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# Large-Scale Ripple Marks on the Shelf Margin of the Northern Okinawa Trough*

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**Abstract**: Trains of large-scale ripple marks (megaripples and sand waves) were found on the Amakusa and East China Sea shelves bordering the northern Okinawa Trough. Side-scan sonar surveys were carried out in 1974 and 1976 to investigate sea-floor features lying along a proposed submarine cable line. Megaripples were found on the outer margin of the Amakusa shelf between depths of 140 and 200 m. The megaripples were especially well developed at a depth of 167 m. They were typically straight-transverse crested with asymmetrical profiles, and measured 7 to 15 m in wavelength and 0.4 to 1.4 m in waveheight. Formation of the megaripples on the Amakusa shelf is probably controlled by relatively complex oceanographic conditions. A secondary circulation associated with the Gotô-nada clock-wise Current may be responsible for formation of the ripple marks. Local vorticities generated in the coastal boundary layer as a result of curvature of the Gotô-nada Current are known to cause the complex flow pattern at the Gotô and Amakusa shelf margins. The main semidiurnal ($M_2$) tidal current may also interact with these fluid processes.

On the East China Sea shelf, megaripples and sand waves were found between depths of 140 and 220 m. Sand waves (~200 m in wavelength) were observed in seismic reflection profiles. Large-scale lunate megaripples were observed at a depth of 154 m by the side-scan sonar. They had wavelengths of 10 to 30 m and waveheights of 1 to as high as 3 m. It appears from the types and nature of distribution of the megaripples that they are responding to the present-day flow regime, and it is partly ascertained from our observations over an interval of two years that the megaripples appear to be short-term response elements compared with the sand waves. We conclude that the megaripples on the East China Sea shelf are current-formed during peak typhoon flow in August to November. From their distribution, the long term path of the main flow of the Tsushima Current is inferred at the edge of the East China Sea shelf. An area of low sediment mud content (less than 20 per cent) coincides with this path giving further support to our interpretation.

## 1. Introduction

When seismic surveys were carried out in 1968 and 1969 during cruises of the R/V *Tansei-Maru* in the East China Sea, sand waves were found at depths of 150 m to 220 m. They were about 200 m in wavelength and roughly 10 m in waveheight. When side-scan sonar surveys were carried out in 1974 and 1976 as part of a cable route survey, large-scale ripple marks were found on both sides of the Okinawa Trough at a depth of more than 150 m (Kubo *et al.*, 1980). In addition, Hoshino *et al.* (1971) reported wave-like topography with wavelengths of 200 m and crestal heights of several meters at depths of 60, 80 and 100 m on the continental shelf off the west of Kyushu, while sand ridges and sand waves were reported from the eastern channel of the Tsushima Strait (Mogi, 1981).

Previous studies on the submarine geology of the eastern margin of the East China Sea have discussed submarine topography (Emery *et al.*, 1969; Kimura *et al.*, 1969; Hoshino *et al.*, 1971; Katsura and Nagano, 1976), sediment distribution (Niino and Emery, 1961; Inako and Takeda, 1972; Kubo and Emery, 1977) and subsurface geology (Emery *et al.*, 1969; Kimura *et al.*, 1969; Nasu and Kagami, 1970; Kagami *et al.*, 1971). Sandy sediments are widely distributed on the shelf margin and these are known to be late Pleistocene relict sediments (Emery, 1968;

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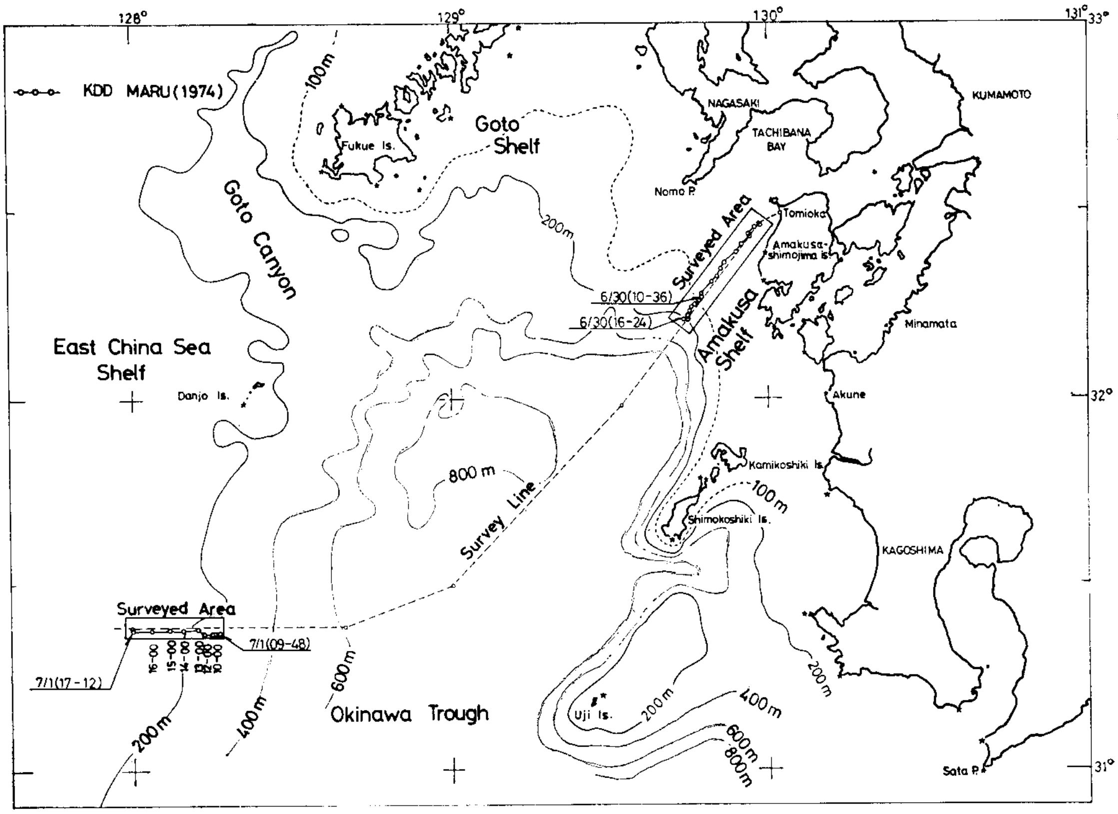


Fig. 1. Index map of the survey line and topographic names of the northern part of the Okinawa Trough area.

Emery *et al.*, 1970). Relict sediments with oyster-shell remains were collected from the shelf margin off Amakusa Island, Kyushu (Mizuno *et al.*, 1971).

