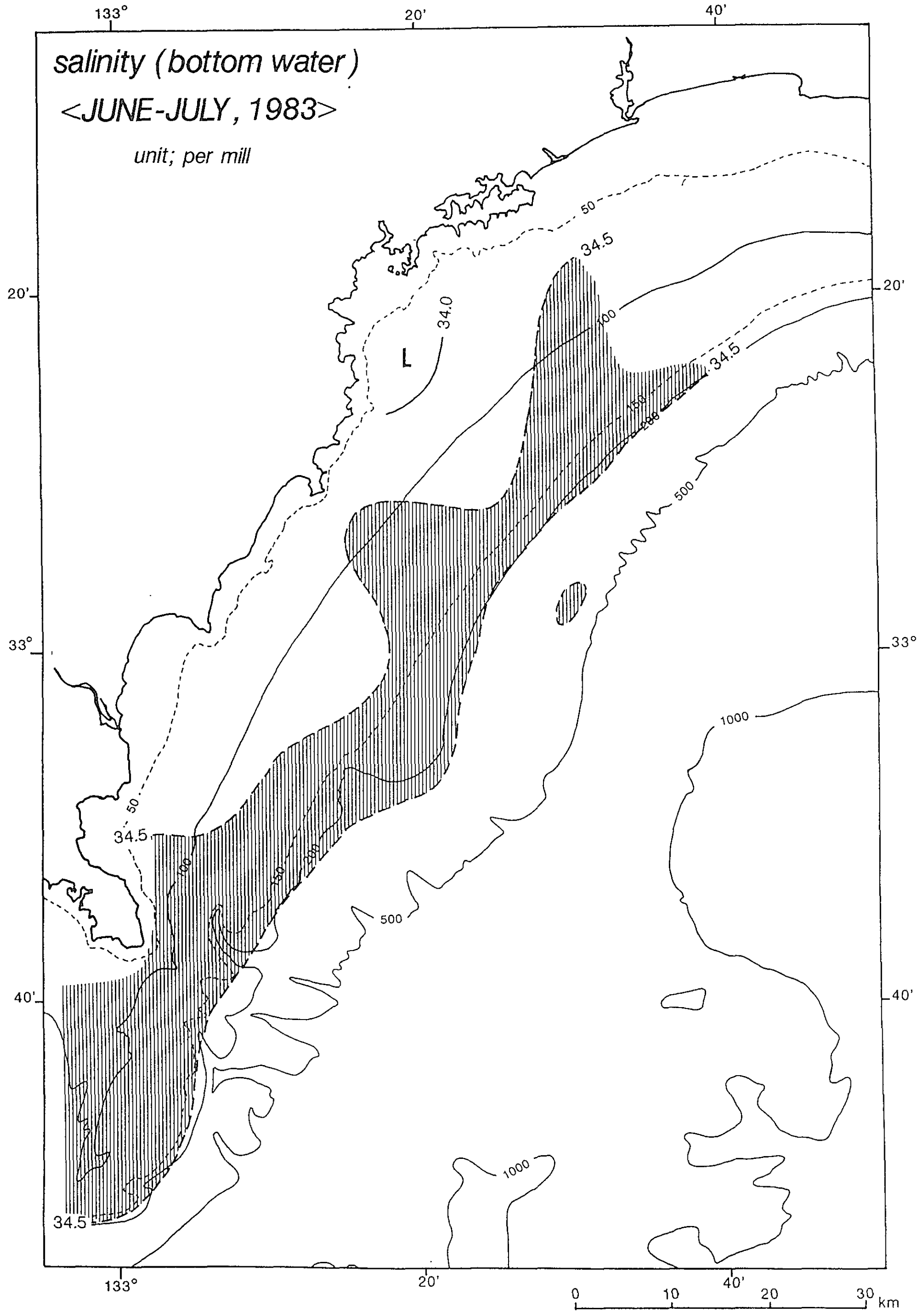


Fig. 45 (Continued)

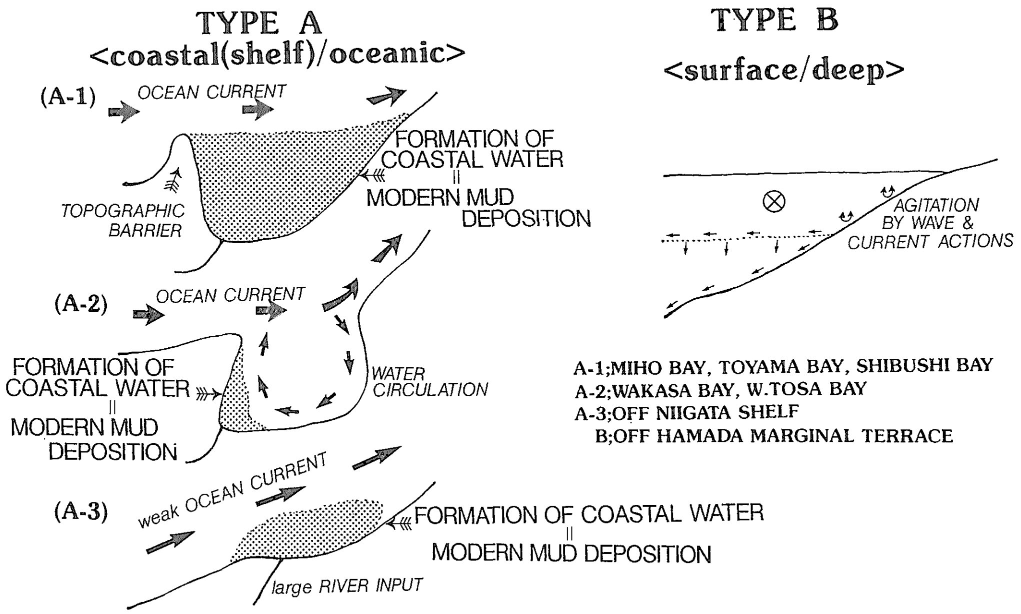


Fig.46 Two types of modern mud deposition around the Japanese Islands.

in the southern Sea of Japan (Fig.5; Asaoka *et al*., 1985; Murayama *et al*., 1990). The percentage of mud fraction in sediments increases at this boundary off Tottori (Fig.19; Ikehara *et al*., 1990a; Ikehara, 1991a). As muddy sediments are not distributed on the shelf of this area, terrigenous materials derived from the land are bypassing the shelf and begin to settle down below the boundary (Ikehara, 1991a). Mud deposition may reflect the quiet condition of the JSPW watermass. At this time, finer clay particles are transported farther from land and, as a result, geographical distribution of sediments with finer grain-size offshorewards is formed (Fig.47; Ikehara, 1991 a). Planktonic remains, which lived in the surface water mass (the Tsushima Warm Current water), are also settling down to the bottom. Terrigenous materials and planktonic remains constitute the hemipelagic mud distributed on the marginal terrace and the trough or basins. Therefore, mud distribution, the upper limit of which is controlled by the water depth, indicates no or little influence of the upper water circulations to the water masses located beneath the boundary.

