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Echo characters and sedimentary processes along a rifting continental margin, northeast of Taiwan

Eason Hong*, I Shih Chen

Department of Oceanography, National Taiwan Ocean University, Keelung, 202 Taiwan, ROC

Abstract

The northeastern offshore of Taiwan, including the southern-most East China Sea continental margin, Ilan Shelf, Ilan Ridge and the western tip of the Okinawa Trough, is characterized by active rifting and an energetically complex hydrodynamic flow regime. In this study, sedimentary processes on the sea floor were inferred from regional mapping of 3.5 kHz echo characters. Eight distinct echo types were mapped, and based on echo type distribution, analysis of sediments and regional bathymetry, these were interpreted as deposits that had been formed under the influence of various local hydrodynamic processes. Different sedimentary processes, interpreted from the lithology and distribution pattern of sediments, were found to prevail on different physiographic provinces. In the southern East China Sea continental shelf margin, it is the outflow of Taiwan Strait Water and the on-shelf intrusion, upwelling and countercurrent induced by the impinging and turning of the Kuroshio Current that largely determine the distribution of sediments. On the narrow Ilan continental shelf, the deposition is mainly influenced by subaqueous deltaic and shallow marine processes. Over the rifting tip of the Okinawa Trough, including the Okinawa Trough Basin and its nearby slopes, the primary seafloor-shaping agents have been the mass-wasting processes and turbidity currents. Since the observed sediment data is in good consistency with other hydrographic data, the studies of transportation and deposition patterns of sediment can provide good constraints for the interpretation of physical oceanographic data.

Keywords: Echo characters; Rifting continental margin; Sedimentary processes; Taiwan

1. Introduction

The island of Taiwan is situated in the conjunction between the Ryukyu Volcanic Arc lying to the northeast and the Luzon Island Arc to the south. The East China Sea,

* Corresponding author. Fax: 886-02-24623073.
E-mail address: eason@ntou66.ntou.edu.tw (E. Hong)

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the Taiwan Strait and the West Philippine Sea are located to the north, west and east of Taiwan, respectively (Fig. 1). In northeastern Taiwan, the actively rifting southern Okinawa Trough extends westwards into the Ilan plain of Taiwan (Ho, 1982; Letouzey and Kimura, 1986; Hsu and Sibuet, 1995) separating the East China Sea continental shelf from the Ilan Ridge, the west-most part of the Ryukyu Volcanic Arc (Fig. 1). This tectonically active area is characterized by a rugged complex physiography and frequent subsidence and earthquakes (Yeh et al., 1989; Hsu, 1990).

The Kuroshio Current, the western Pacific Boundary Current, flows northward along the eastern coast of Taiwan. After crossing the Ilan Ridge into the southern Okinawa Trough, the Kuroshio turns northeastwards along the East China Sea continental slope. Crossing the Ilan Ridge and changing direction cause the Kuroshio to change tremendously in its flow regime (Hsueh et al., 1993; Chen et al., 1995). Accordingly, the hydrodynamics of the northeastern offshore region of Taiwan is very energetic and complex, and the region has long been a focus of study for many oceanographic disciplines. A multidisciplinary program known as the Kuroshio Edge

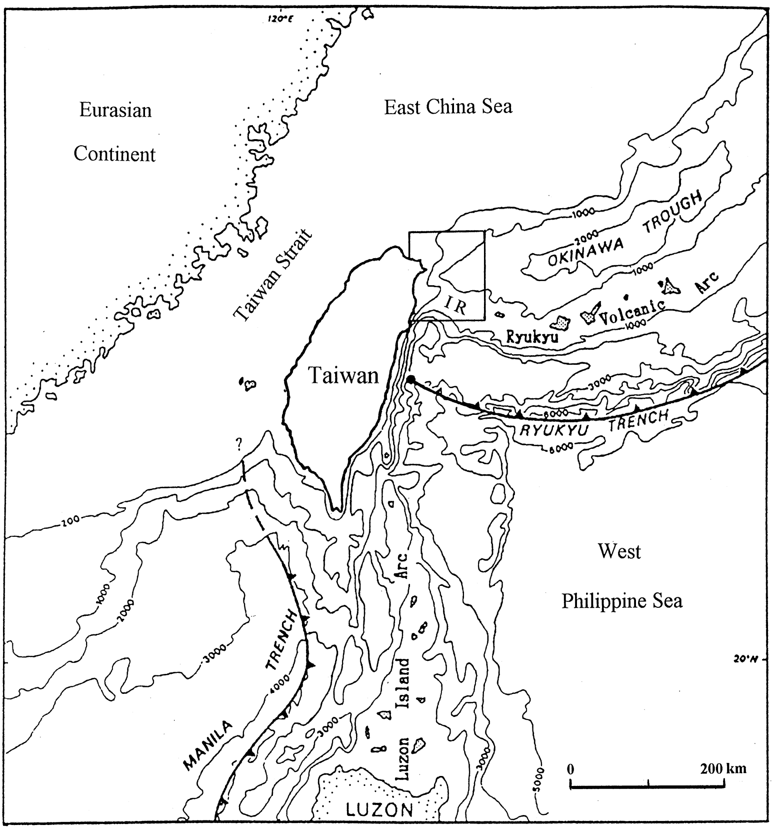


Fig. 1. Simplified regional bathymetry and tectonic setting of Taiwan, modified after Ho (1982). The box shows the study area. Depth contours are in meters. IR: Ilan Ridge.

Exchange Processes (KEEP) was initiated in August, 1989 and recognized as part of the Joint Global Ocean Fluxes Study (JGOFS) in 1997.

Most previous studies emphasized physical and chemical oceanography. However, pioneering general geologic and geophysical investigations in the East China Sea began with Emery et al. (1970) and Wageman et al. (1970). Subsequently, a limited number of sediments were sampled and analyzed by Chou (1972), Boggs et al. (1979), Lin and Chen (1983), Chen et al. (1992) and Hung and Chung (1994). Bathymetry and physiography in the shelf-slope region were studied by Marsset et al. (1987), Yu and Hong (1992), Yu and Hong (1993), and Song (1994) and stratigraphy and structure by Lee et al. (1980), Huang et al. (1992), Yu (1994) and Yu and Shyu (1994). Few lines of 3.5 kHz seismic data (without sediment samples) were also documented by the authors in a preliminary report (Hong et al., 1992).

The purpose of this study, as a sub-project of the KEEP program, is to integrate findings of subprofiler sonar, gravity and box cores as well as bathymetric data in order to understand the general distribution of sediment types and their governing processes.

2. Data

This study is based on more than 4000 km of 3.5 kHz reflection profiles (Fig. 2), 10 box cores and 42 gravity cores (Fig. 3) that were obtained on the cruises of the R/V Ocean Research I through the study area during the operation period of the KEEP program from 1989 to 1993. The quality and consistency of the 3.5 kHz echograms were checked at every point where the seismic lines intersected. Subbottom depths on echograms (from Figs. 4 and 5) are measured by assuming equal sediment and water velocities of 1500 m/s.