In this study we report on the distribution and shape of large-scale ripple marks on both sides of the northern Okinawa Trough, and discuss their occurrence in relation to oceanographic conditions. Nomenclature of the current ripple marks adopted in this study follows that of Reinneck and Singh (1980). Ripple marks having wavelengths between 4 and 60 cm with waveheights of less than 6 cm are called small ripples (not discussed here). Those having wavelengths between 0.6 and 30 m with waveheights between 0.06 and 1.5 m are called megaripples, while those having wavelengths between 30 and 1,000 m with waveheights between 1.5 and 15 m are called sand waves or giant ripples.

The instrument used was a side-scan sonar (EG & G, Mark 1B) with a response frequency of 105 KHz, a horizontal beam angle of 1.2°,

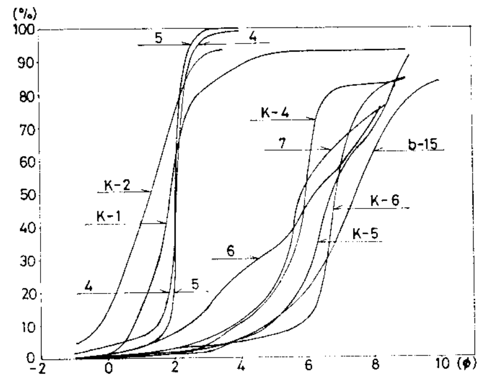


Fig. 2. Cumulative frequency curves of grain size of the collected sediments. Sampling locations and grain size parameters are listed in Table 1.

and a vertical beam angle of 20°. Towing direction and the ship's course were recorded during the operation in order to clarify the real direction of the instrument over the bottom.

## 2. Submarine topography

The survey line runs across the northern part of the Okinawa Trough (Figs. 1 and 3). The trough is surrounded by the Amakusa shelf to the east, the Gotô shelf to the north and the East China Sea shelf to the west. The Amakusa shelf is 30 to 40 km wide and 110 to 120 m deep at the shelf break within the surveyed area (see Fig. 9). The bottom topography in this area where the shelf is connected through the Amakusa Strait to an island basin called Ariake Bay is very complicated. A large and rapid tidal current is known to occur in the bay. The continental slope has a gradient of about 2° and reaches the basin bottom of the Danjo Basin at a depth of 720 m, which is the northern extension of the Okinawa Trough.

Along the shelf margin of the East China Sea,

Table 1. Sampling locations and grain size parameters.

| Sample No. | Location | | Depth (m) | Median diameter Md$\phi$ | Sorting[a] coefficient $\sigma\phi$ | Ratio sand-silt-clay % | | |
|---|---|---|---|---|---|---|---|---|
| | North | East | | | | | | |
| K 1 | 32-22.1 | 129-45.9 | 96 | 1.80 | 0.58 | 88 | 5 | 7 |
| K 2 | 32-15.5 | 129-45.5 | 119 | 1.26 | 0.83 | 94 | 6 | 0 |
| K 4 | 31-59.0 | 129-32.0 | 712 | 5.95 | 0.53 | 10 | 71 | 19 |
| K 5 | 31-52.6 | 129-22.4 | 768 | 6.70 | 1.05 | 5 | 52 | 43 |
| K 6 | 31-46.5 | 129-13.3 | 763 | 6.85 | 0.55 | 5 | 55 | 40 |
| b 15 | 31-30.2 | 128-58.9 | 725 | 7.50 | 1.05 | 11 | 28 | 61 |
| 4 | 31-23.5 | 128-09.8 | 157 | 2.10 | 0.18 | 100 | 0 | 0 |
| 5 | 31-23.7 | 128-19.8 | 247 | 2.05 | 0.08 | 100 | 0 | 0 |
| 6 | 31-23.5 | 128-29.8 | 447 | 6.25 | 2.18 | 35 | 32 | 33 |
| 7 | 31-23.4 | 128-40.0 | 642 | 5.80 | 1.48 | 21 | 53 | 26 |

[a] Phi quartile deviation.

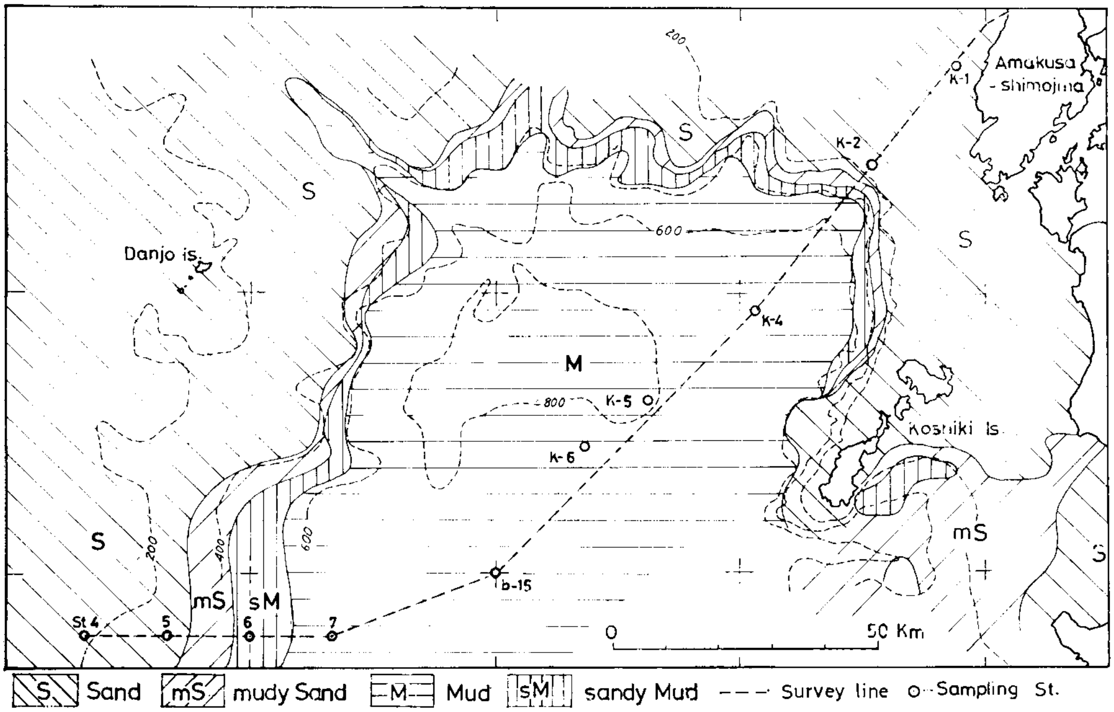


Fig. 3. Sediment distribution map and sampling locations of the northern part of the Okinawa Trough. Sediment distribution data are from Inako and Takeda (1972) with additional data from the present study.

two flat plains were observed between 110 and 120 m and between 150 and 160 m (see Fig. 10). It was mainly on the deeper plain that large-scale ripple marks were developed. The gradient of the continental slope is about 1°.

