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SUBMARINE PHYSIOGRAPHIC FEATURES IN TAIWAN REGION AND THEIR GEOLOGICAL SIGNIFICANCE

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ABSTRACT

The sea floor topography around Taiwan is characterized by its asymmetry of having relatively shallow and flat shelves to the west and markedly deep basins and trenches and high-relief troughs and ridges to the south and east. Tectonics and sedimentation are important factors in forming the submarine topography around Taiwan.

Three Pliocene-Quaternary shelves are distributed north and west of Taiwan: East China Sea Shelf (passive margin shelf), the Taiwan Strait Shelf (foreland shelf) and Kaoping Shelf (island shelf) from north to south along the strike of Taiwan orogen. East-west trending ridges of theYaeyama accretionary wedge and submarine Ryukyu Arc, four offset forearc basins, deep Hualian Canyon-Ryukyu Trench and active backarc basin of southern Okinawa Trough are the major submarine morphologic features in the area off northeastern Taiwan. Off eastern Taiwan, the deep Huatung Basin between the submarine northern Luzon Arc and Gagua Ridge is characterized by relatively flat floor, although several large submarine canyons eroding the basin floor across the basin. Turbidites derived from Taiwan orogen via the submarine canyons are deposited on the basin floor.

Off southwestern Taiwan, the broad Kaoping Slope is the major submarine topographic feature. The boundary separating this slope from the South China Sea Slope is the Penghu Canyon. The lower reach of the Penghu Canyon merges gradually into the Manila Trench south of 21° 30' N. Off southeastern Taiwan, the forearc region of the Luzon Arc has been deformed into N-S trending ridges and troughs during initial arc-continent collision. The Hengchun Ridge is the most prominent physiographic feature and is the seaward continuation of the Hengchun peninsula. Marine geology in Taiwan region generally reflects a transition from a passive margin to an active margin during the last five million years. Before the collision with the Luzon Arc, the Chinese continental margin in Taiwan has been in a bathymetric setting with shelf, slope, basin and trench with increasing depth in a NE-SW regional trend. After collision with the Luzon Arc and rising of the mountain belt of Taiwan, the continental margin became an active one characterized by a paired thrust-belt and foreland basin, bounded by two remnant marginal ocean basins and transitional subduction-collision systems.

Key words: submarine, physiography, tectonics, sedimentation, Taiwan

ITRODUCTION

The island of Taiwan is located at the junction of the Ryukyu and Luzon Arcs on the plate boundary between the Eurasian plate to the west and the Philippine Sea plate to the east in the western Pacific Ocean (Fig. 1). Seafloor topography around Taiwan is characterized by its asymmetry of being relatively shallow and flat to the west and markedly deep with high relief to the east (Mammerickx *et al*., 1976, Boggs *et al*., 1979). The sea floor west of Taiwan is characterized by continental shelves stretching from the East China Sea across the Taiwan Strait to the South China Sea along the eastern edge of China Mainland (Fig. 1). Off east and south Taiwan, the submarine topography are characterized by steep slopes cut by gullies and canyons, linear ridges and deep basins.

In the last twenty years, much work of sea floor topographic mapping around Taiwan has been done by marine geological and geophysical surveys mainly conducted by the Institute of Oceanography, National Taiwan University, including several international cooperative surveys. For example, Liu *et al*. (1998) generated first bathymetric digital elevation model (hereafter DEM) for the offshore area of Taiwan. Most recently, Liu *et al*. (1998) produced a regional DEM for the sea floor around Taiwan, revealing many detailed submarine topographic features and serving a regional framework of the submarine topography of Taiwan.

Morphology of the sea floor around Taiwan is mainly influenced by tectonics and sedimentation (e.g., Bowin *et al*., 1978, Chen and Juang, 1986, Chen, 1989, Huang and Yin, 1990, Huang *et al*., 1992, Yu and Song, 1993, Yu and Chiao, 1994, Yu, 1995, Hsu, *et al*., 1996, Song, *et al*., 1997, Yu, 1997, Liu *et al*., 1998). Among the previous studies, the papers of Yu and Song (1993), Yu (1997) and Liu *et al*. (1998) are the most comprehensive ones, considering the submarine physiographic features around Taiwan as a whole as the results of tectonic imprints and related sedimentation.

Interpretations of the relationships among the submarine physiography, tectonics and sedimentation around Taiwan are strongly influenced by experience and available data, resulting in some overlaps and conflicts of various viewpoints. Therefore, a continued updated examination of this subject is needed. This paper briefly describes the key submarine physiograpic features around Taiwan. Only the relevant background information is reviewed here. Readers may examine the submarine topography around Taiwan in detail as presented by previously papers.

The purpose of this paper presents updated geological and geophysical information and gives new interpretations for the submarine physiographic features around Taiwan. The geological significance of each physiographic feature is emphasized and the existed geological and tectonic interpretations of the submarine topography are not excessively repeated here.