Bathymetric profiling was conducted with a Simrad depth echosounder, mounted on the R/V Ocean Research I. The collected bathymetric data were then processed by the "Grapher" software to generate a regional contour map (Fig. 3). As to the cores, each of them was split and described first on board. Then, only the core top sediments were taken for mean grain size analysis using a combination of sieving and Galai CIS-1 laser sizing technique (Tsai and Rau, 1992).

3. Classification of 3.5 kHz echoes

Echo types were classified mainly on the basis of the acoustic character and microtopography or morphology of the sea floor. Construction of the echo-character map broadly followed Damuth (1980). During mapping, the regional bathymetry and sediment samples were used to constrain echo-type distribution.

Eight distinctive echo types were recognized and mapped in the study area. The echo types were grouped into four major classes: indistinct, distinct, hyperbolic and irregular echoes. The first two classes are classified mainly based on the echo character while the remaining two categories are recognized mainly according to the morphology of the sea floor.

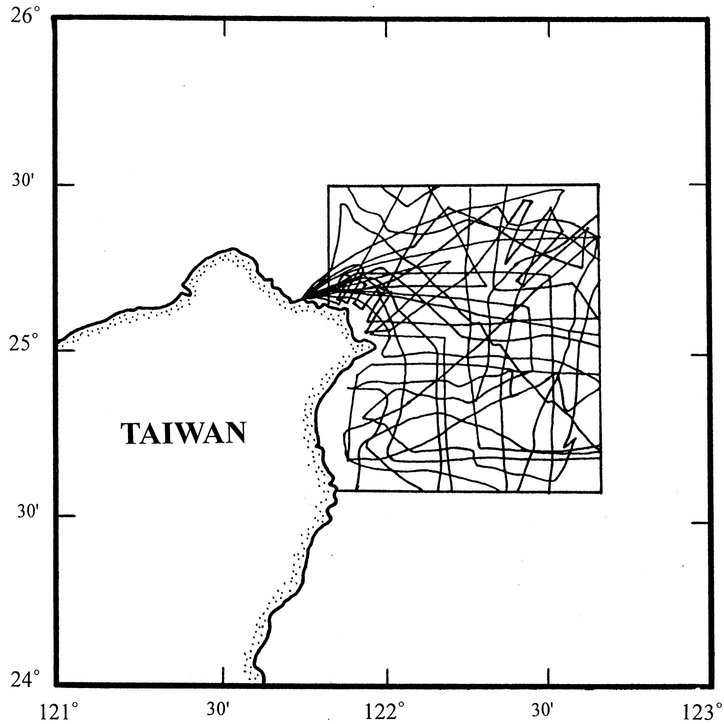


Fig. 2. Locations of 3.5 kHz reflection profiles indicated by solid lines.

3.1. Indistinct echoes

Indistinct echoes have a prolonged or sometimes semi-prolonged bottom echo occurring in areas of flat and locally rippled seafloor. Four subclasses were distinguished and described as follows:

Type Ia. Very prolonged bottom echoes with no sub-bottom reflectors (Fig. 4a). These echoes occur at the East China Sea continental shelf and most parts of the Ilan Shelf. Five fine sandy sediments were sampled from this echo type area. The mean grain sizes of these five samples range from 2.1 to 3.3 in Phi unit.

Type Ib. Prolonged to semi-prolonged echoes with an irregular wavy surface (Fig. 4b). Amplitudes of wavy relief generally range from 5 to 30 m and wavelengths are around 100 m. These echoes occurred only in the areas off northeastern Taiwan between the Mienhua Canyon and the Chilung Sea Valley. Very coarse sands composing mainly of shell debris were recovered both from box core and gravity cores in the area. The mean grain sizes measured are -0.2 and 1.1 Φ respectively.

Type Ic. Semi-prolonged echoes (Fig. 4c). These echoes are mainly returned from the outer southern part of the Ilan Shelf. The mean grain sizes calculated are 3.7 and 4.4 Φ which is in the coarse silt to very fine sand range. Obviously, the sediment is finer than those distributing in the prolonged echo area.

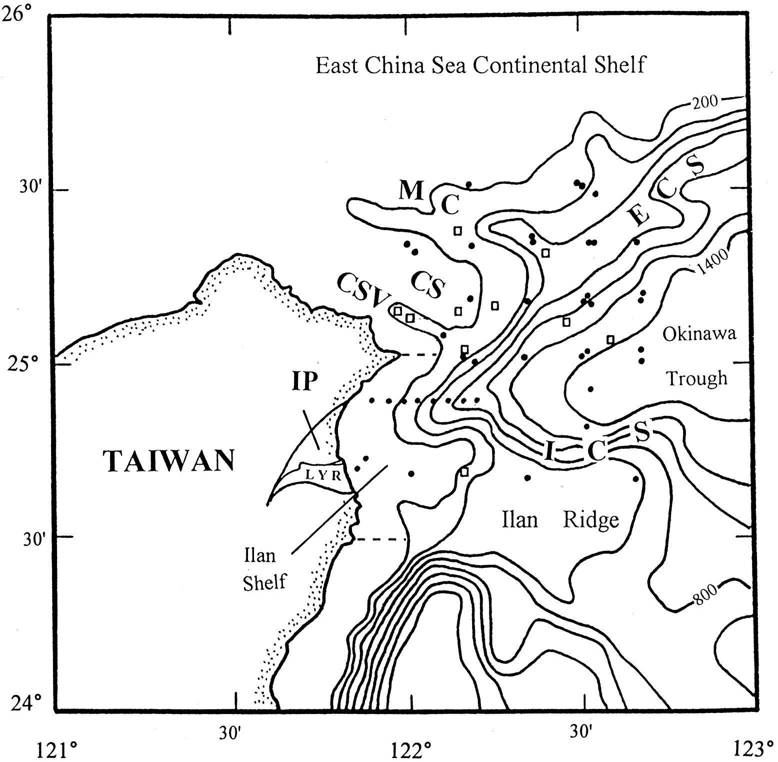


Fig. 3. Physiographic provinces around the northeastern offshore of Taiwan. Locations of gravity and box cores are indicated by dots and open squares, respectively. Depth contours are in meters. IP — Ilan Plain; LYR — Lan-yan River; CSV — Chilung Sea Valley; MC — Mienhua Canyon; ICS — Ilan Continental Slope; ECS — East China Sea Continental Slope.

Type Id. Prolonged to semi-prolonged echoes with inclined sub-bottom reflectors cropping out laterally (Fig. 4d). The most obvious of these echoes are found in the walls of the Chilung Sea Valley and in locally rugged areas of the Ilan Ridge. Two sediments were taken from the head of the Chilung Sea Valley. The mean grain sizes recorded are 0.4 and 2.6 Φ.