On the Gotô shelf, a shelf break is developed at a depth of 115 to 120 m, however there is another flat plain at a depth of 140 m on the western side of the Gotô shelf. The gradient of the continental slope is about 30′.

### 3. Sediment distribution

Sediment distribution in this area and the location of bottom sampling along the cable route are shown in Fig. 3. The results of grain size analysis by sieving and hydrometer are listed in Table 1 and shown in Fig. 2.

The sample from Station K2 on the Amakusa shelf, where large-scale ripple marks were observed, shows a median diameter of 1.26 $\phi$, and a sorting coefficient (Phi quartile deviation) of 0.83 (Krumbein and Pettijohn, 1938). Mud content is six per cent. Station 4 from the East China Sea shelf lies in another ripple mark area and a sample from this station has a median diameter of 2.1 $\phi$ and a sorting coefficient of 0.18. Mud content is negligible. The coarser and more poorly sorted bottom sediments on the Amakusa shelf may be explained by stronger bottom flow and/or by the presence of coarse relict sediments. According to Inako and Takeda (1972), these sands are relict shoreline sediments deposited during the period of lower sealevel in glacial times. If the medium sand on the Amakusa shelf is in fact relict sand as they reported, then bottom flow on the Amakusa shelf is not necessarily stronger.

Inako and Takeda (1972) studied mud content distribution on the shelf margins. They made the interesting finding that the mud content increased with depth from the shelf break to the slope on the Amakusa and Gotô shelf margins, while it reached a minimum value at a depth of 180 m on the East China Sea shelf margin. This former observation may indicate the most common profile on the narrow continental shelf around Japan, while the latter observation on the East China Sea shelf margin may indicate the effects of present day flow on bottom sediments.

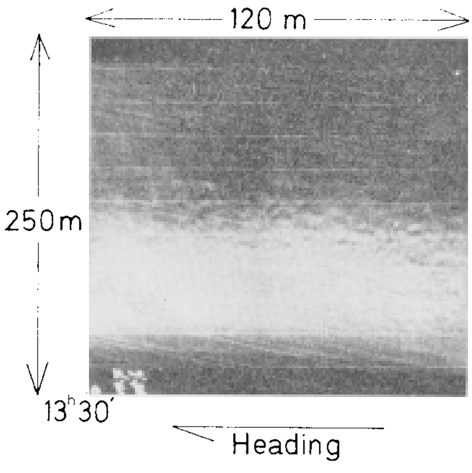


Fig. 4. Side-scan sonar record showing small relief of bedforms at a depth of 140 m on the Amakusa shelf. This record shows the bottom condition at the shallowest area of megaripple development.

### 4. Shape and distribution of large-scale ripple marks on the shelf margins

*4.1. The first survey*

On the Amakusa shelf, ripple marks were observed at depths between 140 and 199 m (see Fig. 9). The bedforms showed only small relief at 140 m (Fig. 4), but had a definite form. By a depth of 150 m, the bedforms clearly showed the typical shape of megaripples and were present over a distance of 3.5 km to a depth of 182 m. The megaripples were particularly well developed at a depth of about 167 m (Fig. 5).

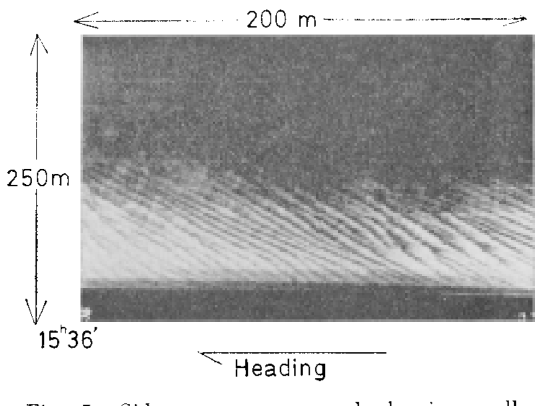


Fig. 5. Side-scan sonar record showing well developed megaripples of straight-transverse type observed at a depth of 167 m on the Amakusa shelf.

They became scarce in deeper water until they finally disappeared at a depth of about 200 m. Typically they were straight-transverse crested with asymmetric profiles, and measured about 7 to 15 m in wavelength and 0.4 to 1.4 m in waveheight.

On the East China Sea shelf, megaripples were developed between 140 to 170 m and deeper. Due to the short cable length of the side-scan sonar and also severe sea conditions, bedforms at depths greater than 170 m could not be studied by the side-scan sonar. Over a distance of about 7 km between depths of 147 and 152 m, straight crested megaripples with a wavelength of 4 to 26 m and a waveheight of 0.4 to 1.5 m were observed (Fig. 6). They were not uniformly distributed, but alternated with areas without megaripples. Over the next 5 km between depths of 153 to 157 m, a train of lunate megaripples were found (Fig. 7). They had a wavelength of 10 to 30 m and a waveheight of 1 to about 3 m, with a horizontal form index (ratio of span to waveheight) of 1.2 to 1.5 and a vertical form index (ratio of wavelength to waveheight) of 10 to 30. These indices are within the ranges reported from other parts of the world (Allen, 1968, pp. 60–71). At these depths the megaripples were not uniformly developed, but rather areas of megaripples alternated with areas in which megaripples were scarcely developed (Fig. 8). In an adjorning area approximately 10 km wide between depths of 158 and 160 m, trains of sinuous and catenary megaripples with wavelengths of 4 to 15 m and waveheights of 1 to 1.5 m were found. Trains of lunate and catenary megaripples with wavelengths of 5 to 20 m and waveheights of 0.5 to 1 m appeared again at depths of 161 to 165 m. Straight crested megaripples became predominant at still greater depths.

Megaripples were thus found on both sides of the northern part of the Okinawa Trough. The submarine topography and arrangement of the megaripples are shown in Figs. 9 and 10. Crestlines of the megaripples on the Amakusa shelf were almost parallel to the depth contours and the direction of the bottom flow was deduced to be to the southwest from the asymmetry of the ripple profile on the records. While, those

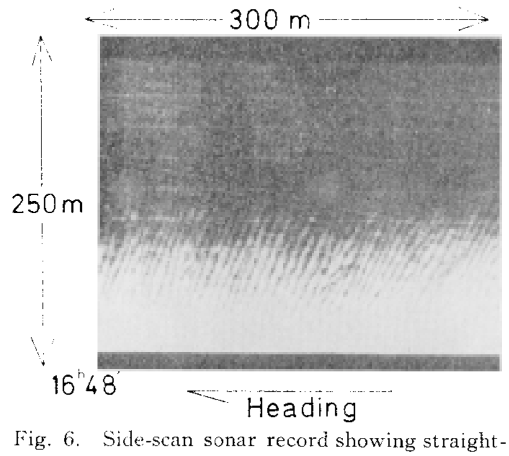


Fig. 6. Side-scan sonar record showing straight-transverse megaripples observed at depths between 147 and 152 m on the East China Sea shelf.