6-4. Effects of water properties to the sediments

The calcium carbonate compensation depth (CCD) in the Sea of Japan is shallower than that in the Pacific and occurs at about 2000m deep (Ichikura and Ujiié, 1976). This is based on the preservation of calcareous microfossils in the sediments. In the study area and its northern adjacent, calcareous plankton remains such as calcareous nannoplanktons and planktonic foraminifers are absent or very poorly preserved where the water depth is deeper than 700-1000m (Tanaka, 1987, 1988; Oda and Ikehara, 1987, 1988). Benthic,foraminiferal assemblages change from calcareous forms on the marginal terrace to agglutinated ones on the Oki Trough (Nomura and Ikehara, 1987). These facts indicate that lysocline is located near the bottom of the Trough. Brown clay layer distributed in the trough and basins below 1000m depth is considered to be the oxidizing layer from its color and high oxidation-reduction potential (Ikehara, 1991a). The bottom layer of JSPW located deeper than 2000m has low temperature and highest oxygen concentration in JSPW (Gamo *et al*., 1986). Although the

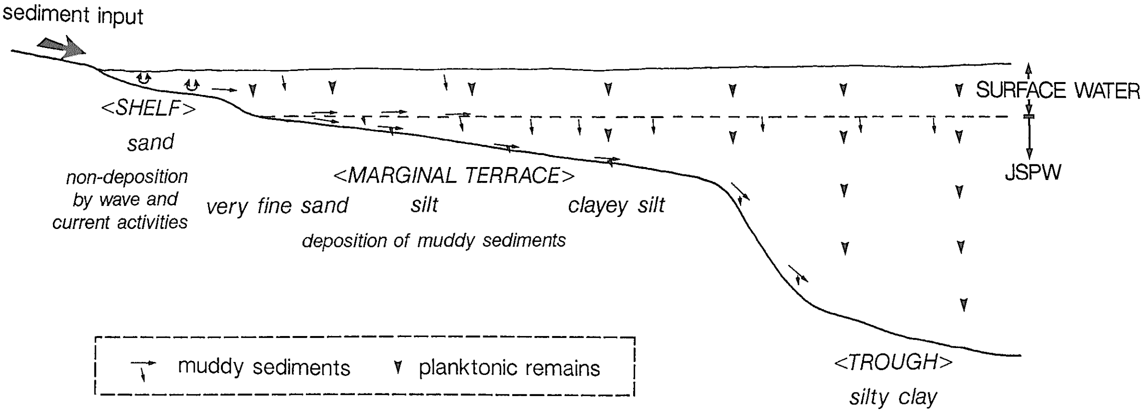


Fig.47 Schematic diagram of mud deposition off San'in district (after Ikehara, 1991a).

water depth of brown clay in the Oki Trough is shallower than that of the JSPW bottom layer, it is considered that low temperature and high oxygen concentration make an oxidizing layer and dissolves calcium carbonates. As the preservation of calcareous nannoplankton tends to become poorer northwards along the Japanese coast of the Sea of Japan (Tanaka, 1989, 1990), there is a possibility that the bottom layer is better developed or more fresh (higher oxygen concentration?) off Tohoku rather than off San'in.

6-5. Comparison of modern sedimentation between the Pacific and the Sea of Japan around Southwest Japan

As discussed above, the influence of the ocean currents is recognized in the sediments and existence of the water mass boundary in both the Pacific and the Sea of Japan is important for modern mud deposition. Besides, difference in the oceanographic conditions between them is clearly reflected on present sedimentation (Fig.48).

Sandy sediments are limited on the shelf and bedforms are poorly developed except in and around the Tsushima Strait in the Sea of Japan, while sandy sediments are widespread from shelf to the upper part of the upper slope and several kinds of bedforms are found in the Pacific. The evidence of influence of the currents is recognized in the sediments at deeper water depth in the Pacific (more than 1000m deep) than in the Sea of Japan (about 500m deep).

On the other hand, predominant mud deposition in the Sea of Japan is caused by the occurrence of the water stratification. The sediments which contain more than 70% of clay content are not found on the Pacific side but characterize the Sea of Japan side. This is due to the difference in water movements between the Pacific and Sea of Japan. The reaction between the bottom water and the sediment grains is different between both the areas, because calcareous microfossils are well preserved at the deeper depth in the Pacific than in the Sea of Japan. This reflects the difference in water properties of the bottom layer.

7. Summary

The present sedimentation around Southwest Japan is closely related to oceanographic conditions. The differences in oceanographic conditions between the Pacific and the Sea of Japan are closely related to modern sedimentation. As the results, the distribution of surface sediments and bedforms is quite different from each other, as summarized below.

1. Sandy sediments are dominant on the shelf to the upper part of the upper slope in the Pacific, while finer sediments in the Sea of

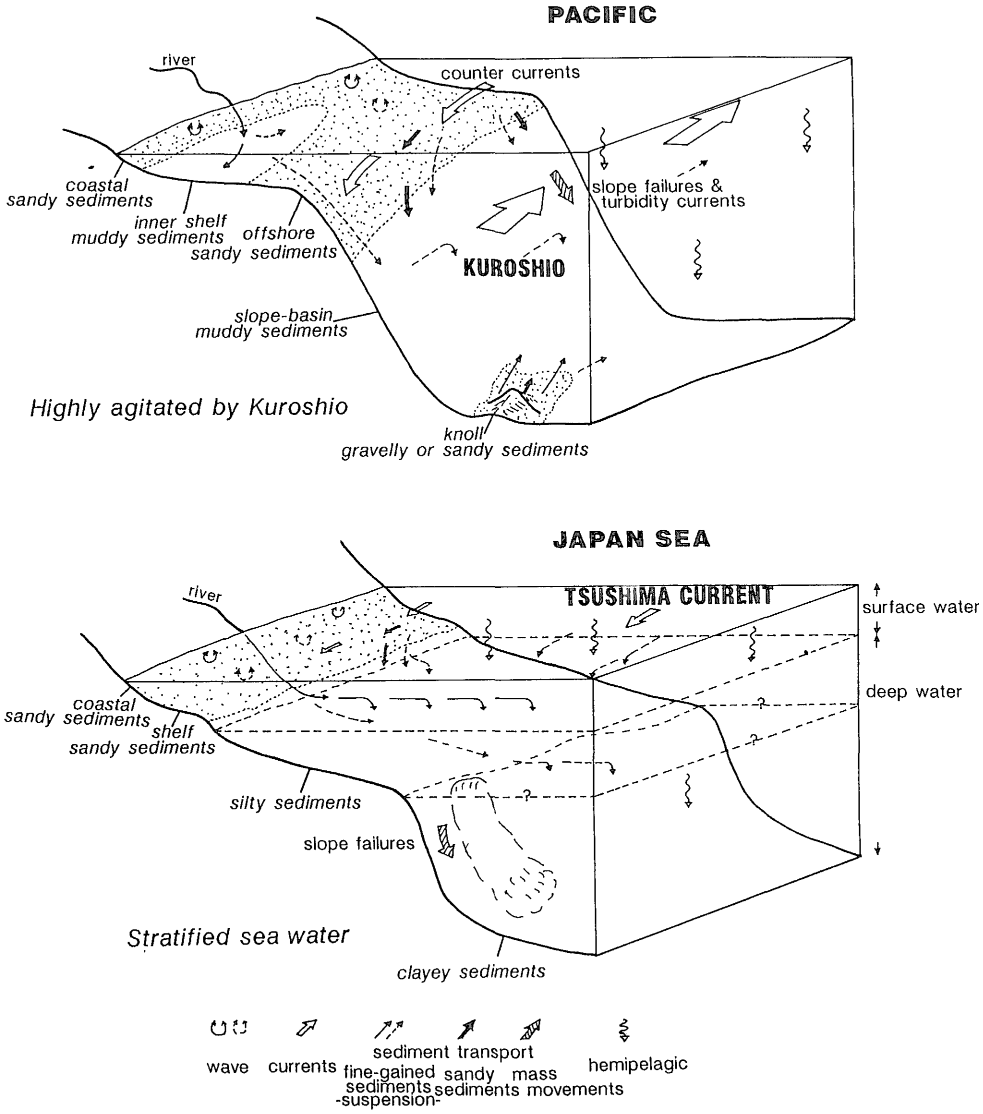


Fig.48 Comparison of modern sedimentation between the Pacific and the Sea of Japan off the Southwest Japan.