3.2. Distinct echoes

Distinct echoes are characterized by a sharply defined, continuous, smooth bottom echo. The sediment which characterized the distinct echoes is clayey and always finer than those of the indistinct types (Damuth, 1980; Addy et al., 1982). Only one type was recognized in this study:

Type II. Distinct echoes with parallel, continuous sub-bottom reflectors (Fig. 5a). The main regions returning this type of echo are the Okinawa Trough, Mienhua

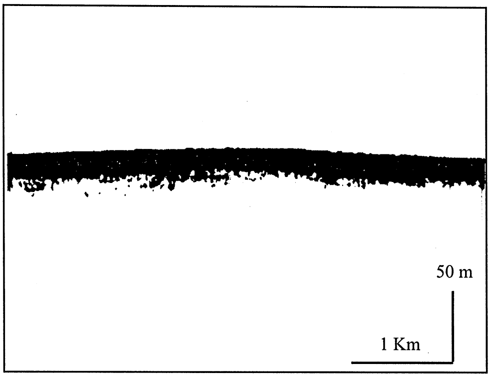
Canyon floor and parts of the continental slope. The sediment found in this type of area is clayey with the mean grain size ranging from 6.9 to 8.8 Φ.

3.3. Hyperbolic echoes

Two types of echo fall into this category:

Type IIIa. Large, irregular hyperbolic echoes with widely varying vertex elevations (Fig. 5b) characterize the upper part of the continental slopes and rugged areas of the Ilan Ridge. The mean grain size ranges from 5.7 to 8.8 Φ.

Type IIIb. Isolated large, broad, gently rolling hyperbolae with conformable parallel sub-bottom reflectors (Fig. 5c). These echoes are observed from the lowermost part of



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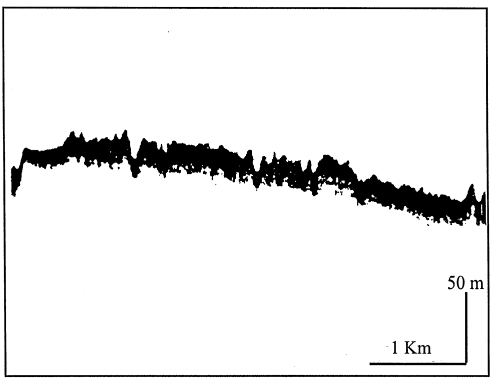

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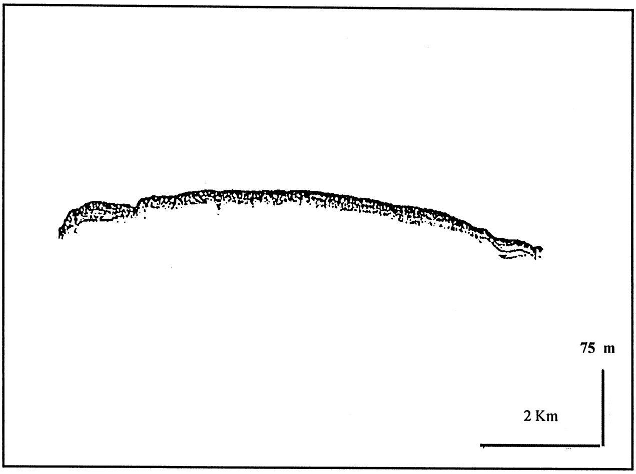
Fig. 4. Examples of echo types: (a) Ia. Very prolonged bottom echoes with no sub-bottom reflectors. (b) Ib. Prolonged to semi-prolonged echoes with an irregular wavy surface. (c) Ic. Semi-prolonged echoes. (d) Id. Semi-prolonged echoes with inclined, sub-bottom reflectors cropping out laterally.



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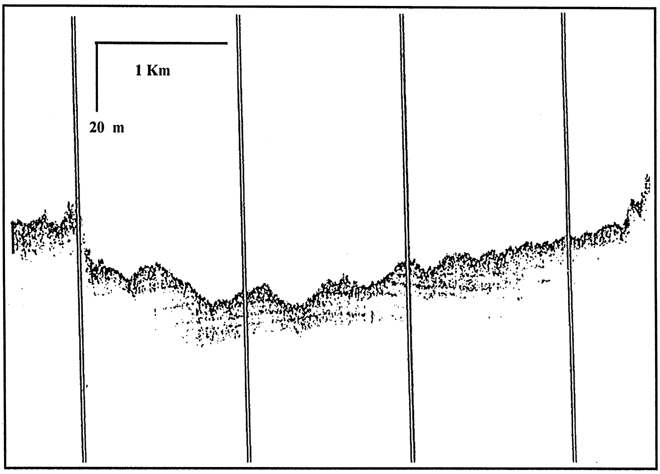


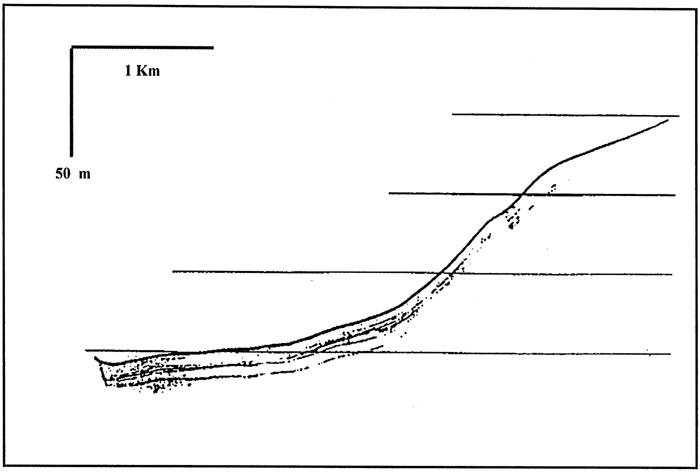
d

Fig. 4. (*Continued.*)

the continental slope that extends eastward into the Okinawa Trough. Only one sediment sample was taken from the Okinawa Trough. The mean grain size is 8.4 Φ.

3.4. *Irregular echoes* (*Type IV*)

These echoes were similar to Type II, i.e. sharp bottom echoes with continuous parallel sub-bottom reflectors. However, their morphology is jumbled (Fig. 5d). This type is confined to a narrow zone extending roughly along the 1400 m deep contour at the lower part of the East China Sea continental slope. Clayey sediment was recovered with the finest mean grain size down to 9.2 Φ.