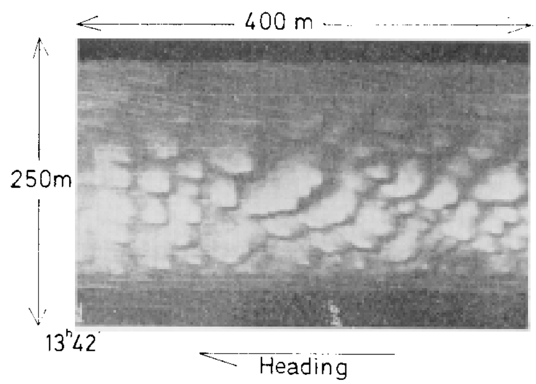


Fig. 7. Side-scan sonar record showing well developed lunate megaripples observed at a depth of 154 m on the East China Sea shelf.

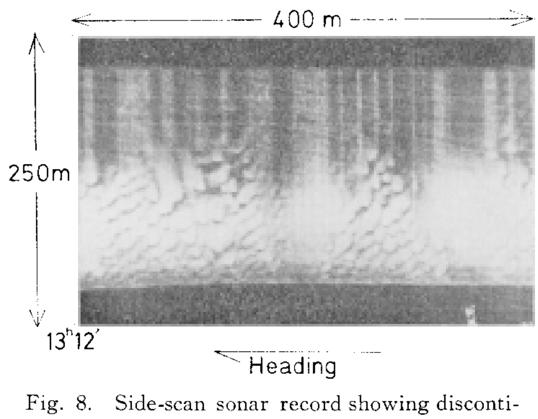


Fig. 8. Side-scan sonar record showing discontinuous development of sinuous and catenary (wavy) megaripples observed at a depth of 156 m on the East China Sea shelf margin.

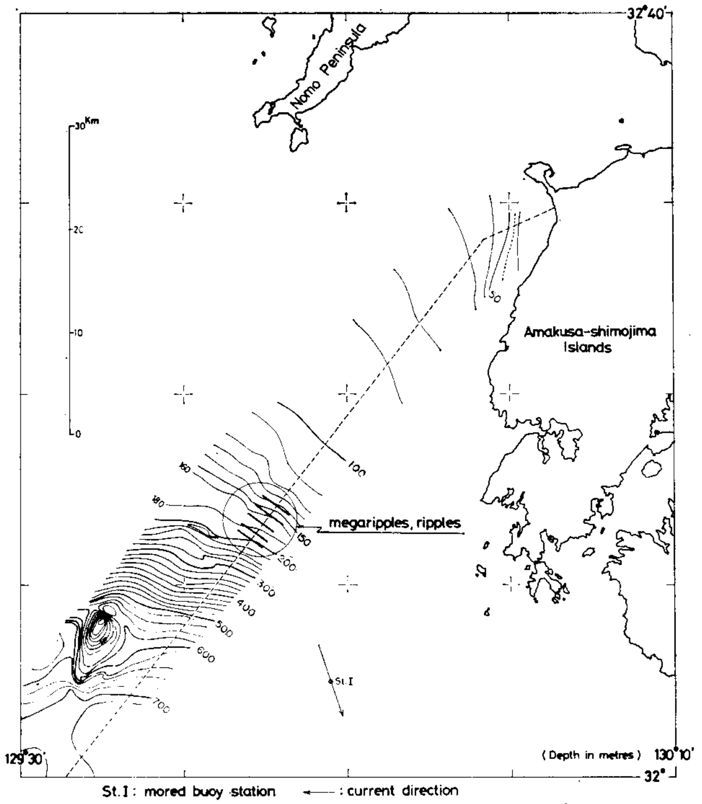


Fig. 9. Bathymetry along the survey line, orientation of crestlines of the megaripples at a depth of 167 m, and direction of bottom flow by current measurement at Station I on the Amakusa shelf. Current measurement data are listed in Table 2.

on the East China Sea shelf were aligned at about 50° to 60° to the contour lines and a northward flow direction was deduced from their profile on the records.

*4.2. The second survey after two years*

The first survey described above was carried out between 30 June and 1 July 1974. A second survey was carried out along the same route after two years and in the same season between 22 June and 1 July 1976.

On the Amakusa shelf, megaripples were observed at depths between 150 and 180 m. They were straight crested, but poorly developed compared with those of the former survey shown in Fig. 5.

On the East China Sea shelf, megaripples were observed between depths of 140 to 170 m and deeper. Again, the deeper portion could not be observed for technical reasons. In an area 13 km wide between the depths of 140 and 146 m, only bedforms of small relief were recognized. Over the next 13 km at depths ranging from 147 to 152 m, areas of well-developed megaripples alternated with areas of scarce megaripple development. The areas of well-developed megaripples were about 200 to 1,000 m wide in the direction roughly perpendicular to the crests. The megaripples were straight crested with a wavelength of 15 m and a waveheight of about 1.5 m. Over the next 12 km at depths of 152 to 157 m, a train of lunate megaripples with wavelengths of 5 to 40 m and waveheights of 0.4 to 1.6 m were found in the same area that lunate megaripples were observed in the former survey (Fig. 7). Over the next 3 km at depths of 158 to 160 m, areas 200 to 1,000 m wide having well-developed megaripples alternated with areas of poorly developed megaripples. From 160 to 170 m depth over a distance of 3.5 km, straight crested megaripples were ob-