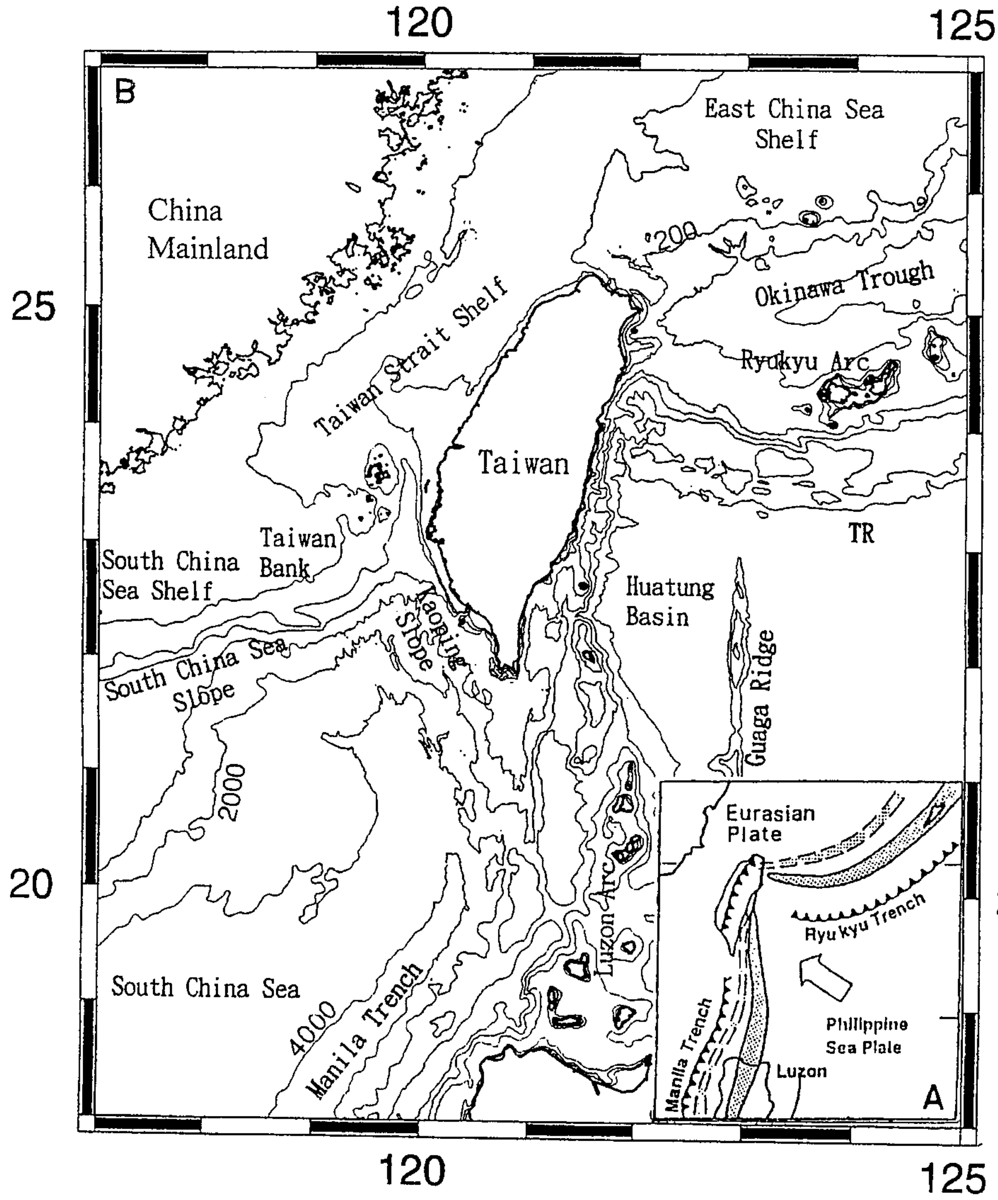

Figure 1. Generalized tectonic setting in Taiwan region (A). Bathymetric map showing shallow and wide shelves covered by the East China Sea, Taiwan Strait and South China Sea along the southeastern Chinese margin. Off eastern Taiwan coast lies the deep Philippine Sea with water depths between 4000 and 5000 meters. The Okinawa Trough and deep Ryukyu Trench with a maximum water depth more than 6,000 meters are located northeast of Taiwan. N-S trending ridges and troughs with irregular surfaces characterize the sea floor off southeastern Taiwan. The sea floor off southwestern Taiwan coast is characterized by a broad submarine slope up to 4,000 m deep cut by numerous canyons. (B). Bathymetric contours are in meters. HR: Hengchun Ridge, NLT: North Luzon Trough, RT: Ryukyu Trench.

SUBMARINE PHYSIOGRAPHIC FEATURES IN TAIWAN REGION

East China Sea Shelf

The sea floor north and northwest of Taiwan is the East China Sea Shelf which is underlain by thick Cenozoic clastic sediments up to 8,000 m accumulated in several rift basins (Sun, 1982). Rifting along the southeastern Chinese margin began in the Late Cretaceous and continued into Miocene. In the Pliocene-Quaternary time, subsequent subsidence and deposition of shallow marine sediments result in a tilting seaward sedimentary wedge to form a passive margin. The East China Sea Shelf rests on the passive margin extending from the coast of China mainland to the upper rim of the East China Sea Slope, facing the Okinawa Trough and the deep Philippine Sea (Fig. 1).

The East China Sea Shelf near Taiwan is characterized by its width of 340 km, flatness less than 0.01 degrees in gradient and shelf edge being shallower than 180 m, showing a typical passive margin shelf (Jin, 1992). South of 26 ° N, the shelf shows a broad, shallow and relatively flat surface with low-relief troughs and ridges resulting from the erosion during the Late Pleistocene low stand of sea level (Boggs *et al.*, 1979). Following the Holocene marine transgression, not much sediments derived both from China mainland and Taiwan enough to cover the Late Pleistocene sediments, resulting in relict sediments widespread over the shelf north of Taiwan (Boggs *et al.*, 1979).