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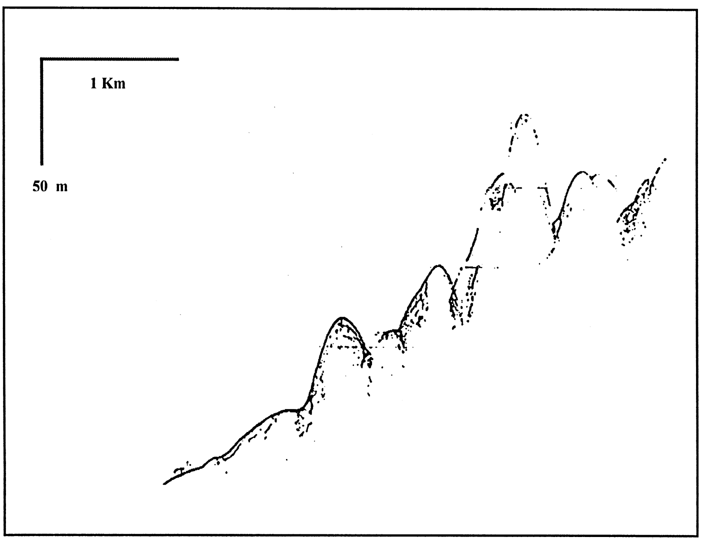

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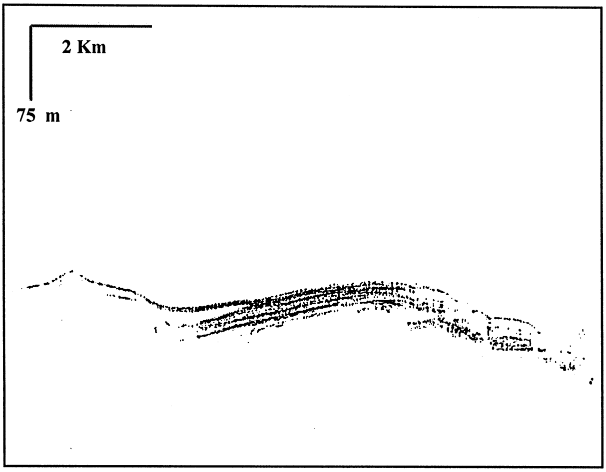
Fig. 5. Examples of echo types: (a) II. Distinct echoes with parallel, continuous sub-bottom reflectors. (b) IIIa. Large, irregular hyperbolic echoes with widely varying vertex elevations. (c) IIIb. Isolated large, broad, gently rolling hyperbolae with conformable parallel sub-bottom reflectors. (d) IV. Similar to type II but with a jumbled morphology.



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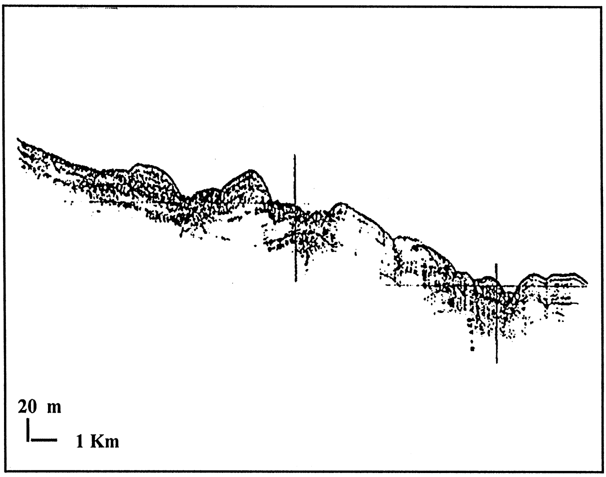

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Fig. 5. (*Continued.*)

4. Interpretation of the echo-character map

It has been demonstrated that of all the lithological and physical properties, the mean grain size of sediment shows the best correlation with the various echo types (Damuth, 1980; Addy et al., 1982). The mean grain sizes of surface sediments measured in this study were also found to correlate well with each echo character in the first two classes (Table 1). Besides, since the last two echo categories are classified on the basis of sea floor morphology it is meaningless to distinguish between them merely based on the grain size of sediment. However, the grain size is still a good reference for recognizing and interpreting the sedimentary deposits reflecting these echo types. We therefore inferred that the 3.5 kHz echograms could be analyzed to delineate the sediment distribution and give gross sedimentologic information for the northeastern offshore area of Taiwan. Our subsequent interpretation of the depositional processes operating in the study area is therefore based mainly on echo character, sediment type and distribution as well as regional topography.

The topography in this rifting continental margin is very complicated. Eight distinct physiographic provinces (Ilan Shelf, East China Sea continental shelf, Chilung Sea Valley, Mienhua Canyon, East China Sea continental slope, Ilan Ridge, Ilan continental slope and Okinawa Trough; please refer to Fig. 3) were recognized (Yu and Hong, 1992). The constructed echo-character map (Fig. 6) suggests that different physiographic provinces exhibit their own distinct echo types. Accordingly, the associated sedimentary processes will be discussed physiographically province by province.

4.1. Ilan shelf

The Ilan plain (Fig. 3) was formed under the fluvial processes of Lan-yan River, which flows from a metamorphic terrain and transports a great amount of slate fragment-bearing sediment to the sea (Ho, 1982). The Ilan Shelf is very narrow, especially the northern part which is only 10 km wide. The southern part of the shelf is the main deposition site of the sediment discharged from Lan-yan River, and it protrudes from the river mouth seaward for about 35 km (Yu and Hong, 1992). The overall geometry of sedimentary deposit on the protruded shelf is better described as lobe-like.

The shelf is mainly characterized by very prolonged echoes with no sub-bottom reflectors (Type Ia, Fig. 4a). Studies that used near-bottom sound sources have shown that prolonged echoes of this type can result from reflections from small erosional/depositional bedforms which have wavelengths that are too small to be resolved into discrete hyperbolae (Ewing et al., 1973; Damuth, 1978). Others have reported that sub-bottom reflections are not recorded when there are high concentrations of bedded silt/sand in the upper meters of the sea floor (Damuth, 1980; Addy et al., 1982; McClennen, 1989).

These explanations are consistent with the cored sediment data, which show that the Ilan Shelf is covered by darkish fine- to medium-grained sands with mean grain sizes ranging from 2.5 to 3.1 Φ (Table 1). All the sampled sediments were composed of slate fragments, suggesting that they were transported via the Lan-yan River. Furthermore, the sediment becomes gradually finer with increasing distance from the coast, with the medium-grained sand near the river mouth giving way to silt at the protruded shelf margin. Such a lobe-shaped distribution of river-borne sediment indicates that subaqueous deltaic processes prevail on this area of the shelf.