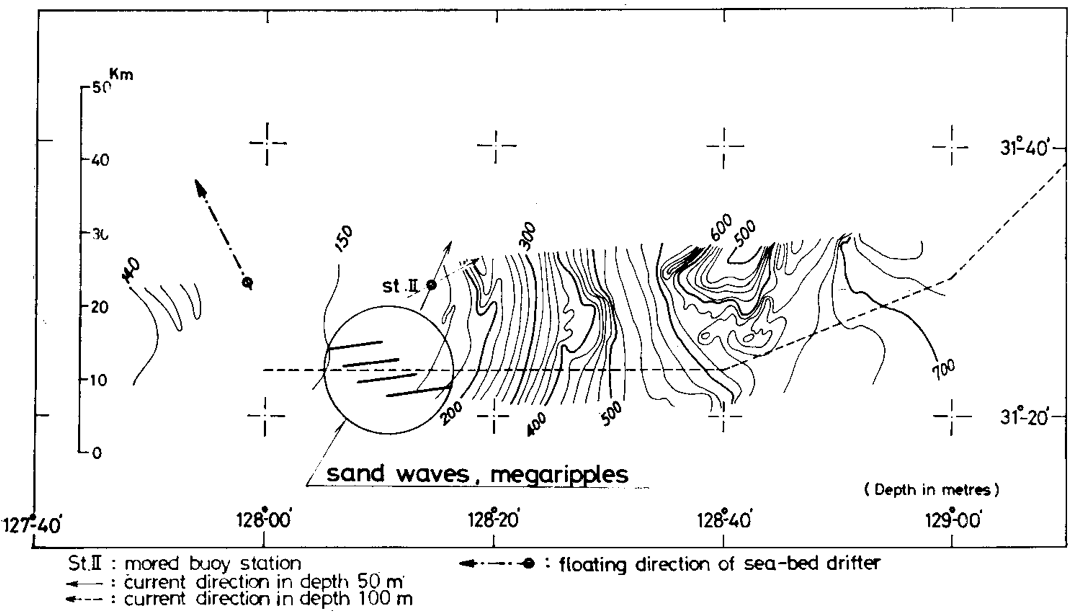


Fig. 10. Bathymetry along the survey line, orientation of crestlines of the megaripples at a depth of 156 m, and directions of bottom flows at Station II and the seabed drifter station on the East China Sea shelf.

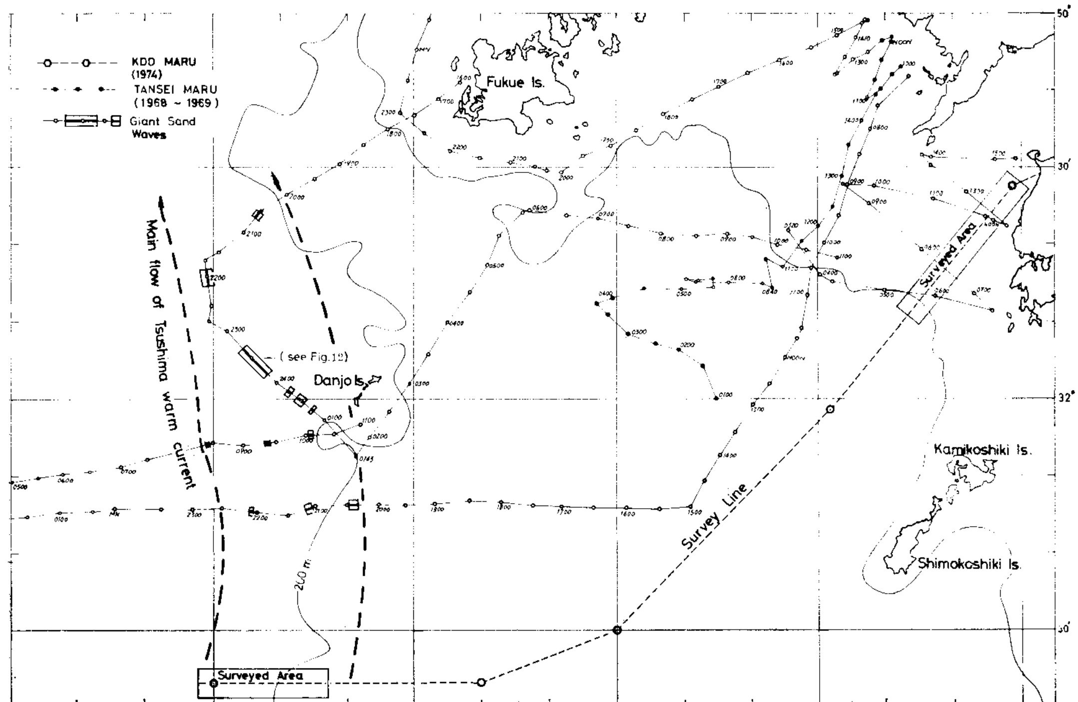


Fig. 11. Track lines of the R/V *Tansei-Maru* for continuous seismic reflection survey and distribution of sand waves observed on the East China Sea shelf. A proposed long term path of the main flow of the Tsushima Current is shown between broken lines.

served with wavelengths of 5 to 10 m and wave-heights of 0.5 to 1 m.

In conclusion, the second survey revealed essentially the same depth related pattern of megaripples as the first survey, but clearly showed that the bedforms are short-term (<2 yr) response elements.

## 5. Sand waves observed on the continuous seismic records

Sand waves were found during the KT 68-13 and KT 69-13 cruises of the R/V *Tansei-Maru* of the Ocean Research Institute, University of Tokyo in 1968 and 1969. Figure 11 indicates the seismic reflection survey lines and localities where sand waves were found. The seismic energy source was a sparker type electric discharge using a total of 90 $\mu$F condensers at 6.5 KV which corresponds approximately to 1,900 joules. The receiving frequency of the record was between 106 and 350 Hz, and the ship's speed was 8 knots. Sand waves were observed as deep as 220 m. The shallowest occurrence was at about 150 m. They were distributed in the areas northwest, west and south of the Danjo Islands as shown in Fig. 11. On the southern most line of the reflection survey, sand waves were observed at depths of 170, 200 and 220 m.

Figure 12 shows the seismic record of sand waves found west of the Danjo Islands between 23:30 and 24:00 on 20 July 1968. This is the shallowest occurrence of sand waves near the Danjo Islands. On the record, sand waves are identified as small crested ridges along the 150 m depth marker. They have a wavelength of about 200 m and a waveheight of roughly 10 m or less, but as the resolution of the profiling did not exceed 4 m in this case, the heights of the sand waves could not be accurately determined.

It is interesting to note that the sand waves described here are one order of magnitude larger than megaripples observed on the side-scan sonar. This matter will be discussed later.