Several volcanic islets (e.g., Pengchiahsu, Fig.7) and many submarine volcanoes are distributed in the East China Sea near Taiwan which are parts of the Southwestern Ryukyu volcanic front (Teng *et al.*, 1992, Teng, 1996). However, Chen (1997) suggested that the volcanic activities in northern Taiwan and offshore area were mainly resulted from the post-collision extension in this whole area, but not related to the extension of the southwestern Ryukyu volcanic front. This view is still debable for more clarification.

The East China Sea Shelf north of Taiwan is a mature passive margin shelf in terms of bathymetric and tectonic settings, and its present morphology results from the effect of Late Pleistocene glaciation about 15,000 years ago (Yu and Song, 1999).

Taiwan Strait Shelf

Lying between Taiwan and China mainland, the sea floor of Taiwan Strait is characterized by its shallowness, generally less than 60 m deep (Fig. 1). Judging from its physiographic setting, the Taiwan Strait Shelf is an atypical shelf, neither similar to the Atlantic type (shelf- slope-basin) nor to the Pacific type (shelf-slope-trench). The geological nature of the Taiwan Strait Shelf, therefore, has been variously interpreted. For example, it has been interpreted to be a passive margin shelf (Sun, 1982,YuandHuang, 1994,Liu, *et al.*, 1998), a relict continental margin rift (Huang et al., 1989, Chung et al, 1994), a relict passive margin (Yu, 1997), or a foreland shelf (Yu,1998, 1999). This paper prefers the foreland shelf to others (Yu, 1999). The following section discusses the geological significance of this shelf more thoroughly.

Lower Tertiary sequences underlying the shelf have similar structure and stratigraphy to those below the East China Sea Shelf, representing a passive rift margin (Sun 1982, Yu and Huang, 1994). Beginning in early Pliocene, the Chinese passive margin in Taiwan region has changed into active margin due to collision of the northern Luzon Arc (Suppe, 1981). The Taiwan orogen produced by the arc-continent collision induced tectonic and topographic loads at the edge of the Chinese margin, downflexing the Chinese margin and creating a foreland basin in front of the Taiwan orogen (Covey, 1984, Chou and Yu, 1997, Yu, 1998). Orogenic sediments from the rising Taiwan mountain belts are transported westwards to fill the foreland basin during Pliocene-Quaternary, forming today's Taiwan Strait Shelf (Yu, 1998,1999). This shelf is called foreland shelf because its geological setting is a part of foreland in front of the nearby Taiwan orogen. A schematic cross-section through the Taiwan Strait and Taiwan orogen shows the downflexing of the foreland plate on the continental side and the resultant foredeep west of the Taiwan orogen and the distributions of Pliocene-Quaternary orogenic sediments over the shelf (Fig. 2).

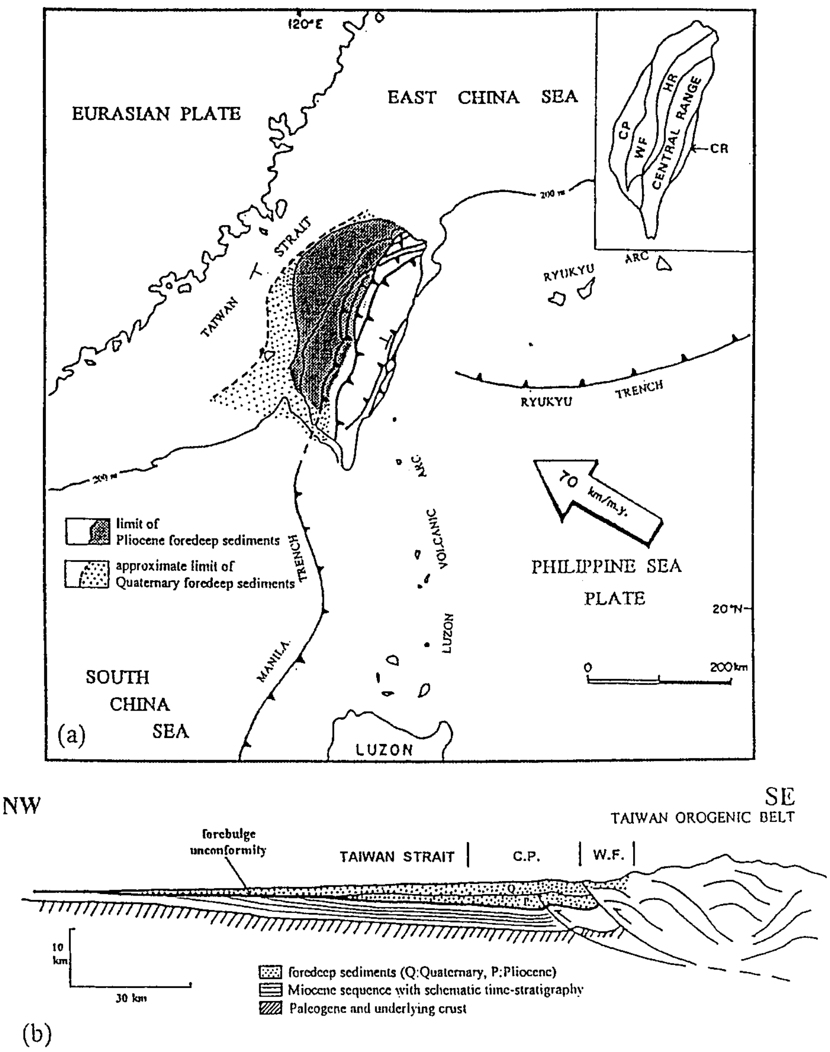

Figure 2. A schematic cross-section through the Taiwan Strait and Taiwan orogen shows downflexing of the foreland plate on the continental side and the resultant foredeep west of Taiwan orogen (b) and the distributions of Pliocene-Quaternary orogenic sediments over the Taiwan Strait (a). (After Chou and Yu, 1997).