Japan.

2. Varieties of bedforms are common on the Pacific shelves but rare on the Sea of Japan shelves. Especially, larger bedforms such as large subaqueous dunes are poorly developed in the Sea of Japan. Sediment transport by the currents on the slope and basin areas is recognized on the Pacific bottom but not on the Sea of Japan bottom. These differences on sediments and bedforms between the Pacific and the Sea of Japan reflect the difference in the strength of bottom currents.

3. In the Sea of Japan, the shallower limit of slope (and marginal terrace) and basin mud is almost same throughout the study area and is controlled by the water depth, which reflects the water mass boundary, while in the Pacific, it changes spatially, reflecting the water circulations related to the Kuroshio movements.

4. Calcium carbonate compensation depth is shallower in the Sea of Japan than in the Pacific, probably reflecting the difference in bottom water properties.

Most basic factors controlling modern sedimentation, however, are considered not only to be the water movements, such as by waves, tidal and ocean currents, and to be the water mass boundaries but also to be the rate of sediment supply and the origin of sediments. Around Southwest Japan, most of sandy shelf sediments on the mid-outer shelves are revealed to have been deposited during the lower sea level stages based on their compositions and ^{14}C ages of shells in the sediments. On the other hand, muddy, or well-sorted sandy, or poorly-sorted gravelly sediments on the inner shelves and in the bays are thought to be modern sediments. From a viewpoint of the sediment transport and deposition, the ocean current is major factor to control modern sedimentation on the mid-outer shelves.

Effects of wave actions to the sediments are recognized only in the inner shelves shallower than around 50m, and tidal influences on sedimentation are restricted in the shelf in and around the Bungo Channel. Also, sediment slidings and tectonic movements do not control the sediment distributions even in the basins. For example, especially on the mid-outer shelves, rearrangement of older sediments, which were deposited during the lower sea level, and modern sediments produced by present sea bottom erosions by the currents controls the sediment distribution.

Throughout this study, modern sedimentation around Southwest Japan is checked from the oceanographic viewpoints, which clears the importance of oceanographic conditions on sedimentation. The clarification of modern sedimentation will give us a key to solve the ancient sedimentary processes and environments.

Acknowledgements

This paper is originally written for my doctral thesis for Kyushu University. I express my hearty thanks to Professor Hakuyu Okada of Kyushu University for his critical reading of an early version of manuscript, instructive comments and encouragements. I would like to thank Professors Atsuo Aihara of Kyushu University and Yujiro Ogawa of University of Tsukuba for their discussions and encouragements. I am grateful to Dr. Masafumi Arita of the Geological Survey of Japan for his critical readings of several versions of manuscripts, constructive discussions and continuous encouragements. I thank our research leader, Dr. Yukinobu Okamura, and bulletin reviewer, Dr. Akira Nishimura, for their valuable suggestions for improvement of the manuscript. Acknowledgements are due to the captains, officers, crew and scientists of R/V Hakurei-Maru for kind help throughout the surveys. I am indebted to the members of the Marine Geology Department, Geological Survey of Japan, especially to Drs. Masafumi Arita, Yasumasa Kinoshita, Hodaka Kawahata and Mr. Hajime Katayama, for their cooperations in field and laboratory works and discussions. Thanks are due to Drs. Ritsuo Nomura of Shimane University, Motoyoshi Oda of Kumamoto University, Yuichiro Tanaka of the Geological Survey of Japan, and Professor Hiroshi Machida of Tokyo Metropolitan University for their identifications of benthic and planktonic foraminifers, calcareous nannoplanktons and submarine tephras. I also express my hearty thanks to Dr. Tatsuaki Kimura of Institute of Natural History for introducing me to earth sciences and encouragement. I thank Professor Takashi Ichiye of Texas A&M University and the other members of JECSS(Japan and East China Seas Study) workshop for their discussions from the oceanographic standpoints. This work was financially supported by the AIST(Agency of Industrial Science and Technology) special research program on geological mapping of the conti nental shelf areas in Japan by the Geological Survey of Japan.

References

Akagi, S. (1981) *Palaeoloxodon naumanni*

(Makiyama) from the sea bottom off the coast of San'in. *J. Fac. Educ., Tottori Univ., Natl. Sci.*, no.30, p.57-64. (in Japanese with Eng. abstracts)

Akiyama, M., Kamei, T. and Nakai, N. (1988) ^{14}C ages of Naumann's elephant *Palaeoloxodon naumanni* (Makiyama) from the sea bottom off San'in district in the Sea of Japan by accelerator mass spectrometry –^{14}C age of the Quaternary deposits in Japan (168)–, *Earth Science* (*Chikyu-Kagaku*), vol. 42, p.29-31. (in Japanese)

Allen, J.R.L. (1972) Instability of an upper-phase plane bed: a test of Bagnold's criterion. *Sed. Geol.*, vol.8, p.309-316.

Allen, P.A. and Homewood, P. (1984) Evolution and mechanics of a Miocene tidal sandwave. *Sedimentology*, vol.31, p. 63-81.

Anma, K., Hanba, Y., Matsuoka, K., Tanioka, S., Fukushima, Y. and Yoshida, T. (1992) Marine environments and geology of Oobatake strait, Seto Inland Sea. *Abstracts, 99th Annul Meeting, Geol. Soc. Japan*, p.604. (in Japanese)

Arita, M. (1976a) *Report of the investigation for marine fine aggregates around the Japanese Islands –Genkai-nada Sea–*. Cons. Goods Indust. Bureau, Minist. Intern. Trade Indust. and Geol. Surv. Japan, 21p. (in Japanese)

——— (1976b) A concept of sedimentary mixing. *Chishitsu News*, no.268, p. 22-29. (in Japanese)

——— (1982) Significance of sedimentological maps around the Japanese Islands. *Chishitsu News*, no.337, p.176-177. (in Japanese)

——— and Kinoshita, Y. (1991) Sedimentological map offshore of Cape Muroto (with explanatory notes). Mar. Geol. Map Ser., no.37, Geol. Surv. Japan, 36 p. (in Japanese with Eng. abstracts)

Asaoka, O., Hashimoto, Y. and Katayama, K. (1985) Physical oceanography in the Wakasa Bay, in Coast. Oceanogr. Res. Commit., Oceanogr. Soc. Japan, ed., *Coastal Oceanography of Japanese Islands*, Tokai Univ. Press, Tokyo, 958-968. (in Japanese)

Ashley, G.M. (1990) Classification of large-scale subaqueous bedforms: a new look at an old problem. *J. Sed. Petrol.*, vol.60, p.160-172.

Awaji, T., Akimoto, K. and Imasato, N. (1987) Numerical study on shelf-water movement caused by the Kuroshio. *Abstract papers on 4th JECSS Workshop*, p.24-25.

Belderson, R.H., Johnson, M.A. and Kenyon, N.H. (1982) Bedforms, in Stride A. H., ed., *Offshore Tidal Sands, Processes and Deposits*, Chapman and Hall, London, p.27-57.

Berné, S., Bourillet, J-F., Durand, J. and Lericolais, G. (1989) Les dunes subtidales geantes de Surtainville (Manche Ouest). *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, vol.13, p.395-415. (in French with Eng. abstracts)

Blum, P. and Okamura, Y. (in press) Sea level and physiographic controls on late Quaternary clastic depositional systems in SW-Japan forearc basins: a 3.5kHz acoustic facies analysis.

Bruun, P. (1962) Sea level rise as a cause of shore erosion. *Proc. Am. Soc. Civil Eng., J. Water Harb. Div.*, vol.88, p 117-130.