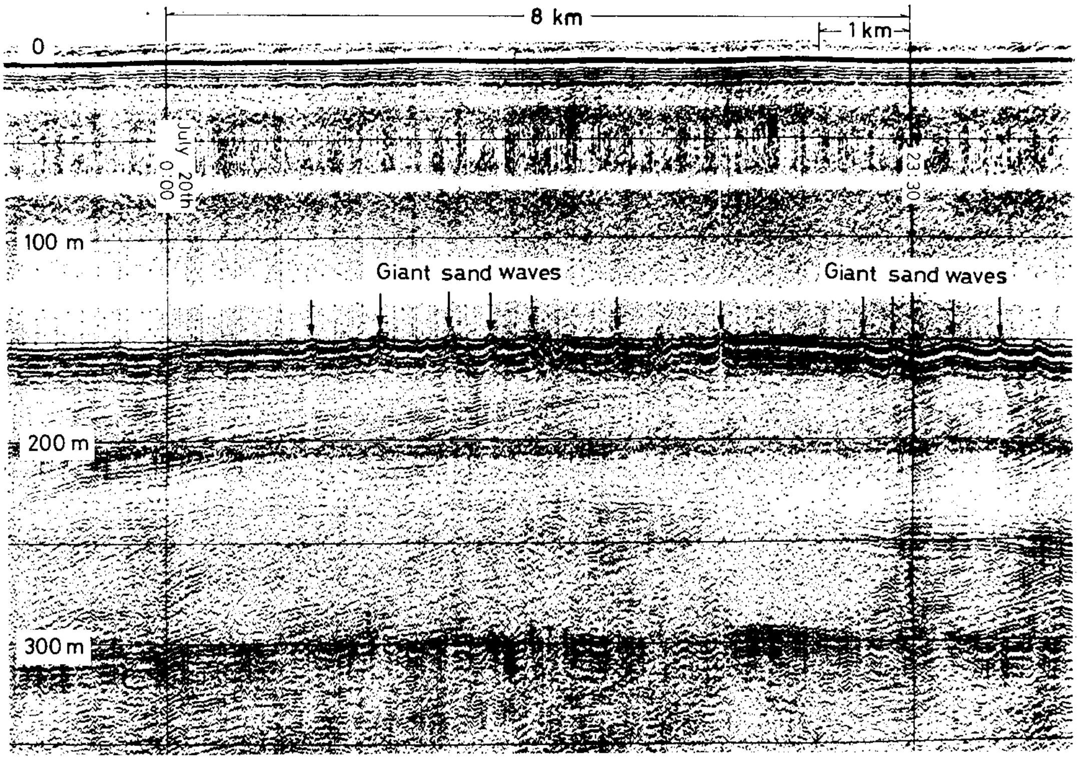


Fig. 12. A record of continuous seismic reflection profiling showing sand waves found west of the Danjo Islands on the East China Sea shelf.

## 6. Estimation of bottom flow along the shelf margins

In order to clarify the real direction of the instrument (side-scan sonar) over the bottom, Fig. 13 gives a vector diagram of the ship's heading, its true course relative to the ground, and the inferred current (wind) or drift direction. The inferred current (wind) on the Amakusa shelf was about 1 knot (51.4 cm $sec^{-1}$) to the SSW at 15:30 on 30 June 1974. This direction was only 15° off perpendicular to the crestlines of the megaripples shown in the figure. The tidal record at nearby Hayasaki-Seto Station on the Amakusa Islands shows that the tide was flooding toward the NE at 14:54 and was slack at 18:22. Therefore, the inferred current (wind) from the vector diagram was due mainly to a wind-driven component or to a constant current component.

The vector diagram for the East China Sea shelf shows a southward flow of 2.65 knot (136 cm $sec^{-1}$) during the survey at approximately 13:30 on 1 July 1974. The tidal record at Hirado Station in northern Kyushu indicates that the tide was ebbing toward the Station at 11:13 and was slack at 14:52. Since the tidal station is located north of the surveyed area, the tide in the surveyed area may have already been slack at the time of the survey. Therefore, most of the inferred drifting was probably due to a wind-driven component with a small tidal current component.

Current measurements were carried out in 1967 and 1968 by Kondo and Tamai (1975) using moored buoys over both the Amakusa and East China Sea shelves. Table 2 lists current measurement stations near the megaripple observation sites. Station I was located on the margin of the Amakusa shelf at a depth of 145 m. A constant flow of 12.5 cm $sec^{-1}$ to the SSE (161°) was observed at 30-m depth over a period of two days (Fig. 9). Almost the same result was obtained by GEK current measurements in autumn 1979 (Odamaki, 1982). These authors concluded that the constant flow is due to the southeasterly branch of the warm Tsushima Current (Gotô-nada Current). Diurnal and semidiurnal tidal ellipticities were calculated by Kondo and Tamai (1975) from the data from Station I, but neither directions fitted the direction perpendicular to the ripple crestlines.

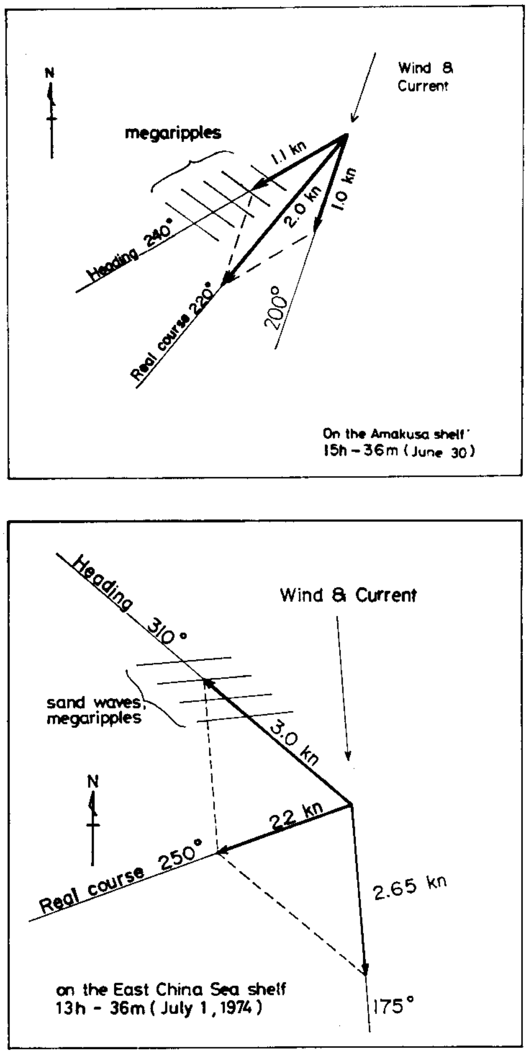


Fig. 13. Vector diagrams of the ship's heading, real course, and inferred current (wind) direction are made on condition that the towing direction of the instrument was aligned with the course of the ship. In this way the orientation of the crestlines of the megaripples is determined on the Amakusa and East China Sea shelf margins.

Station II was located on the margin of the East China Sea shelf at a depth of 158 m. A constant flow of 27 to 31 cm $sec^{-1}$ to the NNE (21° to 56°) at a depth of 50 m, and of 28 to 73 cm $sec^{-1}$ to the ENE (61° to 76°) at a depth of 100 m was measured at Station II (Table 2 and Fig. 10). Tidal data at a depth of 50 m indicated predominance of semidiurnal tidal flow with a

Table 2. Current measurements after Kondo and Tamai (1975) and the estimated average flow from bedform data on the Amakusa and East China Sea shelf margins

| Station No. | Date | Location | | Water depth (m) | Measured depth (m) | Constant flow | |
|---|---|---|---|---|---|---|---|
| | | North | East | | | direction (degree) | velocity (cm sec$^{-1}$) |
| I | 19-20 May 1967 | 32-05.0 | 129-49.0 | 145 | 30 | 161 | 12.5 |
| II | 7- 8 May 1968 | 31-29.5 | 128-14.8 | 158 | 50 | 23 | 27.2 |
| | 7- 8 May 1968 | | | | 100 | 61 | 31.3 |
| | 8- 9 May 1968 | | | | 50 | 21 | 31.5 |
| | 8- 9 May 1968 | | | | 100 | 76 | 37.8 |
| | 9-10 May 1968 | | | | 50 | 56 | 31.6 |
| | 9-10 May 1968 | | | | 100 | 75 | 28.5 |
| Side-scan record Amakusa at 15:36 | 30 June 1974 | 32-13.3 | 129-44.6 | 167 | 167 | 215 | 9-(56) |
| Side-scan record East China Sea at 13:36 | 1 July 1974 | 31-23.2 | 128-10.7 | 157 | 157 | 355 | 13-(47) |

WNW-ESE orientation, while diurnal and semi-diurnal tidal flows calculated at a depth of 100 m changed their direction frequently, resulting a rather complex flow pattern (Kondo and Tamai, 1975).