There are three noticeable bathymetric lows in the Taiwan Strait Shelf, namely, Kuanyin Depression, Wuchu Depression and Penghu Channel (Fig. 3). The Kuanyin Depression, defined by the 60 m isobath, trends northeast and is located about 50 km off the Tanshui River, northwestern Taiwan. The formation of this depression is poorly understood. In western Taiwan Strait off the Fujian coast, there exists the elongate Wuchu Depression with a NE-SW trend (Mao and Hsieh, 1989). It is about 125 km long and 15 to 18 km wide with an average water depth about 70 m. Another prominent bathymetric low is the Penghu Channel located between the Penghu Islands and the coast off southwestern Taiwan. It is about 120 km long, trending N-S with a steeper slope on the eastern bank (Yu and Lee, 1993). The northern end of Penghu Channel terminates against the Yunchang Rise and turns towards northwest and merges into the Wuchu Depression. The Yunchnag Rise extends towards land into the Coastal Plain for a distance of about 100 kilometers. This rise is a Paleocene uplifted basement high composed of acidic igneous rocks (Lee, 1997). The surface sediments on the Yunchang Rise are reworked fine sands of Late Pleistocene and Holocene in age (Yu *el al.*, 1999).

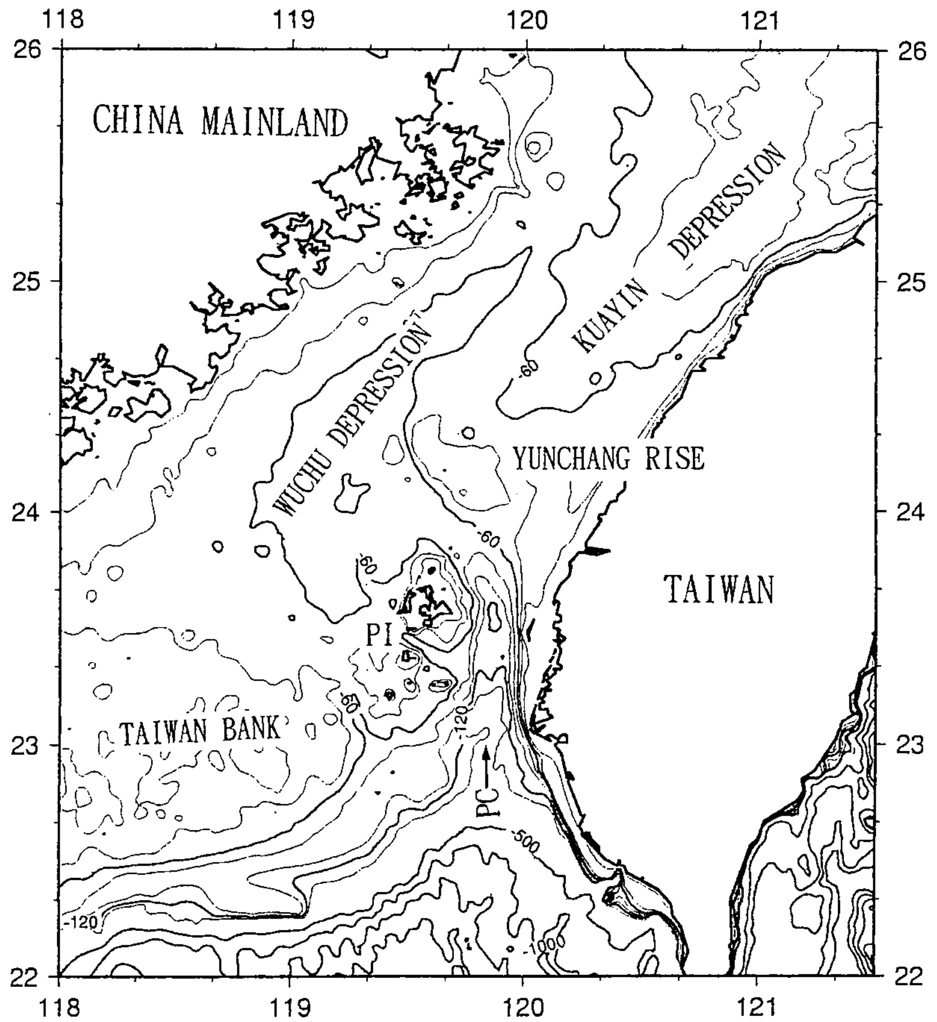

Figure 3. Bathymetric map showing three major bathymetric depressions: Kuanyin Depression, Wuchu Depression and Penghu Channel on the Taiwan Strait. A relatively large sandy shoal of the Taiwan Bank is present southwest of the Penghu Channel. Depth contours are in 20 m interval. PC: Penghu Channel, PI: Penghu Islands.