Caddah, L.F.G., Tokuhashi, S., Nishimura, A., Kinoshita, Y. and Arita, M. (1991) An attempt of sedimentological analysis based on 3.5kHz SBP and gravity core data in the Kumano Trough, offing of Southwest Japan. *J. Sed. Soc. Japan*, no.35, 29-40.

Chaen, M. (1985) Physical oceanography of Hyuga-nada, in Coast. Oceanogr. Res. Commit., Oceanogr. Soc. Japan, ed., *Coastal Oceanography of Japanese Islands,* Tokai Univ. Press, p.759-763. (in Japanese)

Chough, S.K., Jeong, K.S. and Honza, E. (1985) Zoned facies of mass-flow deposits in the Ulleung (Tsushima) Basin, East Sea (Sea of Japan).

Mar. Geol., vol.65, p.113-125.

Damuth, J.E. (1980) Use of high-frequency (3.5-12kHz) echograms in the study of near-bottom sedimentation processes in the deep-sea: a review. *Mar. Geol.*, vol.38, p.51-75.

Emery, K.O. (1952) Continental shelf sediments off southern California. *Geol. Soc. Am. Bull.*, vol.63, p.1105-1108.

——— (1968) Relict sediments on continental shelves of world. *Am. Assoc. Petrol. Geol. Bull.*, vol.52, p.445-464.

Flemming, B.W. (1978) Underwater sand dunes along the southeast African continental margin - observations and implications. *Mar. Geol.*, vol.26, p.177-198.

——— (1980) Sand transport and bedform patterns on the continental shelf between Durban and Port Elizebeth (southeast African continental margin). *Sed. Geol.*, vol.26, p.179-205.

Fujimoto, M. (1987) On the flow types and current stability in Tosa Bay and adjacent seas. *Umi to Sora (Sea and Sky)*, vol.62, p.127-140. (in Japanese with Eng. abstracts)

Gamo, T. and Horibe, Y. (1983) Abyssal circulation in the Japan Sea. *J. Oceanogr. Soc. Japan*, vol.39, p.220-230.

———, Nozaki, Y., Sakai, H., Nakai, T. and Tsubota, H. (1986) Spacial and temporal variations of water characteristics in the Japan Sea bottom layer. *J. Mar. Res.*, vol.44, p.781-793.

Hanaoka, F., Konishi, Y. and Koto, T. (1986) Distributions of sardines, sardine eggs and larvae, and the Kuroshio Current in the waters off the Shikoku and Kyushu Islands during February and March in 1986. *Rep. Res. Prog., Kuroshio Exploit.&Utiliz.*, no.9, Sci. Tech. Agency, p.400-410. (in Japanese)

Harms, J.C., Southard, J.B., Spearing, D.R. and Walker, R.G. (1975) Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences. *Short Course Notes*, no.2, SEPM, Dallas, 161p.

———, ——— and Walker, R.G. (1982) Shallow marine environments: a comparison of some ancient and modern examples. *Short Course Notes*, no.9, SEPM, Dallas, p.8-1-8-51.

Honza, E., Arita, M., Kinoshita, Y., Okuda, Y. and Tamaki, K. (1984) Marine geological activities around the Japanese Islands —cruise reports on FY1983 by Hakurei-Maru—. *Chishitsu News*, no. 355, p.26-48. (in Japanese)

———, Kinoshita, Y., Arita, M. and Inoue, E. (1983) Marine geological activities around the Japanese Islands—cruise reports on FY1982 by Hakurei-Maru—. *Chishitsu News*, no.343, p. 22-45. (in Japanese)

Hoshino, M. (1952) On the muddy sediments of the continental shelf adjacent to Japan. *J. Geol. Soc. Japan*, vol.58, p. 41-53. (in Japanese with Eng. abstracts)

——— (1958) The shelf sediments in the adjacent seas of Japan. *Monogr. Assoc. Geol. Collab.*, no.7, p.1-41. (in Japanese with Eng. abstracts)

Hosimi, K. and Morioka H, (1987) ^{14}C age of Palaeoloxodon naumanni (Makiyama) from the sea bottom off the coast of San'in —^{14}C age of the Quaternary deposits in Japan (165)—. *Earth Sci. (Chikyu-Kagaku)*, vol.41, p.248-250. (in Japanese)

Ichikawa, H. (1990) Physical oceanography around the Satunan Islands, in Coast. Oceanogr. Res. Commit., Oceanogr. Soc. Japan, ed., *Coastal Oceanography of Japanese Islands, Supplementary Volume*, Tokai Univ. Press, Tokyo, p.642-653. (in Japanese)

Ichikura, M. and Ujiié, H. (1976) Lithology and planktonic foraminifera of the Sea of Japan piston cores. *Bull. Natl. Sci. Mus.*, Tokyo, ser.C, vol.2, p.151-178.

Ikehara, K. (1985) The characteristics of grain size distributions of muddy sediments off Southwest Japan. *J. Sed. Soc.*

Japan, nos.21/22, p.71-77. (in Japanese with Eng. abstracts)

——— (1988a) Ocean current generated sedimentary facies in the Osumi Strait, south of Kyushu, Japan. *Prog. Oceanog*., vol.21, p.515-524.

——— (1988b) Sedimentological map of Tosa Wan (with explanatory notes). Mar. Geol. Map Ser., no.35, Geol. Surv. Japan, 29p. (in Japanese with Eng. abstracts)

——— (1989a) The Kuroshio-generated bedform system in the Osumi Strait, southern Kyushu, Japan, in Taira, A. and Masuda, F., eds., *Sedimentary Facies in the Active Plate Margin*, Terra Sci. Publ., Tokyo, p.261-273.

——— (1989b) Some physical properties of shelf to basin deposits off San'in and Hokuriku district, southern part of Japan Sea. *Bull. Geol. Surv. Japan*, vol.40, p.239-250. (in Japanese with Eng. abstracts)

——— (1990a) Sedimentary and erosional features on the sea bottom of the Bungo Strait. *Trans. Japan. Geomorph. Union*, vol.11, p.55. (in Japanese)

——— (1990b) Modern sedimentation of shelf to basin deposits offshore of Southwest Japan —effects of the strong ocean current, Kuroshio to the sedimentation. *J. Sed. Soc. Japan*, no.32, p.89-90. (in Japanese with Eng. abstracts)

——— (1991a) Modern sedimentation off San'in district in the southern Japan Sea, in Takano, K. ed., *Oceanography of Asian Marginal Seas*, Elsevier, Amsterdam, p.143-161.

——— (1991b) Bedforms in the Oki Strait, southern Japan Sea: An example of inactive bedform system under modern oceanographic conditions. *J. Sed. Soc. Japan*, no.35, p.19-28. (in Japanese with Eng. abstracts)

——— (1991c) Submarine tephras in the Japan Sea —their distribution and implications—. *The Earth Monthly* (*Gekkan Chikyu*), vol.13, p.218-224. (in Japanese)

——— (1992) Formation of duned sand bodies in the Osumi Strait, south of Kyushu, Japan. *J. Sed. Soc. Japan*, no.36, p. 37-45.

——— (in press) Influence of surface water circulations on the sea bottom in the southern Japan Sea. *La mer*, vol.30 (submitted).