Sea-bed drifter tracking on the East China Sea shelf was carried out by Inoue (1975) in November 1969 and May 1970. One of the stations was close to the megaripple site as shown in Fig. 10. The direction of the bottom current indicated NNW drifting, which is in close agreement with the current direction inferred from the megaripples. It is known that the main flow of the warm Tsushima Current passes this area, and it peaks during the period of August to November (Inoue, 1981; Huh, 1982).

According to Allen (1968, pp. 144), the order of flow magnitude can be estimated from bedform and grain size. The megaripples on the Amakusa shelf were of asymmetrical straight crested type and the median grain size was 0.4 mm (Table 1). Megaripples of this type are formed when the flow power $U\tau_0$ is in the range of 0.74 to 2.66 g cm$^{-1}$ sec$^{-1}$. The shear stress $\tau_0$ is generally of the order of 0.048 to 0.078 g cm$^{-2}$. Therefore, the average flow $U$ is estimated to be 9 to 56 cm sec$^{-1}$ on the Amakusa shelf.

In the same way, the megaripples found on the East China Sea shelf with a median grain size of 0.23 mm are formed when $U\tau_0$ is in the range of 1.03 to 2.22 g cm$^{-1}$ sec$^{-1}$ which corresponds to an average flow of 13 to 47 cm sec$^{-1}$. The lower ranges of the estimates are consistent with the direct current measurements (Table 2), and the bottom flow on the East China Sea shelf may be stronger than that on the Amakusa shelf. It should be noted that sand waves are only recognized on the East China Sea shelf, and the mud content is higher on the Amakusa shelf (Table 1).

## 7. Discussion and conclusion

In the preceeding sections, tidal and constant currents have been discussed in order to determine the principal causes of formation of the large-scale ripple marks on the Amakusa and East China Sea shelves.

The crestlines of magaripples found at a depth of 157 m on the East China Sea shelf were aligned at 50° to 60° to the depth contours. From the profile on the record, the ripple-creating bottom flow was estimated to be a northward flow having an average velocity of the order of 10 cm sec$^{-1}$. We think the warm Tsushima Current is the most likely cause of the northward direction of bottom flow. The Tsushima Current peaks during the period of August to November (Huh, 1982). In addition, the shelf is strongly and frequently affected by southerly typhoon swell during that period. These fluid processes may cause bedform response jointly and interdependantly. According to Swift *et al.* (1979), megaripples on the New York-New Jersey shelf are current-formed during peak storm flows. The flow on the New York-New Jersey shelf is primarily alongshore to the southwest, and storms that intensify the mean southwestward flow appear to transport the most fluid and do the most work on the bottom.

Periodical interaction of the main semidiurnal ($M_2$) tidal current with a WNW-ESE orientation may be effective in forming bedforms on the East China Sea shelf. Tidal current is strong in autumn, therefore the combined effects of current, swell, and tide may cause bedform response especially in autumn.

The direction of the large-scale ripple marks on the Amakusa shelf does not fit any of the tidal harmonics or the constant flow system (Kondo and Tamai, 1975). Crestlines of the megaripples found at a depth of 167 m on the Amakusa shelf were nearly parallel to the depth contours, and the direction of bottom flow estimated from the megaripple profiles was to the SW. According to Odamaki (1982), the cotidal lines of the semidiurnal ($M_2$) tide are in general aligned well with the bathymetric contours in this area, and the tidal difference becomes larger toward land. As a result, the return flow near the bottom perpendicular to the contour lines may be stronger, as diurnal ($K_1$) tidal current harmonics partly indicated. There is another possibility that internal tidal waves or seiches may form the megaripples, but we have no actual data on such phenomena in this area.

Local vorticity currents may be responsible for creation of the megaripples on the Amakusa shelf. Heathershaw and Hammond (1980) proposed a secondary circulation effect associated with the primary flow. The secondary circulation is likely to consist of helical motions of the type that are commonly found at river bends where centrifugal forces carry fluid particles at the surface to the outside of the bend and the resultant pressure gradient and frictional effects produce a return flow at the bottom. On the Amakusa shelf, eddies may be maintained by vorticity generated in the coastal boundary layer as a result of curvature of the Gotô-nada Current, the SE branch of the Tsushima Current, near the Gotô and Amakusa shelf margins as Odamaki (1982) showed in his Fig. 10. His observations are suggestive of a near bottom convergence across the outer shelf margin of Amakusa, combined with the present study. It is known that the secondary current is about an order of magnitude lower than the primary flow (Heathershaw and Hammond, 1980). On this point, our observations and the estimated average velocity seem to be consistent with the vorticity theory. Probably, the combined effects of both tidal and local vorticity currents contribute to formation of the megaripples on the Amakusa shelf.

There seems to be a good relationship between a paucity in mud content in the sediment and development of ripple marks. Analysis of sediment grain size has been carried out extensively on the East China Sea shelf (Inako and Takeda, 1972; Inoue, 1975). Inako and Takeda (1972) showed the relationship of mud content to water depths in their Fig. 5. On the East China Sea shelf, mud contents of less than 20 per cent are observed at depths between 150 to 230 m, and the minimum mud content of less than 5 per cent is distributed at a depth of 180 m, although only a few analyses of grain size were given from depths deeper than 200 m in their figure. It is clear that the mud content increases in both the deeper and shallower areas outside the 150–230 m zone. We found megaripples developed at depths between 140 and 220 m on the East China Sea shelf. Therefore, there is a good coincidence between the distribution of mud content and ripple marks in this depth range. From the above-mentioned facts and from present knowledge of oceanographic conditions, we suspect that the area of development of ripple marks and minimum mud content may indicate the main path of bottom flow, and, further, that the bottom flow may represent the long term path of the main flow of the Tsushima Current on the shelf margin (Fig. 11). We can not determine the whole cross section of the Tsushima Current from our sedimentlogical evidence alone. The Tsushima Current may be much wider tha is shown in Fig. 11, even though we know the bottom configuration of the Tsushima Current in part. It is unlikely that a western extension of the current exists, because thick mud deposition has occurred on the inner shelf (Inoue, 1975). There is, however, a possibility that an eastern extension of the current exists. If this is the case, it may become the Gotô-nada Current after being forced to separate from the main Tsushima Current by the Danjo Islands which are located at the eastern margin of the proposed path of the Tsushima Current.