It has been long held that the paleo-drainage system of the ancestral Minchiang river on the Taiwan Strait Shelf during late Pleistocene follows the path from today's Wuchu Depression through the Penghu Channel and finally to Penghu Canyon in the northern South China Sea (Boggs *et al*., 1979). However, this postulate of paleo-drainage system on the shelf has not been supported by concrete geological evidence yet.

However, from the modern sedimentological and hydrodynamic viewpoints, Liu *et al*. (1998) suggested that the Taiwan Strait Shelf as a whole is a modern tidal deposition system. The Penghu Channel and Yuchang Rise are considered to be a tidal erosional-depositional system. Under the influence of the tidal currents, the Penghu Channel becomes a scour furrow due to the erosion by the strong tidal currents. In contrast, the Yuchang Rise results in a tidal sand sheet due to the accumulation of sands carried by the waning tidal currents.

Southwest of the Penghu Islands lie the Taiwan Banks which are wide and shallow and 20 to 40m deep (Fig. 3). Taiwan Banks consist of many subaqueous sand dunes in water depths between 30 to 40m (Mao and Hsieh, 1989). Because of its shallowness and being covered dominantly by sands, Taiwan Banks are also called Taiwan Shoal and are described as a relict feature, such as Late Pleistocene paleo-delta (Mao and Hsieh, 1989, Jin, 1992). Lately, using current measurements and observations of bedforms of sands, Liu *et al*. (1998) suggested that the banks consist of modern tidal sand ridges with S shape or en echelon shape. South China Sea Shelf and Slope

South China Sea Shelf

Southwest of the Taiwan Banks is the northern South China Sea Shelf with a NE-SW trend similar to Taiwan Strait Shelf (Fig. 1). The South China Sea Shelf is the southwestward continuation of the Taiwan Strait Shelf. There is no apparent physiographic boundary separating these two shelves. The sea floor of the South China Sea Shelf is shallow and relatively flat and has a width about 200 km. The South China Sea Shelf is the seaward extension of the coastal plains along the South China coast (Liu, 1982).

Beyond the edge of South China Sea Shelf is the South China Sea Slope that varies laterally in slope gradient and topography, marked by erosional gullies and canyons. It is noted that the large Formosa Canyon with its head near the southwestern end of Taiwan Banks cuts the East China Sea Slope and extends southeastwards over 110 km and joins the Penghu Canyon and Manila Trench (Fig. 4).

The thick Cenozoic syn-rifting and post-rifting sequences under the South China Sea Shelf and Slope indicate that the South China Sea margin is a typical passive margin characterized by clastic sediments accumulated in the grabens or half grabens overlain by a seaward tilting younger sedimentary wedge.

Kaoping Shelf and Slope

Opposite to the South China Sea Shelf and Slope are the Kaoping Shelf and Slope bordering the coast of southwestern Taiwan (Fig.4). The Kaoping Shelf is a short, narrow and shallow shelf (100 km long, 20 km wide and 80 m deep) and is the seaward prolongation of the coastal plain of southwestern Taiwan (Yu and Chiang, 1997). It stretches in a NW-SE direction, diagonal to the regional trend of the Chinese margin, along the mountainous coast at an unstable convergent margin. During late Quaternary, sediments transported by the major rivers of Tsengwen His and Kaoping Hsi flowing on the coastal plain were emptied into the sea and were redistributed on the sea floor, prograding seaward to form the present-day Kaoping Shelf (Yu and Chiang, 1997). Considering its characteristic morphology and tectonic setting, Yu and Chiang (1997) called the Kaoping Shelf as island shelf, distinguishing it from the passive margin shelf of East China Sea and the foreland shelf of the Taiwan Strait.