———, Bi, D., Suzuki, T. and Kinoshita, Y. (1988a) Heavy mineral distributions in the surface sediments of the Osumi Strait, south of Kyushu, Japan. *J. Sed. Soc. Japan*, no.29, p.9-18. (in Japanese with Eng. abstracts)

——— and Katayama, H. (1987) Sea water properties off San'in district — salinity, temperature and pH—, in Arita, M., Okuda, Y. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1986*, Geol. Surv. Japan, Tsukuba, p. 192-196. (in Japanese)

——— and ——— (1992) Submersible observations of the depression caused by slope failure at the north of the Gentatsu-se Bank, off Hokuriku, in the southern Japan Sea. *JAMSTEC Deep-sea Res*., no.8, p. 47-53. (in Japanese with Eng. abstracts)

———, ——— and Satoh, M. (1990b) Sedimentological map offshore of Tottori (with explanatory notes). Mar. Geol. Map Ser., no. 36, Geol. Surv. Japan, 42 p. (in Japanese with Eng. abstracts)

——— and Kawahata, H. (1985a) Sea bottom observations by sea bottom photography in the south of Kyushu (Off Tanegashima and Yakushima Islands and Cape Noma-misaki), in Moritani, T. and Nakao, S., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1984*, Geol. Surv. Japan, Tsukuba, p.46-51. (in Japanese)

——— and ——— (1985b) Surface sediments in the south of Kyushu (off Tanegashima and Yakushima Islands and

Cape Noma-misaki), in Moritani, T. and Nakao, S. ,eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1984*, Geol. Surv. Japan, Tsukuba, p.55-62. (in Japanese)

——— and ——— (1986a) Surface sediments off Kita-Kyushu and San'in region, in Nakao, S., Tamaki, K. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1985*, Geol. Surv. Japan, Tsukuba, p. 68-102. (in Japanese)

——— and ——— (1986b) Sea bottom observations off Kita-Kyushu and San'in region, in Nakao, S., Tamaki, K. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1985*, Geol. Surv. Japan, Tsukuba, p.59-62. (in Japanese)

———, Kikkawa, K., Katayama, H. and Seto, K. (in press) Late Quaternary paleoenvironments of the Japan Sea: a tephrochlonological and sedimentological study. *Proc. Intern. Symp. Global Change*, (submitted).

——— and Kinoshita, Y. (1989) Bedforms and their migration patterns in the southern Bungo Strait, Japan, in Taira, A. and Masuda, F., eds, *Sedimentary Facies in the Active Plate Margin*, Terra Sci. Publ., Tokyo, p.251-260.

———, ——— and Nishimura, K. (1988c) Sea bottom (geological) sonar mosaic —southern Bungo Strait—, 1:10,000, Miscellaneous Map Ser., no.28-1, Geol. Surv. Japan. (in Japanese with Eng. abstracts)

———, ———, ———, Nakamura, K. and Kawahata, H. (1988b) Morphology and distribution of bedforms in the Osumi Strait, south Kyushu, Japan. *Bull. Geol. Surv. Japan*, vol.39, p. 95-113. (in Japanese with Eng. abstracts)

——— and Okamura, Y. (1985) Geology of Tosa Bay, in Coast. Oceanogr. Res. Commit., Oceanogr. Soc. Japan, ed., *Coastal Oceanography of Japanese Islands*, Tokai Univ. Press, Tokyo, p. 723-731. (in Japanese)

———, Satoh, M. and Yamamoto, H. (1990a) Sedimentation in the Oki Trough, southern Japan Sea, as revealed by high resolution seismic records (3.5 kHz echograms). *J. Geol. Soc. Japan*, vol.96, p.37-49. (in Japanese with Eng. abstracts)

Inouchi, Y. (1981) Sediments and Quaternary sedimentological history of the Osumi Strait and its vicinity, in relation to the evolution of the Osumi Strait. *Bull. Geol. Surv. Japan*, vol.32, p. 693-716. (in Japanese with Eng. abstracts)

——— (1982) Distribution of bottom sediments in the Seto Inland Sea —The influence of the tidal currents on the distribution of bottom sediments—. *J. Geol. Soc. Japan*, vol.88, p.665-681. (in Japanese with Eng. abstracts)

——— (1988) Sedimentation models of Lake Biwa. *Clastic Sed. (J. Res. Gr. Clastic Sed. Japan)*, no.5, p.49-72. (in Japanese with Eng. abstracts)

——— (1990) Origin of sand and its distribution pattern in the Seto Inland Sea, Southwest Japan. *Bull. Geol. Surv. Japan*, vol.41, p.49-86.

Ishii, H., Iwanaga Y. and Yoritaka, H. (1991) Ocean current measurements in the Tokara Strait (3). *Rep. Res. Prog., Kuroshio Exploit.&Utiliz.*, FY1989, Sci. Tech. Agency, p.37-46. (in Japanese)

Iwabuchi, Y. (1968) Submarine geology of the southeastern part of the Japan Sea. *Contr. Inst. Geol. Palaeont., Tohoku Univ.*, no.66, p.1-76. (in Japanese with Eng. abstracts)

——— and Kato, S. (1988) Some features of the continental shelf around the Japanese Islands on compilation of the Quaternary Map. *The Quat. Res. (Daiyonki-kenkyu)*, vol.26, p.217-225. (in Japanese with Eng. abstracts)

Japan Association for Quaternary Research (1987) Quaternary Maps of Japan I, Landforms, geology and Tectonics, C. Southwest Japan, in Japan Association for Quaternary Research, ed., *Quaternary Maps of Japan* (*with explanatory text*), Univ. Tokyo Press, Tokyo.

Japan Oceanographic Data Center (1979) *Marine Environmental Atlas, Currents —adjacent seas of Japan*. Japan Oceanographic Data Center, Tokyo, 71p.

Johnson, H.D. and Baldwin, C.T. (1986) Shallow siliciclastic sea, in Reading, H.G., ed., *Sedimentary Environments and Facies*, 2nd ed., Blackwell, Oxford, p. 229-282.

Kamei, T. (1967) *Elephas naumanni* Makiyama from the sea bottom of the southern Sea of Japan. *Earth Sci. Rep. Coll. Liberal Arts & Sci., Kyoto Univ.* (*Tsukumo Earth Sci.*), no.2, p. 24-31. (in Japanese)

———, Akagi, S., Otsuka, H., Okada, N. and Shibata, H. (1986) Elephant fossils collected from the sea bottom around the Japanese Islands. *Abst 93rd Annual Meeting, Geol. Soc. Japan*, p. 135. (in Japanese)

Kaneko, I., Nishizawa, J., Nakano, T. and Hanzawa, Y. (1991) The Kuroshio structure and volume transport in the Tokara Strait, measured with shipboard long-range ADCP. *Rep. Res. Prog., Kuroshio Exploit.&Utiliz.*, FY1989, Sci. Tech. Agency, p.73-87. (in Japanese)

Katayama, H., Ikehara, K., Yamamoto, H. and Satoh, M. (1988) Occurrence of debris flow deposits from the Oki Trough, southern part of the Japan Sea. *Jour. Geol. Soc. Japan*, vol.94, p.633-636. (in Japanese)

———, Satoh, M. and Ikehara, K. (1993) Sedimentological map offshore of Kyo-ga-misaki (with explanatory notes). Mar. Geol. Map Ser., no. 38, Geol. Surv. Japan, 48p. (in Japanese with Eng. abstracts)

Katsura, T. and Nagano, M. (1982) Geomorphology of Goto shelf channels off northern Kyushu, Japan. *Rep. Hydrogr. Res.*, no.17, p.71-92. (in Japanese with Eng. abstracts)

Kawabe, M. (1982) Branching of the Tsushima Current in the Japan Sea Part I. Data Analysis. *J. Oceanogr. Soc. Japan*, vol.38, p.95-107.

——— (1986) Study on the Kuroshio and the Tsushima Current—variations of the current path. *J. Oceanogr. Soc. Japan*, vol.42, p.319-331.