The relationship of the sand waves revealed on the continuous seismic records to the megaripples observed on side-scan sonar records on the East China Sea shelf is another problem yet to be solved. There are two possible explanations for the origin of the sand waves. They may be relict features which have survived since the early Holocene when the sea level was much lower (Swift and Ludwick, 1976), or they may be formed by the present flow regime as long term response elements (Swift *et al.*, 1979). Sand waves may have been observed on the side-scan sonar records. We described the alternation of zones where megaripples were developed extensively with zones in which they were not developed on the side-scan sonar records. The width of these zones ranged from 30 to 1,000 m. This is approximately of the same size as the wavelengths of the sand waves. Thus, it is possible that these zones represent troughs and crests of the sand waves. If this observation is correct, the megaripples develop as short term response elements on the sand waves which are sustained for longer periods. Further study will be needed before a conclusion can be reached on this matter.

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## References

Allen, J. R. L. (1968): Current Ripples. North-Holland, Amsterdam, 433 pp.

Emery, K.O. (1968): Relict sediment on continental shelves of the world. Am. Assoc. Petrol. Geol. Bull., **52**, 445-464.

Emery, K.O., Y. Hayashi, T. W. C. Hilde, K. Kobayashi, J. H. Koo, W.C.S. Meng, and S.J. Yang (1969): Geological structure and some water characteristics of the East China Sea and Yellow Sea. ESCAFE, CCOP, Tech. Bull., **2**, 3-43.

Emery, K.O., H. Niino and B. Sullivan (1970): Post-Pleistocene sea levels of the East China Sea. Silliman vol., Yale Univ., 381-390.

Heathershaw, A. D. and F. D. C. Hammond (1980): Secondary circulation near sand banks and in coastal embayments. Deut. hydrogr. Z., **33**, 135-151.

Hoshino, M., S. Kimusuna and H. Sugano (1971): Topography and geology of the continental margin in the west of Kyushu Island and near Senkaku Islands. Proc. Symposium Geol. Soc. Japan, 71-79 (in Japanese).

Huh, O.K. (1982): Satellite observations and annual cycle of surface circulation in the Yellow Sea, East China Sea and Korea Strait. La mer, **20**, 210-222.

Inako, M. and M. Takeda (1972): The sediments near Koshiki Island in the west of Kyushu island. Bull. Depart. Sci. and Culture, Nihon Univ., **7**, 1-12.

Inoue, N. (1975): Bottom current on the continental shelf of the East China Sea. Monthly Marine Science, **7**, 12-18 (in Japanese).

Inoue, N. (1981): Hydrographic condition in the East China Sea and Tsushima warm current area. in Biology of Goto Islands, Biological Soc. Nagasaki Pref., 29-72 (in Japanese).

Kagami, H., N. Nasu and H. Niino (1971): Submarine geology of the East China Sea. Proc. Symposium Geol. Soc. Japan, 81-87 (in Japanese).

Katsura, T. and M. Nagano (1976): Submarine topography and geological structures in the offshore area of the northwestern Kyushu. J. Oceanogr. Soc. Japan, **32**, 139-150.

Krumbein, W.C. and F.J. Pettijohn (1938): Manual of Sedimentary Petrography. New York, Plenum, 549 pp.

Kimura, M., T. Hiroshima and E. Inoue (1969): Geological structure beneath the East China Sea. Monthly Marine Science, **7**, 45-51 (in Japanese).

Kondo, M. and K. Tamai (1975): On the currents in the East China Sea. Monthly Marine Science, **7**, 27-33 (in Japanese).

Kubo, S. and K.O. Emery (1977): Shelf sediments of Japan. Petrol. Geol. Taiwan, **14**, 241-248.

Kubo, S., H. Kagami and N. Nasu (1980): Sand waves on the outer shelves around the Okinawa Trough found by side-scan sonar. Abstr. Intern. Geol. Congr. Paris, **2**, 497.

Mizuno, A. and Marine Geology Research Group (1971): Submarine Geology in the west of Kyushu Island. Proc. Symposium Geol. Soc. Japan,

61-69 (in Japanese).
Mogi, A. (1981): Geomorphological evolution of continental shelves of Tsushima Strait. Quaternary Research, **20**, 243-256.
Nasu, N. and H. Kagami (1970): Survey report of submarine geology in the west of Nagasaki Prefecture. Rep. to Nagasaki Pref., 1-4 (in Japanese).
Niino, H. and K.O. Emery (1961): Sediments of shallow portions of East China Sea and South China Sea. Geol. Soc. Amer. Bull., **72**, 731-762.
Odamaki, M. (1982): Tidal current system and coastal flow pattern in the Gotô Sea area. Bull. Coastal Oceanogr., **19**, 112-120 (in Japanese).
Reinneck, H.E. and I. B. Singh (1980): Depositional Sedimentary Environments (2nd Edition). Springer-Verlag, Berlin, 549 pp.
Swift, D.J.P. and J.C. Ludwick (1976): Substrata response to hydraulic process: Grain size frequency distributions and bedforms. In: Marine Sediment Transport and Environmental Management, ed. by Stanley and Swift, pp. 159-196.
Swift, D.J.P., G.L. Freeland and R.A. Young (1979): Time and space distribution of megaripples and associated bedforms, Middle Atlantic Bight, North American Atlantic shelf, Sedimentology, **26**, 389-406.

# 沖縄トラフ北部の大陸棚縁辺にみられるリップルマークについて

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**要旨**: 天草大陸棚および男女群島南方の東支那海大陸棚の縁辺にみられるリップルマークとよぶ海底に残された砂紋を記載した. 天草大陸棚のリップルマークは水深140～200 m に分布する. その配列は等深線に平行であり, かつ深い方へ流れたことを示した. この成因に関しては五島灘を南東に流れる対島暖流の分流が関与する渦の作用によるものと推定した.

東支那海大陸棚のリップルマークは水深140～220 m にわたり, かつ等深線に対して60° の方向に配列していることから, 大陸棚縁辺に平行な流れの存在が考えられ, 断面から北向きの流れであることが判った. この成因に関しては夏～秋の台風時に最強流となる対島暖流によるものと考察した. また, 2年の間をおいて観察したリップルマークの変化は, 波長30 m 以下のものについてはかなり変動していることが明らかとなった.

以上のような事実は, リップルマークは現海況に支配された流れの良い指標となることを示し, その成果として東支那海大陸棚の長期的な意味で対島暖流の本流の位置を示すことが可能となった.

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