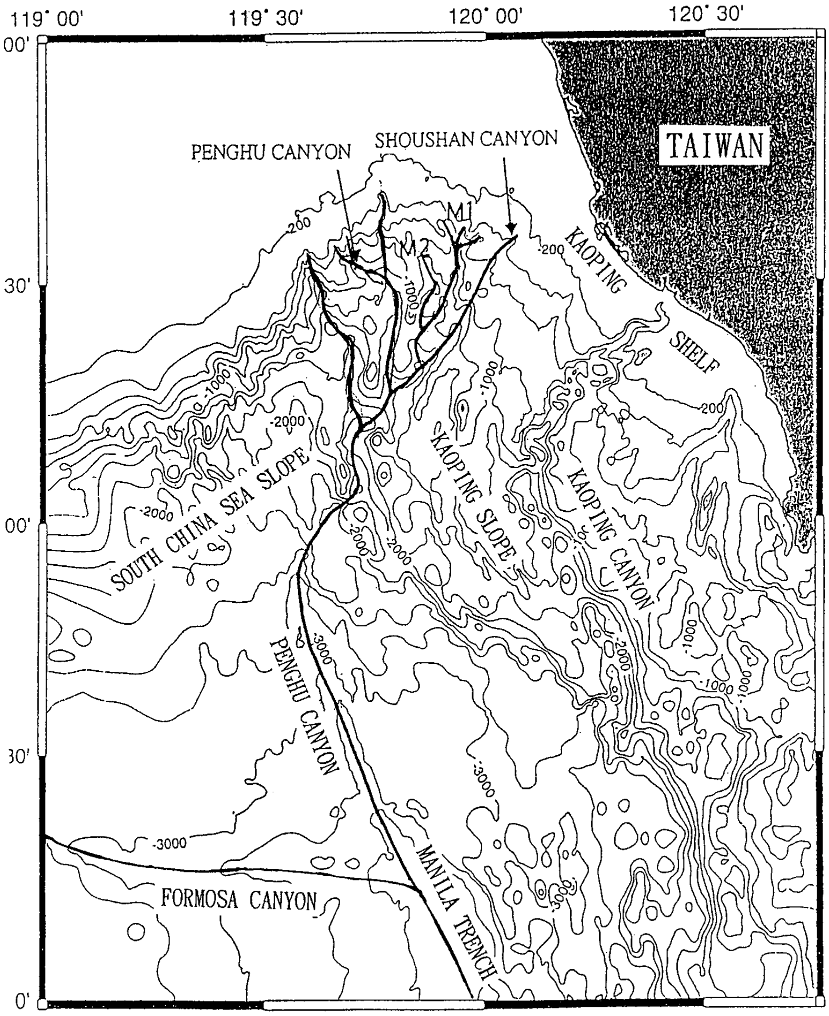

Figure 4. The submarine area between South China and Southwest. Taiwan is characterized by the presence of two broad and deep (greater than 3000 m) slopes marked by outward bowing bathymetric contours. Note that the Formosa Canyon on the South China Sea Slope and the Penghu Canyon at the toe of the Kaoping Slope merge into the Manila Trench.

The Kaoping Slope extends from the edge of Kaoping Shelf southwestwards to the northern South China Sea and ends at the Penghu Canyon north of the Manila Trench (Fig. 4). The slope is characterized by a very irregular surface. It is further divided into two parts around the isobaths of 1000 to 1200 m: the upper slope and the lower slope (Chen, 1983, Yu and Wen, 1992). Morphologically, the boundary between these two slopes is marked by one or more scarps with more than 1000 m relief, producing a steep upper slope and a gentle sloping-surface of the lower slope (Reed *et al*., 1992). The Upper Slope is deeply cut by NE-SW trending gullies and canyons. The canyons more or less orthogonal to the coastline show transverse transport of orogenic sediments shed from Taiwan orogen. The Kaoing Canyon is the most prominent one (Liu *et al*., 1993). In contrast, the Lower Slope is characterized by closely spaced NW-SE trending ridges and troughs formed by structural deformation and surface erosion (Fig. 4). West-vergent imbricated folds and thrusts are dominant structures in this slope (Liu *et al*., 1997). The coincidence in location of the Penghu Canyon and the structures together with relatively straight course suggest that submarine down-cutting along the structurally weak zone is the main cause for the formation of the Penghu Canyon (Yu and Huang, 1998). It is noted that some orogenic sediment has been transported longitudinally along the tectonic strike via bathymetric troughs on the lower slopes into the northern South China Sea. The Penghu Canyon is a major one for sediment dispersal in the lower slope.

The Formosa and Penghu Canyons merging into the northern Manila Trench have significant implications for tectonics and sedimentation in this region. The Manila Trench terminates its northern end about 20 15' N where it loses its identity as a deep bathymetric depression and connects to the southern end of the Penghu Canyon. The transition from subduction of the South China Sea crust in the south to initial arc-continent collision in the north is located at the junction between the Penghu Canyon and Manila Trench where the continent-ocean boundary in the Eurasian plate intersects the Manila Trench (Reed *et a*l., 1991, Liu *et al*., 1992).

In addition, the South China Sea north of 20 N can be considered as a remnant marginal ocean basin, resulting from the convergence of the Eurasian and Philippine Sea plates. A part of synorogenic sediments shed from the Taiwan orogen are transported longitudinally through the Penghu Canyon and adjacent NNW-SSE trending linear troughs into this remnant marginal ocean basin that was subsequently deformed and incorporated into the fold-and-thrustbelt of Taiwan. In contrast, the South China Sea Shelf and Slope supply passive-margin sediments to the basin floor via down-slope processes and canyon routes. The South China Sea Shelf and Slope region is much less deformed than the juxtaposed Kaoping Slope. It is noted that the Manila Trench receives orogenic detritus from the Penghu Canyon and passive-margin sediments from the Formosa Canyon, respectively. Subsequently, the Manila Trench is progressively buried by sediments southward. Hengchun Ridge-Northern Luzon Arc

Hengchun Ridge-Northern Luzon Arc

East of the Kaoping Slope is the submarine Hengchun Ridge, extending from the southern tip of Hengchun Peninsula southwards and ending at about 20 ° 45' N (Fig.5). The N-S trending ridge has a rough surface and irregular shape. Its northern part is cut by a NE-SW trending lineament showing discontinuity in bathymetry (Liu *et al*., 1998). This submarine ridge is interpreted as an accretionary wedge east of the Manila Trench (Suppe, 1988, Huang *et al.*, 1992, Reed *et al.*, 1992). Alternatively, we consider the ridge to be a part of southern Central Range submerging below sea surface, representing an undersea Taiwan orogen in its early development.