Kimura, H. (1956) Mechanism of sorting —a fundamental study of sedimentation (Part 7). *J. Geol. Soc. Japan*, vol. 62, p.472-489. (in Japanese with Eng. abstracts)

Kinoshita, Y. (1987) K(Kinoshita)-type grab sampler and its results for practical use, in Arita, M., Okuda, Y. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1986*, Geol. Surv. Japan, Tsukuba, p.232-233. (in Japanese)

——— (1988) *Marine Geology off Sanriku District —especially, marine geological significance of "Continental Shelf"—*. Doctoral Thesis, Tokai Univ., 81p. (in Japanese with Eng. abstracts)

Ljunggren, P. and Sundborg, Å. (1968) Some aspects of fluvial sediments and fluvial morphology. II. A study of some heavy mineral deposits in the valley of the River Lule Alv. *Geogr. Annal.*, vol.50A, p.121-135.

Machida, H. (1988) Preliminary reports on tephras occurred in the cores collected from off Tottori and Wakasa Bay, in Arita, M. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1987*, Geol. Surv. Japan, Tsukuba, p. 147-153. (in Japanese)

——— and Arai, F. (1976) The widespread tephra —the Aira-Tn ash. *Kagaku*, vol.46, p.339-347. (in Japanese)

——— and ——— (1978) Akahoya Ash —a Holocene widespread tephra erupted from the Kikai Caldera, south Kyushu, Japan. *The Quat. Res.* (*Daiyonki-kenkyu*), vol.17, p.143-163. (in Japanese with Eng. abstracts)

——— and ——— (1983) Extensive ash falls in and around the Sea of Japan from large late-Quaternary eruptions. *J. Volc. Geotherm. Res.*, vol.18, p. 151-164.

Maritime Safety Agency (1949) *Bottom sediment chart of the adjacent seas of Japan, sheet 1-4*. Chart No. 7051-7054, Maritime Safety Agency, Tokyo.

——— (1971) *The Current Charts in the Adjacent Seas of Nippon, 2nd series.*

——— (1977) *The Current Charts in the Adjacent Seas of Nippon, 3rd series.*

Matsumoto, E., Maeda, Y., Takemura, K, and Nishida, S. (1987) New radio carbon age of Aiva-Tn ash (AT). *The Quat. Res.* (*Daiyonki-Kenkyu*), vol. 26, p. 79-83. (in Japanese with Eng. abstracts)

McCave, I.N. (1971) Sand waves in the North Sea off the coast of Holland. *Mar. Geol.*, vol.10, p.199-225.

——— (1972) Transport and escape of fine-grained sediment from shelf areas, in Swift, D.J.P., Duane, D.B. and Pilkey, O.H., eds., *Shelf Sediment Transport: Process and Pattern*, Dowden, Hutchinson & Ross, Stroudsburg, p. 225-248.

Miller, M.C., McCave, I.N. and Komar, P.D. (1977) Threshold of sediment motion under unidirectional currents. *Sedimentology*, vol.24, p.507-527.

Minami, H., Hashimoto, Y., Konishi, Y. and Shuto, K. (1984) On the current pattern in the Oki Channel. *Umi to Sora* (*Sea and Sky*), vol.59, p.115-125. (in Japanese with Eng. abstracts)

Miyata, K., Sakamoto, H. and Momota, M. (1980) Oceanographical structure in the Tosa Bay -1. *Bull. Nansei Reg. Fish. Res. Lab.*, no.12, p.115-124. (in Japanese with Eng. abstracts)

———, Yamashige, M. and Sugiura, K. (1985) Physical oceanography of Tosa Bay, in Coast. Oceanogr. Res. Commit., Oceanogr. Soc. Japan, ed., *Coastal Oceanography of Japanese Islands*, Tokai Univ. Press, p.732-735. (in Japanese)

Mogi, A. (1973) Some characters of the sand wave. *Annal. Tohoku Geogr. Assoc.*, vol.25, p.165. (in Japanese)

——— (1977) *Atlas of Submarine Topography around Japan*. Univ. Tokyo Press, Tokyo, 90p. (in Japanese)

——— (1981) Geomorphological evolution of continental shelves of Tsushima Strait —with reference to the Tsushima land bridge—. *The Quat. Res.* (*Daiyonki-kenkyu*), vol.20, p.243-256. (in Japanese with Eng. abstracts)

Murayama, T., Kuwabara, A. and Ogawa, Y. (1990) Physical oceanography off San'in coast, in Coast. Oceanogr. Res. Commit., Oceanogr. Soc. Japan, ed., *Coastal Oceanography of Japanese Islands, Supplementary Volume*, Tokai Univ. Press, Tokyo, p.755-767. (in Japanese)

Naganuma, K. (1972) *The oceanographical conditions in the Japan Sea*. Gyokaikyo Handobukku (Handbook of Fishery Oceanography), Zengyoren Gyokaikyo Center, p.32-38. (in Japanese)

Nardin, T.R., Hein, F.J., Gorsline, D.S. and Edward, B.D. (1979) A review of mass movement processes, sediment and acoustic characteristics, and contrasts in slope and base-of-slope systems versus canyon-fan-basin floor systems, in Doyle, L.J. and Pilkey, O. H., eds., *Geology of Continental Slopes*, SEPM Spec. Publ., no.27, p. 61-73.

Nitani, H. (1972a) Beginning of the Kuroshio, in Stommel, H. and Yoshida, K., eds., *Kuroshio, its physical aspects*, Univ. Tokyo Press, Tokyo, p.129-163.

——— (1972b) On the deep and bottom waters in the Japan Sea, in Shoji, D., ed., *Re-*

search in Hydrography and Oceanography, Hydrogr. Dept. Japan, Tokyo, p.151-201.

———, Yoshida, S., Okumoto, J. and Nakamura, H. (1979) Statistics on the currents in the seas adjacent to Japan. *Rep. Hydrogr. Res.*, no.14, p.57-91.

Nomura, R. and Ikehara, K. (1987) Benthic foraminiferal assemblage off San'in district, in Arita, M., Okuda, Y. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1986,* Geol. Surv. Japan, Tsukuba, p.165-176. (in Japanese)

Oba, T. (1987) Upper Pleistocene of the Japan Sea floor. *The Quat. Res.* (*Daiyonki-kenkyu*), vol.25, p.319-321. (in Japanese with Eng. abstracts)

———, Kato, M., Kitazato, H., Koizumi, I., Omura, A., Sakai, T. and Takayama, T. (1991) Paleoenvironmental changes in the Japan Sea during the last 85,000 years. *Paleoceanography*, vol.6, p. 499-518.

Oda, M. and Ikehara, K. (1987) Preliminary reports on the planktonic foraminiferal assemblage off San'in district, in Arita, M., Okuda, Y. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1986,* Geol. Surv. Japan, Tsukuba, p.162-164. (in Japanese)

——— and ——— (1988) Preliminary reports on the planktonic foraminiferal assemblage at the northeast of San'in district, in M. Arita and T. Moritani, eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1987*, Geol. Surv. Japan, Tsukuba, p.167-169. (in Japanese)

Ohshima, K. (1990) The history of straits around the Japanese Islands in the Late-Quaternary. *The Quat. Res.* (*Daiyonki-kenkyu*), vol.29, p.193-208. (in Japanese with Eng. abstracts)

———, Inouchi, Y., Kinoshita, Y., Yokota, S., Murakami, F., Onodera, K., Nohara, M., Aoki, I. and Arita, M. (1978) Sediments of Shibushi bay and its vicinity in Kyushu. *Res. Rep. Natl. Inst. Prev. Pollution, FY1977*, Agen. Indust. Sci. Techn., p.56-3-56-33. (in Japanese)

———, Inoue, E., Onodera, K., Yuasa, M. and Kuroda, K. (1982) Sediments of the Tsushima Strait and Goto-nada Sea, northwestern Kyushu. *Bull. Geol. Surv. Japan*, vol.33, p.321-350. (in Japanese with Eng. abstracts)

Okada, H. (1989) Anatomy of trench-slope basins: examples from the Nankai Trough. *Palaeogeogr. Palaeoclim. Palaeoecol.*, vol.71, p.3-13.