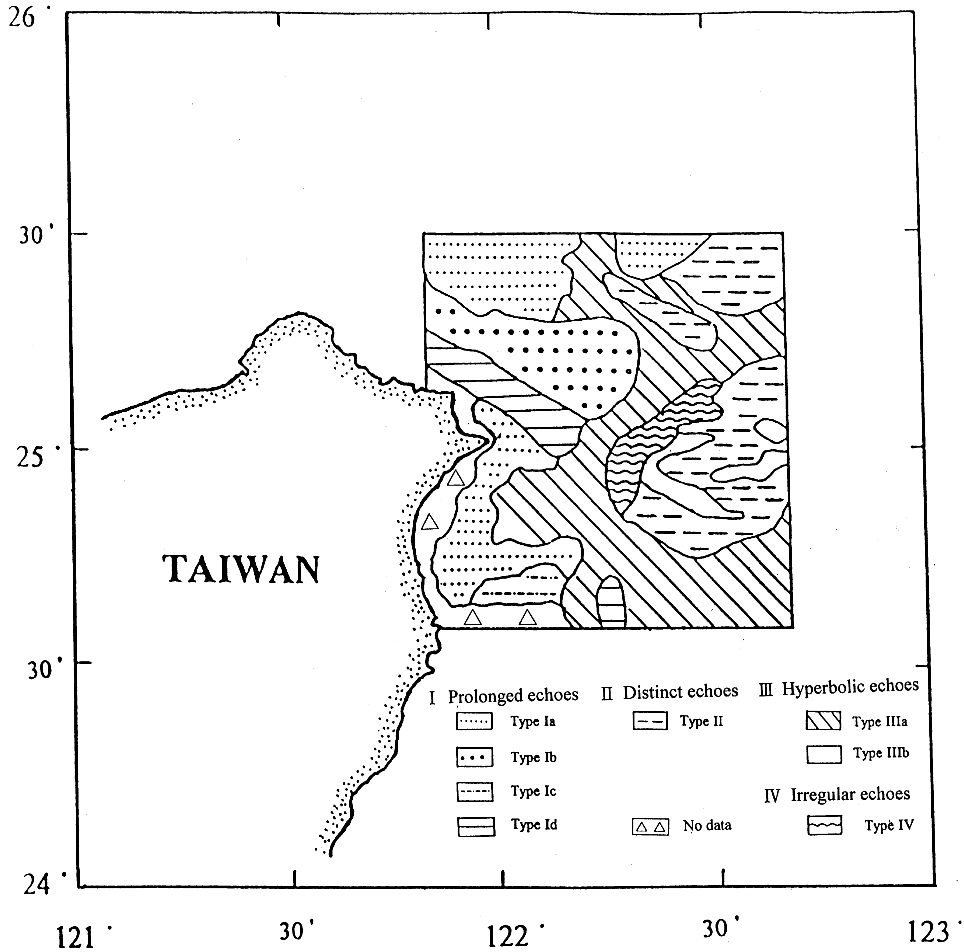

Fig. 6. Echo character map of the study area.

This is also an area of strong currents. These currents are enhanced by tidal, topographic and Kuroshio Current effects, and have been measured at velocities up to 145 cm/s (Lee, 1996). The region is also often disturbed by seasonal storm activities. The sandy, rippled surface of the Ilan Shelf can thus be attributed to shallow marine hydrodynamics.

4.2. East China Sea continental shelf

The East China Sea is the eastern marginal sea of Mainland China. The continental shelf is very broad and wide with dimensions of about 900×500 km. However, only

Table 1
Distribution of echo types vs. mean grain size

Basis for classification	Echo type	Distribution area	Mean grain size (Φ)	No. of samples
Echo character	Ia	East China Sea continental shelf	2.1, 3.3	2
		Ilan continental shelf	2.5–3.1	4
	Ib	East China Sea continental shelf	−0.2, 1.1	2
	Ic	Ilan continental shelf	3.7, 4.4	2
	Id	Upper Chilung Sea Valley	0.4, 2.6	2
	II	East China Sea continental slope	6.9–8.8	6
		Okinawa Trough	8.0–8.1	5
Seafloor morphology	IIIa	Continental lopes	6.1–8.8	18
		Ilan Ridge & Mienhua Canyon	5.7–8.7	5
	IIIb	Okinawa Trough	8.4	1
	IV	Lower East China sea continental slope	7.5–9.2	5

the southern end of the East China Sea continental shelf was investigated in this study (Fig. 1). The most prominent physiographic features in the study area include the Mienhua Canyon, the Chilung Sea Valley and the Chilung Shelf, a rectangular central shelf between these two linear depressions (Fig. 3).

This Chilung Shelf is characterized mainly by prolonged to semi-prolonged echoes with a wavy surface (Type Ib, Fig. 4b). Based on several intersecting seismic profiles, these wavy features were identified as large 2-D dunes (terminology follows Ashley et al., 1990). Their amplitude ranges from 5 to 30 m and their wavelength is generally around 100 m (Fig. 4b). Both box and gravity cores show that the sediments are mainly composed of very coarse to pebbly shell debris and a few rounded quartzose and sandstone pebbles. Most of the shell debris and pebbles are strongly stained by iron to a brownish or dark reddish color. The coarse sediment found in this region has long been recognized and interpreted as a relict sediment (Niino and Emery, 1961; Boggs et al., 1979).

This part of shelf is too far away (more than 200 km) to receive sediments from the Eurasian continent. Although Taiwan Island is much closer, sediment input from this source is cut off by the Chilung Sea Valley. Furthermore, the Kuroshio Current impinges upon and is deflected by this part of the shelf margin. This turning results in the intrusion and upwelling of Kuroshio water, and disturbances in the form of eddies, internal waves and countercurrent (Lin et al., 1992; Liu et al., 1992; Chuang et al., 1993; Chern and Wang, 1994; Chen et al., 1995; Mitnik et al., 1996). Thus, lack of sediment input and the highly energetic local hydrodynamics both prevent the relicts from being covered by younger sediments. Furthermore, the wavelength and amplitude of these dunes were varied during different cruises indicating that this part of sediment should be termed as palimpsest rather than relict.

4.3. Chilung Sea Valley

In the late Pleistocene, when the eustatic sea level was lower than at present, this linear depression would have been the lower reach of the Tanshui River (Boggs et al., 1979). The channel runs NW-SE roughly parallel to the northern coast of Taiwan and terminates at the 300-m contour (Fig. 3). All the echograms from seven intersecting seismic lines show semi-prolonged echoes with inclined sub-bottom reflectors that crop out laterally from the channel wall (Fig. 4d) indicating incising of the channel.

The sediments sampled from the upper reach of the channel floor are made up of the same coarse shell debris, clastic sands and pebbles that are found in the palimpsestic sediments on the nearby shelf. Down the channel, the grain size decreases gradually from sandy through clayey at the distal end of the channel floor. This suggests that the Chilung Sea Valley was and probably still is a main conduit for transporting terrigenous sediments from the northern Taiwan Strait southeastward along the coast down to the continental slope. The southeastward transportation pattern in the channel and on the nearby shelf is also consistent with the outflow path of the Taiwan Strait Water observed by Chern and Wang (1992).

4.4. Mienhua Canyon

The Mienhua Canyon is another linear depression running parallel to the Chilung Sea Valley in the continental margin of the East China Sea (Fig. 3). The canyon cuts across the continental shelf and continues through the upper continental slope, where its cross-sectioned profile exhibits a narrow, V-shaped trough with steep walls (Yu and Hong, 1993). Large irregular hyperbolic echoes are returned from the steep canyon walls while distinct echoes with continuous reflectors characterize the canyon floor. Distinct echoes with continuous reflectors are usually interpreted as muddy sediment or turbidite deposits (Damuth, 1980; Addy et al., 1982; Pratson and Laine, 1989; Satterfield and Behrens, 1990), and in this instance too, all the sediments cored from the canyon floor were clayey mud. Among the muddy sediments sampled from the canyon head, a thin (less than 2 cm), graded, shell-bearing, sandy layer was found below one core top. The coarse, iron-stained character of this thin layer of sand suggests that it too was a relict sediment, probably one that had been transported downward by a turbidity current.