East of the Hengchun Ridge lies the forearc basin of the North Luzon Trough, a major morpho/tectonic unit of the Luzon Arc-Manila Trench System. This trough is about 120 km long, 36 km wide and 3600 m deep (Liu *et al.*, 1998) and is filled with thick sediments shed from various sources from Taiwan, Hengchun Ridge and Luzon Volcanic Arc (Lundberg *et al.*, 1992). At its eastern flank is Luzon Arc. North of 20 ° N this arc is mostly submerged with several volcanic islands emerging above the sea. For example, the Lanhsu and Lutao Islands off southeastern Taiwan and the Batan Islands east of the North Luzon Trough (Fig. 5).

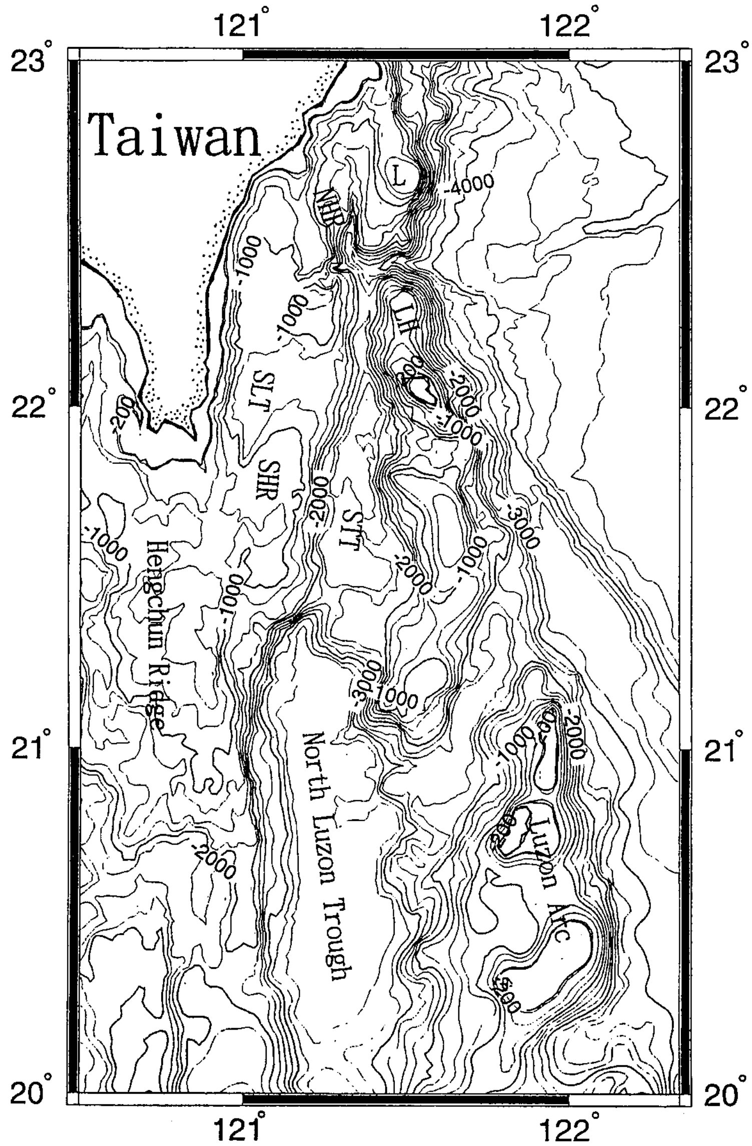

Figure 5. Bathymetric map showing a series of N-S trending submarine ridges and troughs off southeastern Taiwan. Note that the northern tip of Luzon Arc gradually merges into Taiwan near 23 ° N in a NW direction. HR: Hengchun Ridge, SLT: Southern Longitudinal Trough, NHR: Northern Huatung Ridge, SHR: Southern Huatung Ridge, STT: Southern Taitung Trough, L: Lutao, LH: Lanhsu.

South of 21 ° N, the Manila Trench, Hengchun Ridge, North Luzon Trough and Luzon Arc lying from west to east and represent a typical subduction-related trench-island arc system. However, the morpho/tectonic features of the Luzon subduction system are changed into an emergent mountain (southern Central Range in Taiwan) and linear submarine troughs and ridges in the region between 22 ° N and 23 ° N east of 120 ° 40' E (Fig. 5). Chen *et al*. (1988) named these submarine physiographic highs and lows off southeastern Taiwan from west to east as follows: (1) Hengchun Ridge, (2) Southern Longitudinal Trough, (3) Huatung Ridge, (4) Taitung Trough and (5) Lutao-Lanhsu Ridge (Fig. 5). Various geological meanings and tectonic implications were given to these submarine features (Chen and Juang, 1986,Huang et al., 1992, Chen *et al*., 1992, Yu and Chiao, 1994, Yu, 1997, Fuh and Liu, 1998, Liu, *et al*., 1998). Readers may refer to these papers for detailed discussions.

This paper considers that initial arc-continent collision took place in the region north of 22 ° N where the submarine Hengchun Ridge has been deformed into mountain ranges above the sea level. The North Luzon Trough could be deformed into Southern Longitudinal Trough, Huatung Ridge and Taitung Trough. The northern Luzon Arc changed its strike to NNW and collided with the Central Range near the Tatung city at 121 ° 22' E, 23 ° N (Fig. 5). The Coastal Range has formed as a result of this collision. On the other hand, the region between 21 ° N and 22 ° N east of the Hengchun Ridge is the transition zone from subduction to collision where neither a subduction zone exists nor fold-and-thrust belts emerge above the sea level.