Okamura, M., Arita, M. and on board scientists of GH82-1 (1985) Fine grained sediment dispersal based on the tracer of calcareous nannoplankton. *J. Sed. Soc. Japan,* nos.22/23, p.50-53. (in Japanese with Eng. abstracts)

Okamura, Y. (1989) Multi-layered progradational sequences in the shelf and shelf slope of the Southwest Japan forearc, in Taira, A. and Masuda, F., eds., *Sedimentary Facies in the Active Plate Margin*, Terra Sci. Publ., Tokyo, p. 295-317.

——— (1990) Geologic structure of the upper continental slope off Shikoku and Quaternary tectonic movement of the outer zone of southwest Japan. *J. Geol. Soc. Japan*, vol.96, p.223-237. (in Japanese with Eng. abstracts)

———, Kisimoto, K., Murakami, F. and Joshima, M. (1987) Geological map of Tosa Wan (with explanatory notes). Mar. Geol. Map Ser., no.29, Geol. Surv. Japan, Tsukuba, 31p. (in Japanese with Eng. abstracts)

———, Tanaka, T. and Nakamura, K. (1986) Diving survey of the knolls on the trench slope break off Kochi, Southwest Japan. *JAMSTECR Deep-sea Res.*, p.173-192. (in Japanese with Eng. abstracts)

Oki, K. (1989) Ecological analysis of benthonic foraminifera in Kagoshima Bay, South Kyushu, Japan. *South Pacific Study*, no.10, p.1-191.

——— (1991) Origin of mixed sediments of clay-sand-gravel. *Abst. 1991 Fall Meeting, Sed. Soc. Japan*, p.20-23. (in Japanese)

Oyama, N. (1985) Calcareous nannoplanktons, in Oba, T., ed., *Paleoenvironmental Reconstruction by Oxygen and Carbon Isotopic and Micropaleontological Analysis in the Seas around the Japanese Islands*, Rep. Grant-In-Aid Sci. Res., Minist. Educ., Sci.&Cult., Kanazawa Univ., p.9-10. (in Japanese)

Reineck, H.E. and Singh, I.B. (1980) *Depositional Sedimentary Environments*, 2nd ed., Springer-Verlag, Berlin, 549p.

Rubin, D.M. and McCulloch, D.S. (1980) Single and superimposed bedforms: a synthesis of San Francisco Bay and flume observations. *Sed. Geol.*, vol.26, p. 207-231.

Saito, Y. (1989a) Modern storm deposits in the inner shelf and their recurrence intervals, Sendai Bay, northeast Japan, in Taira, A. and Masuda, F., eds., *Sedimentary Facies in the Active Plate Margin*, Terra Sci. Publ., Tokyo, p. 331-344.

——— (1989b) Late Pleistocene coastal sediments, drainage patterns, and sand ridge systems on the shelf off Sendai, northeast Japan. *Mar. Geol.*, vol.89, p. 229-244.

——— (1989c) Classification of shelf sediments and their sedimentary facies in the storm-dominated shelf: a review. *Geogr. Mag.*, vol.98, p.350-365. (in Japanese with Eng. abstracts)

——— (1989d) Sediments in the Akita Bay, in *Submarine Topography and Sediments in the Akita Bay— Reports of Anthropogenic Influence of the Sedimentary Regime of an Open Type Bay*. Geol. Surv. Japan, Tsukuba, p.14-70. (in Japanese)

———, Nishimura, A. and Matsumoto, E. (1989) Transgressive sand sheet covering the shelf and the upper slope off Sendai, northeast Japan. *Mar. Geol.*, vol.89, p.245-258.

Sakamoto, H. (1987) Inflowing processes of the Kuroshio surface water to the Tosa Bay. *Bull. Japan. Soc. Fish. Oceanogr.*, no.51, p.165-168. (in Japanese)

———, Fujimoto, M. and Nakagawa, N. (1986) The behavior of the Kuroshio surface water at the south of Honshu. *Rep. Res. Prog., Kuroshio Exploit. & Utiliz.*, no.9, Sci. Tech. Agency, p. 381-389. (in Japanese)

Sato, H., Ikehara, K. and Kawahata, H. (1985) Distribution of pumice and scoria in surface sediments at the sea south of Kyushu (off Tanegashima and Yakushima Islands and Cape Noma-misaki), in Moritani, T. and Nakao, S., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1984,* Geol. Surv. Japan, Tsukuba, p.63-71. (in Japanese)

Sato, S., Ijima, T. and Tanaka, N. (1963) A study of critical depth and mode of sand movement using radioactive glass sand. *Proc. 8th Intern. Conf. Coast. Eng., Mexico City*, p.304-323.

Sato, T. and Mogi, A. (1982) Sea level change in the Japan Sea deduced from submarine terraces and buried shelf channels. *The Quat. Res.* (*Daiyonki-kenkyu*), vol.21, p.203-210. (in Japanese with Eng. abstracts)

Shigemura, T. (1980) Tidal prism-throat area relationships of the bays of Japan. *Shore&Beach*, vol.48, no.3, p.30-35.

Simons, D.B., Richardson, E.V. and Nordin, C. F., Jr. (1965) Sedimentary structures generated by flow in alluvial channels. *SEPM, Spec. Publ.*, no.12, p.34-52.

Southard, J.B. (1971) Representation of bed configurations in depth-velocity-size diagrams. *J. Sed. Petrol.*, vol.41, p. 903-915.

——— (1975) Bed configuration, in Harms, J. C., Southard, J.B., Sprearing, D.R. and Walker, R.G., *Depositional Environments as interpreted from Primary Sedimentary Structures and Stratification Sequences. Short Course Notes*, no.2, SEPM, Dallas, p.5-43.

Suda, K. (1932) On the bottom water in the Japan Sea (preliminary report). *J. Oceanogr.*, vol.4, p.221-241.

——— and Hidaka, K. (1932) The results of the oceanographical observations on board R.M.S." Syunpu Maru" in the southern part of the Japan Sea in the summer of 1929, Part 1. *J. Oceanogr.*, vol.3, p.291-375.

Sugawara, K., Kobune, K., Sasaki, H., Hashimoto, N., Kameyama, Y. and Narita, A. (1986) Wave statistics with 15-year data in the coastal wave observation network. *Tech. Note, Port & Harb. Res. Inst.*, no.554, p.1-872.

Sunamura, T. (1986) Coastal cliff erosion in Nii-jima Island, Japan: present, past, and future —an application of mathematical model, in Gardiner, V., ed., *International Geomorphology, Part I.*, John Wiley and Sons, Chichester, p. 1199-1212.

——— (1990) A dynamical approach to wave-base problems. Trans. *Japan Geomorph. Union*, vol.11, p.41-48.

Sundborg, Å. (1956) The river Klaralven. A study of fluvial processes. *Geogr. Annl.*, vol.38, p.127-316.