The predominance of muddy sediments and the lack of coarse palimpsestic sediments in the Mienhua Canyon indicate that the dominant sedimentary processes are different from those in the Chilung Sea Valley. Besides, the question is that why the distinct coarser sediment was not transported eastward along the continental shelf margin nor largely dumping down to the nearby continental slope and the Mienhua Canyon.

On the other hand, during the same period of KEEP program, several important oceanographic phenomena induced by the turning of Kuroshio Current such as the upwelling, countercurrent, branching and frontal eddies were for the first time observed or confirmed in this region. According to these hydrographic observations (Lin et al., 1992; Liu et al., 1992; Chern and Wang, 1994; Chen et al., 1995; Mitnik et al.,

1996) the Mienhua Canyon acts as a conduit for the subsurface Kuroshio water that upwells to the sea surface. Furthermore, as observed and confirmed by Miyaji and Inoue (1983) and Chuang et al. (1993), a countercurrent flowed over along the shelf edge. This countercurrent flowed southwestward across the Mienhua canyon onto the Chilung Shelf (Chuang et al., 1993). Whether transported by the countercurrent from northeast or by the upwelling water from beneath the canyon, only fine sediment is available to be transported and deposited in the canyon and nearby continental margin. These two local hydrographic processes further block the sediments from being transported northeastward and thus cause a change in the local transportation direction and deposition. Therefore, the observed sediment distribution here is most probably controlled by and thus reflect well the distinct local hydrodynamic processes just discussed above.

4.5. Continental slope

In the southeastern part of the East China Sea continental slope and the Ilan continental slope (Fig. 3), the gradient is greater in the upper part of the slopes (1–6°) than in the lower part (0.5–4°). As revealed by bathymetric profiles, gently inclined, smooth surfaces and relatively steep, rugged terrains coexist in these continental slopes.

Distinct echoes with parallel, continuous sub-bottom reflectors (Type II) were collected from the smooth, gentle part of the slopes. The surface sediment here is mainly clayey with mean grain size ranging from 6.9–8.8 Φ (Table 1). On the other hand, the rugged part of the continental slopes is characterized by large, irregular hyperbolic echoes with widely varying vertex elevations (Type IIIa, Fig. 5b). This type of echo has been reported from other very rugged terrains, not only on continental slopes, but also on the steep sides of seamounts and plateaus, canyon walls, and rugged mid-ocean ridges (Damuth and Hayes, 1977; Damuth, 1980; Pratson and Laine, 1989; Satterfield and Behrens, 1990). Other studies (Jacobi, 1976; Klaus and Ledbetter, 1988; Lee et al., 1991) have found that this type of echo could also be returned from regions with slides and slump blocks. Our data are consistent with the 3.5 kHz subbottom echograms and multichannel seismic reflection profiles of earlier reports (Emery et al., 1970; Huang et al., 1992; Yu and Hong, 1992), which identified steep slopes, various erosional gullies, faulting blocks, and slumping and/or sliding scars and blocks in the same region.

Sharp bottom echoes with a jumbled morphology (Type IV, Fig. 5d) were observed from a narrow belt at the foot of the East China Sea continental slope. This narrow belt is roughly parallel to the regional continental margin and extends from the tip of the Okinawa Trough to immediately below the Mienhua Canyon (Fig. 6). Taken together, parallel and perpendicular seismic reflection profiles suggest that the irregular surfaces of this region are in fact slide or slump blocks cut by channels or valleys. Such an interpretation is supported by the fact that the same type of surface morphology and acoustic reflection has been documented from many other parts of the world's oceans (Jacobi, 1976; Embley and Jacobi, 1977; McGregor, 1977; Pratson and Laine, 1989; Carter and Carter, 1996; Papatheodorou and Ferentinos, 1997).

The jumbled morphology of the slide or slump blocks in the lower slope was found only on the southwestern side of Mienhua Canyon, and especially in the area immediately below the Chilung Sea Valley. The same hydrodynamic processes that occur on the shelf margin (see above) also determine the location of slumping blocks: the Taiwan Strait Water flows down the gradient at the southeastern part of shelf and accelerates the accumulation of sediments at the shelf break and in the channel, which in turn promotes the sliding or slumping of sediments later on. On the other hand, at the head of the Mienhua Canyon and on the shelf to the northeast, the on-shelf intrusion, upwelling and countercurrent all impede sediment input, thereby precluding the possibility of gravity-induced mass movements.

4.6. Okinawa Trough

The basin floor of the Okinawa Trough is mainly characterized by distinct echoes with parallel, continuous sub-bottom reflectors (Type II, Fig. 5a). Previous studies indicated that areas returning this echo type contain mainly fine sediments with or without bedded sand or silt and are dominated by weak, waning turbidity currents and/or by pelagic sedimentation processes (Damuth and Hayes, 1977; Damuth, 1980; Pratson and Laine, 1989; Satterfield and Behrens, 1990). In this study, the sediment sampled from the trough is gray, slightly sticky, clayey mud. Chen et al. (1992) reported that these clayey sediments are non-biogenic, although two small patches with traces of biogenic material were found. Any biogenic sediment in this area would probably be diluted by terrigenous sediment transported by turbidity currents.

Approximately below the Chilung Sea Valley, a few slim belts extend from the foot of the continental slope and lie along the axis of the Okinawa Trough. These slim belts gradually pinch out eastward. The isolated, large, broad, gently rolling hyperbolae (Type IIIb, Fig. 5c) returned from these belts resemble sediment waves of a type reportedly formed by turbidity or contour currents (Jacobi et al., 1975; Damuth, 1979; Normark et al., 1980; Flood and Shor, 1988; Klaus and Ledbetter, 1988; Carter et al., 1990). In light of the distinct sediment deposits and the associated slumping and/or sliding scars and mass gravity transport deposits observed on the surrounding continental slope, we therefore conclude that the basin of the Okinawa Trough was mainly shaped by turbidity currents and to a lesser extent by pelagic deposition.

4.7. Ilan Ridge

The Ilan Ridge is the western extension of the Ryukyu Island Arc (Fig. 3). From here, both prolonged or semi-prolonged echoes with inclined sub-bottom reflectors cropping out laterally (Type Id, Fig. 4d) and large, irregular hyperbolic echoes with widely varying vertex elevations (Type IIIa, Fig. 5b) were collected. These echo types and previous studies in the area (Niino and Emery, 1961; Emery et al., 1970; Boggs et al., 1979) indicate that the Ilan Ridge is characterized by steep slopes, seamounts, and submarine troughs and channels as well as slumping and/or sliding blocks.

5. Conclusions

Based on the 3.5 kHz echo-sounding and 52 core samples the regional sediment distribution in the actively rifting continental margin off northeastern Taiwan is for the first time presented in this study. The sedimentary processes on the sea floor as summarized in Fig. 7 are inferred and interpreted from the distribution of sediments. Over the Ilan Shelf the sediment derives mainly from the Lan-yan River and under the subaqueous deltaic processes it forms a lobe-shaped deposit, the various rippled appearances of which indicate that the surface sediment is further subject to shallow marine processes. On the shelf margin of the southern East China Sea, the outflow of the Taiwan Strait Water transports terrigenous sediment along the northern coast of Taiwan southeastward through the Chilung Sea Valley and then down the slope to the Okinawa Trough. In other areas, including the Chilung Shelf, Mienhua Canyon and the shelf further to the northeast, the on-shelf intrusion, upwelling and counter-

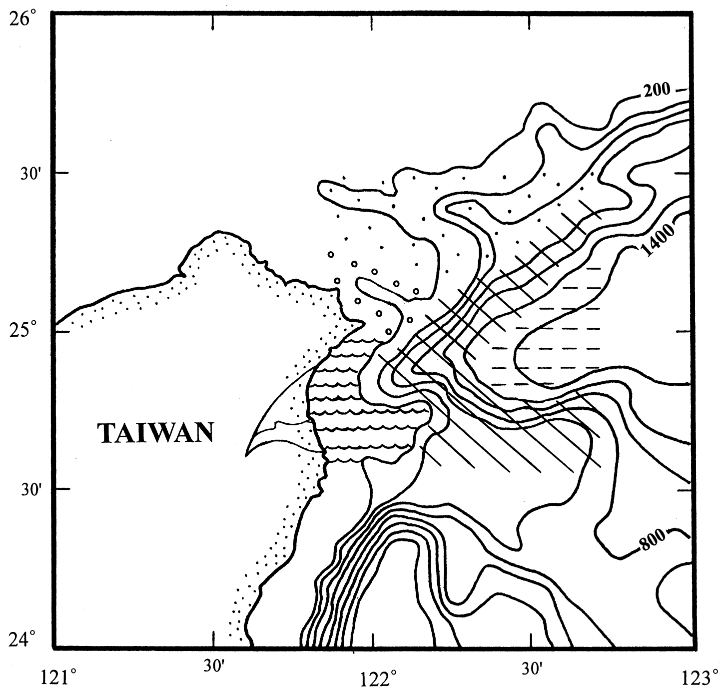

Fig. 7. Spatial distribution of the major sedimentary processes. The transportation and sedimentation in the area with small open circles is mainly controlled by the Taiwan Strait Water. The on-shelf intrusion, upwelling and the countercurrent dominate the sedimentation of the dotted area. The rippled area of the Ilan shelf is predominated by subaqueous deltaic and shallow marine processes. Furthermore, the gravity-induced down-slope processes are the main shaping agents over the hatched and dashed continental slope and Okinawa Trough.

current caused by the impinging and turning of the Kuroshio Current have dominated the local sediment transportation and sedimentation.

Furthermore, due to the active spreading of the Okinawa Trough (Lee et al., 1980), the surrounding continental slopes are steep and rugged as revealed by the bathymetry and echogram. On the upper continental slopes, many slumping or sliding scars and blocks give rise to large, irregular, hyperbolic echoes, while the accumulation of slumping or sliding deposits that dominate the lower part of the slopes are characterized by their own jumbled distinct echo types. Sediment waves induced by turbidity currents and turbidite deposits are also observed on the basin floor of the Okinawa Trough as indicated by sharp echoes with parallel sub-bottom reflectors and distinct, gently rolling hyperbolae. Accordingly, the gravity-induced down-slope processes are the main shaping agents along this tectonically active area of the continental margin.

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References

Addy, S.K., Behrens, E.W., Haines, T.R., Shirley, D.J., Worzel, J.L., 1982. High-frequency subbottom reflection types and lithologic and physical properties of sediment. Marine Geotechnology 5, 27–49.

Ashley, G.M., et al., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem [symposium]. Journal of Sedimentary Petrology 60, 160–172.

Boggs Jr., S., Wang, W.C., Lewis, F.S., Chen, J.C., 1979. Sediment properties and water characteristics of the Taiwan shelf and slope. Acta Oceanographica Taiwanica 10, 10–49.

Carter, L., Carter, R.M., Nelson, C.S., Fulthorpe, C.S., Neil, H.L., 1990. Evolution of Pliocene to recent abyssal sediment waves on Bounty Channel levees. New Zealand. Marine Geology 95, 97–109.

Carter, R.M., Carter, L., 1996. The abyssal Bounty Fan and lower Bounty Channel: evolution of a rifted-margin sedimentary system. Marine Geology 130, 181–202.

Chen, C.T.A., Ruo, R., Pai, S.C., Liu, C.T., Wong, G.T.F., 1995. Exchange of water masses between the East China Sea and the Kuroshio off northeastern Taiwan. Continental Shelf Research 15, 19–39.

Chen, M.P., Lo, S.C., Lin, K.L., 1992. Composition and texture of surface sediment indicating the depositional environments off northeast Taiwan. Terrestrial, Atmospheric and Oceanic Sciences 3 (3), 395–418.

Chern, C.S., Wang, J., 1992. The influence of Taiwan Strait Water on the circulation of the southern East China Sea. La mer 30, 223–228.

Chern, C.S., Wang, J., 1994. Influence of the seasonal thermocline on the intrusion of Kuroshio across the continental shelf northeast of Taiwan. Journal of Oceanography 50, 691–711.

Chou, J.T., 1972. Sediments of Taiwan Strait and the southern part of the Taiwan Basin. United Nations Economic Community Asia Far East. Technical Bulletin 6, 75–97.

Chuang, W.S., Li, H.W., Tang, T.Y., Wu, C.K., 1993. Observation of the countercurrent on the inshore side of the Kuroshio northeast of Taiwan. Journal of Oceanography 49, 581–592.

Damuth, J.E., 1978. Echo character of the Norwegian-Greenland Sea: relationship to Quaternary sedimentation. Marine Geology 28, 1–36.

Damuth, J.E., 1979. Migration sediment waves created by turbidity currents in the northern South China Basin. Geology 7, 520–523.

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

Damuth, J.E., Hayes, D.E., 1977. Echo character of the east Brazilian continental margin and its relationship to sedimentary processes. Marine Geology M73–M95.

Emery, K.O., Hayashi, Y., Hilde, T.W.C., Kobayashi, K., Koo, J.H., Meng, C.Y., Niino, H., Osterhagen, J.H., Reynolds, L.M., Wageman, J.M., Wang, C.S., Yang, S.J., 1970. Geological structure and some water characteristics of the East China Sea and the Yellow Sea. Petroleum Geology of Taiwan 7, 243–279.

Embley, R.W., Jacobi, R.D., 1977. Distribution and morphology of large submarine sediment slides and slumps on Atlantic continental margins. Marine Geotechnology 2, 205–228.

Ewing, M., Embley, R.W., Shipley, T.H., 1973. Observations of shallow layering utilizing the pinger-probe echo sounding system. Marine Geology 14, M55–M63.

Flood, R.D., Shor, A.N., 1988. Mud waves in the Argentine Basin and their relationship to regional bottom circulation patterns. Deep-Sea Research 35, 943–971.