Tamai, K., Sakamoto, H., Nakagawa, N., Mimoto, K. and Momota, M. (1991) Oceanographical study in the southwest areas of Japan during 1980's. *Bull. Nansei Natl. Fish. Res. Inst.*, no. 24, p.177-192. (in Japanese with Eng. abstracts)

Tanahashi, M. and Yamamoto, H. (1986) Submarine geology of the margin of San'in and Oki Islands. *Mar. Sci. Monthly* (*Gekkan Kaiyo-kagaku*), vol. 20, p.649-653. (in Japanese)

——— and ——— (1990) Geology off San'in coast, in Coast. Oceanogr. Res. Commit., Oceanogr. Soc. Japan, ed., *Coastal Oceanography of Japanese Islands, Supplementary Volume*, Tokai Univ. Press, p.739-754. (in Japanese)

Tanaka, Y. (1986) Calcareous nannofossils in the surface sediments around the Tsushima Strait, in Nakao, S., Tamaki, K. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1985,* Geol. Surv. Japan, Tsukuba, p.128-136. (in Japanese)

——— (1987) Calcareous nannofossil assemblages in the surface sediments around the Oki Islands, in Arita, M., Okuda, Y. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1986*, Geol. Surv. Japan, Tsukuba, p.177-185. (in Japanese)

——— (1988) Calcareous nannofossil assemblages in the sediments off Wakasa Bay, in Arita, M. and Moritani, T., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1987*, Geol. Surv. Japan, Tsukuba, p.170-175 (in Japanese)

——— (1989) Calcareous nannofossil assemblages in the sediments around the Noto Peninsula, in Arita, M. and Okamura, Y., eds., *Preliminary Reports of Geological Mapping Program of the Continental Shelf Areas in Japan in 1988*, Geol. Surv. Japan, Tsukuba, p.145-152. (in Japanese)

——— (1990) Preliminary reports on calcareous nannofossil assemblages in the sediments off Joetsu to Tsugaru, in Okamura, Y., Arita, M. and Okuda, Y., eds., *Preliminary Reports of Marine Geological Investigations around the Continental Shelf at central eastern Japan Sea*, Geol. Surv. Japan, Tsukuba, p.141-145. (in Japanese)

Tanimura, Y. (1985) Diatoms, in Oba, T., ed., *Paleoenvironmental Reconstruction by*

Oxygen and Carbon Isotopic and Micropaleontological Analysis in the Seas around the Japanese Islands, Rep. Grant-In-Aid, Sci. Res., Minist. Educ., Sci & Cult., Kanazawa Univ., p.8-9. (in Japanese)

Uda, M. (1934) The results of simultaneous oceanographical investigations in the Japan Sea and its adjacent water in May and June, 1932. *J. Imper. Fish. Exper. Sta.*, vol.5, p.57-190.

van Alphen, J.S.L.J. and Damoiseaux, M.A. (1989) A geomorphological map of the Dutch shoreface and adjacent part of the continental shelf. *Geol. Mijnbouw*, vol.68, p.433-443.

Vanoni, V.A. (1974) Factors determining bed forms of alluvial streams. *Proc. Am. Soc. Civ. Eng., J. Hydraul. Div.*, vol. 100, p.363-377.

Werner, F. and Newton, R.S. (1975) The pattern of large scale bedforms in the Langeland Belt (Baltic Sea). *Mar. Geol.*, vol.19, p.29-59.

Yamamoto, H. (1991) A submarine sediment slide on the continental slope off Fukui Prefecture, Southern Japan Sea. *Bull. Geol. Surv. Japan*, vol.42, p. 221-232. (in Japanese with Eng. abstracts)

——— (1992) Pliocene-Quaternary sedimentary basins off the San-in Hokuriku district, southern Japan Sea. *Bull Geol. Surv. Japan*, vol.43, p.113-117. (in Japanese with Eng. abstracts)

———, Joshima, M. and Kisimoto, K. (1990) Geological map offshore of Tottori (with explanatory notes). Mar. Geol. Map Ser., no.35, Geol. Surv. Japan, Tsukuba, 27p. (in Japanese with Eng. abstracts)

Yanagi, T. (1990a) Currents and sediment transport in the Seto Inland Sea, Japan, in Cheng, R.T., ed., *Residual Currents and Long-term Transport, Coast. Estuar. Studies*, vol.38, p.348-355.

——— (editor) (1990b) *Oceanographic features of front area —physical, chemical and biological processes at coastal fronts—*. Koseisha-koseikaku, Tokyo, 169p. (in Japanese)

———, Nukada, K., Ichikawa, H. and Higashikawa, S. (1986) Kuroshio front in Hyuga-Nada. *Umi to Sora (Sea and Sky)*, vol.62, p.1-7. (in Japanese with Eng. abstracts)

Yokota, M., Okada, H., Arita, M., Ikehara, K. and Moritani T. (1990) Distribution of heavy minerals in the bottom sediments of the southern Sea of Japan, off the Shimane Peninsula, Southwest Japan. *Sci. Rep., Dept. Geol., Kyushu Univ.*, no.16, p.59-86. (in Japanese with Eng. abstracts)

西南日本周辺海域の現世堆積作用，堆積作用と海洋環境との関係を中心として

池原　研

要　旨

西南日本周辺海域の海洋環境は，太平洋側には西岸境界流の代表である黒潮が流れ，その海洋環境に大きな影響を与えている．これに対して日本海では，黒潮系の対馬海流は存在するがその流れは弱く，また水深200m付近を境として，低温で均質な日本海固有水が発達し，顕著な成層構造を形成している．このように異なる海洋環境を含む西南日本周辺海域の全域について，現世堆積作用を海洋環境との関係から論じた．その上で，海水準変動や構造運動が堆積物分布に与える影響を再

評価した.

その結果，西南日本周辺海域の現世堆積作用は，波浪，潮流，海流，海水の成層構造，沿岸水の発達，海水の物理•化学的性質に大きく影響されていることが明らかとなった. 海流による堆積物への直接的な影響は，西南日本太平洋側の中部ー外側陸棚の砂質堆積物やベッドフォームの分布と堆積物移動に認められる. 海流の直接的な影響は，太平洋側の上部陸棚斜面や海丘部でも認められ，ここでは砂質堆積物の分布やその移動に伴って形成されるベッドフォームが分布している. これに対して日本海側では，砂質堆積物の分布の広さ，ベッドフォームの大きさや分布は太平洋側より小さく，砂質堆積物の移動量は小さいが，海流の影響は陸棚外縁部などで認められる. このように，海流の影響は太平洋側•日本海側両方の多くの場所で認められる. 太平洋側と日本海側での砂質堆積物の移動量の違いは，両者での底層流の強さの違いに起因し，それはそれぞれを流れる海流の強さの違いによっている. 一方，細粒堆積物の分布は，沿岸水と外洋水との境界や躍層などの水塊境界に規制されているが，内側陸棚域の細粒堆積物の分布域はどちらの海域においても，海流（外洋水系）に起因した流れによって規制され，流れの流入しない水域（沿岸水域）に分布している. したがって海流は，細粒堆積物の堆積する沿岸水発達域を形作るという点でも堆積物分布に影響を与えている（間接的な影響）. これに対して波浪は，水深50m以浅の堆積物に影響を与えており，淘汰の良い砂質堆積物あるいは砂礫質の残留堆積物を形成している. また潮流の影響は，豊後水道で顕著に認められるが，他の海域ではその影響は小さい. したがって波浪や潮流は，陸棚全体の堆積物分布を決めるほど大きくない. このように，堆積物分布の概要は海洋環境と密接な関係にある. これに対して海洋環境以外の要素の一つの海水準変動は，中部ー外側陸棚の砂質堆積物の形成(低海水準期の残存堆積物)，陸棚上の砂質堆積体の形成に深く関わっている. また構造運動は，堆積盆の形成やその埋積過程に関係している.