Ho, C.S., 1982. Tectonic evolution of Taiwan: explanatory text of the tectonic map of Taiwan. The Ministry of Economic Affairs, Republic of China. 126 pp.

Hong, E., Yu, H.S., Chen, I.S., 1992. A preliminary study of the echo characters and sedimentary processes along the continental margin, northeast of Taiwan. Terrestrial, Atmospheric and Oceanic Sciences 3 (3), 435–447.

Hsu, S.K., Sibuet, J.C., 1995. Is Taiwan the result of arc-continent or arc-arc collision? Earth and Planetary Science Letters 136, 315–324.

Hsu, V., 1990. Seismicity and Tectonics of a Continental-Island Arc collision zone at the island of Taiwan. Journal of Geophysical Research 95 (B4), 4725–4734.

Hsueh, Y., Chern, C.S., Wang, J., 1993. Blocking of the Kuroshio by the Continental shelf northeast of Taiwan. Journal of Geophysical Research 98, 12 351–12 359.

Huang, S.T., Ting, H.H., Chen, R.C., Chi, W.R., Hu, C.C., Shen, H.C., 1992. Basin framework and tectonic evolution of offshore northern Taiwan. Petroleum Geology of Taiwan 27, 47–72.

Hung, G.W., Chung, Y.C., 1994. Sedimentation rates on the continental slope off eastern Taiwan. Marine Geology 119, 99–109.

Jacobi, R.D., 1976. Sediment slides on the northwestern continental margin of Africa. Marine Geology 22, 157–173.

Jacobi, R.D., Rabinowitz, D., Embley, R.W., 1975. Sediment waves on the Morocan continental rise. Marine Geology 19, M61–M67.

Klaus, A., Ledbetter, M.T., 1988. Deep-sea sedimentary processes in the Argentine Basin revealed by high-resolution seismic records (3.5 kHz echograms). Deep-Sea Research 35, 899–917.

Lee, C.S., Shor, G.G., Bibee, L.D., Lu, R.S., Hilde, T.W.C., 1980. Okinawa Trough origin of a backarc basin. Marine Geology 35, 219–241.

Lee, H.J., Chough, S.K., Chun, S.S., Han, S.J., 1991. Sediment failure on the Korea Plateau slope. East Sea. Marine Geology 97, 363–377.

Lee, Y.H., 1996. Study on the coastal current of the estuary of Lan-Yan River. Masters Thesis, National Taiwan Ocean University, 47 pp, unpublished.

Letouzey, J., Kimura, M., 1986. The Okinawa Trough: genesis of a back-arc basin developing along a continental margin. Tectonophysics 125, 209–230.

Lin, C.Y., Shyu, C.Z., Shih, W.H., 1992. The Kuroshio fronts and cold eddies off northeastern Taiwan observed by NOAA-AVHRR imageries. Terrestrial, Atmospheric and Oceanic Sciences 3 (3), 225–242.

Lin, F.J., Chen, J.C., 1983. Textural and mineralogical studies of sediments from the southern Okinawa Trough. Acta Oceanographica Taiwanica 14, 26–41.

Liu, K.K., Gong, G.C., Shyu, C.Z., Pai, S.C., Wei, C.L., Chao, S.Y., 1992. Response of Kuroshio upwelling to the onset of the northeast Monsoon in the sea north of Taiwan: observations and a numerical simulation. Journal of Geophysical Research 97 (C8), 12 511–12 526.

Marsset, B., Sibuet, J.C., Letouzey, J., Maze, J.P., 1987. Bathymetric map of the Okinawa Trough. Scale: 1:1000000. IFREMER, Brest, France.

McClennen, C.E., 1989. Microtopography and surficial sediment pattens in the central Gulf of Maine: a 3.5 kHz survey and interpretation. Marine Geology 89, 69–85.

McGregor, B.A., 1977. Geophysical assessment of submarine slide northeast of Wilmington Canyon. Marine Geotechnology 2, 229–244.

Mitnik, L.M., Hsu, M.K., Liu, C.T., 1996. ERS-1 SAR observations of dynamic features in the southern East-China Sea. La mer 34, 215–225.

Miyaji, K., Inoue, N., 1983. Characteristics of the flow of the Kuroshio in the vicinity of Senkaku Islands. Bulletin of the Seikai Regional Fisheries Research Laboratory 60, 57–70.

Niino, H., Emery, K.O., 1961. Sediments of shallow portions of East China Sea and South China Sea. Geologic Society of America Bulletin 72, 731–762.

Normark, W.R., Hess, G.R., Stow, D.A.V., Browen, A.J., 1980. Sediment waves on the Monterey Fan levee: a preliminary physical interpretation. Marine Geology 76, 1–15.

Papatheodorou, G., Ferentinos, G., 1997. Submarine and coastal sediment failure triggered by the 1995, Ms = 6.1 R Aegion earthquake. Gulf of Corinth, Greece. Marine Geology 137, 287–304.

Pratson, L.F., Laine, E.P., 1989. The relative importance of gravity-induced versus current-controlled sedimentation during the Quaternary along the Mideast U.S. outer continental margin revealed by 3.5 kHz echo character. Marine Geology 89, 87–126.

Satterfield, W.M., Behrens, E.W., 1990. A late Quaternary canyon/channel system, northwest Gulf of Mexico continental slope. Marine Geology 92, 51–67.

Song, G.S., 1994. Bathymetry of offshore area, northeast of Taiwan, 1:150,000. Chinese Naval Hydrographic and Oceanographic Office, Taiwan, Republic of China.

Tsai, C.H., Rau, S.R., 1992. Evaluation of Galai CIS-1 for measuring size distribution of suspended primary particles in the ocean. Terrestrial, Atmospheric and Oceanic Sciences 3 (2), 147–163.

Wageman, J.M., Hilde, T.W.C., Emery, K.O., 1970. Structural framework of the East China Sea and Yellow Sea. Bull. American Association of Petroleum Geology 54, 1611–1643.

Yeh, Y.H., Lin, C.H., Roecker, S.W., 1989. A study of upper crustal structures beneath northeastern Taiwan: possible evidence of the western extension of Okinawa Trough. Journal of Geological Society of China 32 (2), 139–156.

Yu, H.S., 1994. Structure, stratigraphy and basin subsidence of Tertiary basins along the Chinese southeastern continental margin. Tectonophysics 235, 63–76.

Yu, H.S., Hong, E., 1992. Physiographic characteristics of the continental margin, northeast Taiwan. Terrestrial, Atmospheric and Oceanic Sciences 3 (3), 419–434.

Yu, H.S., Hong, E., 1993. The Huapinghsu channel/canyon system off northeastern Taiwan: morphology, sediment character and origin. Terrestrial, Atmospheric and Oceanic Sciences 4 (3), 307–319.

Yu, H.S., Shyu, C.T., 1994. Topography, geomagnetism and structure in the shelf-slope region off northeastern Taiwan. Journal of Geological Society of China 37, 247–260.