Huatung Basin and Guaga Ridge

The deep basin floored by oceanic crust off eastern Taiwan is the Huatung Basin, which is bounded to the north by the Yaeyama Ridge, to the east by the Guaga Ridge and to the southwest by the Luzon Arc (Fig.6). Liu *et al*. (1998) divided this basin into three zones: the arc slope, submarine fan and deep-sea basin. The arc slope off eastern Taiwan coast is relatively steep about 6 degrees with irregular sea floor. Numerous canyons cut the arc slope and transport sediments to the foot of the slope to form submarine fans. The deep-sea basin is relatively flat in general. The northern part of this basin is cut by at least five large canyons that flow eastwards and merge into the intersection of the Ryukyu Trench and Guaga Ridge. Also, a series of small ridges emerge above the sea in the east part of the basin. The nature of these ridges is poorly known.

A thin layer of sediments about 0.2 to 1,6 km in thickness is accumulated on the bottom of the Huatung Basin inferred from seismic velocity. The sediment is mainly derived from Taiwan via the Taitung Canyon. A possible older sequence ofvolcaniclastics with a thickness up to 4 km is also found between the arc slope and the Taitung Canyon (Yang and Wang, 1998).

It is noted that the Hualian Canyon extends along the western and southern edge of the Yaeyama Ridge (accretionary wedge) and merges into the Ryukyu Trench. It can be regarded as the surface trace of the plate boundary separating the Philippine Sea plate from the Eurasian continental plate. Morphologically, a submarine canyon continuing into a deep trench as a plate boundary is not uncommon. For example, in a similar setting of arc-continent collision, the Markham Submarine Canyon in southeastern Pupua New Guinea continuing into the deep Markham Trench serves as the plate boundary separating the South Bismark oceanic plate from the Australian continental plate (Crook, 1989).

The prominent N-S trending Guaga Ridge runs approximately parallel to the 123 ° E for a about 350 km length east of the Huatung Basin (Fig.6). This ridge is about 20 to 30 km wide and has a maximum relief of nearly 2500 m above the sea floor. It was called the Palaui Ridge extending southward to the Palaui Island at the northeast corner of Luzon (Karig, 1973). This ridge has variously been interpreted as an extinct spreading center (Bowin *et al.*, 1978), an old fracture zone (Mrozowski *et al.*, 1982, Hilde and Lee, 1984), a remnant arc (Lewis, 1992), or an up-faulted sliver of the oceanic crust (Karp *et al.*, 1997, Deschamps *et al.*, 1997).

Indentation of the Gauga Ridge into the Yaeyama Ridge produces a reentrant and terminates the westward continuation of the Ryukyu Trench. Schnurle et al. (1998) suggested that a part of the Guaga Ridge has been subducted beneath the Yaeyama Ridge. Significance of this indentation needs further investigation.

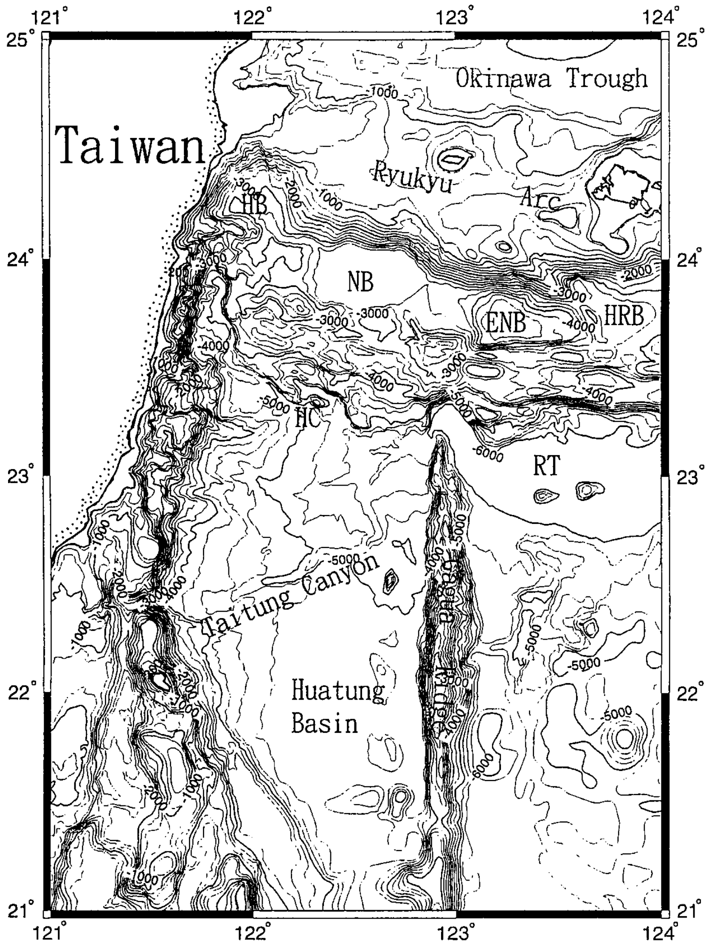

Figure 6. Off eastern Taiwan lies the deep Huatung Basin which is bordered by a prominent N-S trending Gagua Ridge to the east. The large Taitung Submarine Canyon flows from the arc slope across the Huatung Basin and ends at the Ryukyu Trench to the north. E-W trending morpho/tectonic features of the Ryukyu Arc-Subduction System include the Ryukyu Trench, Yaeyama Ridge, four forearc basins, Ryukyu Arc and Okinawa Trough. HC: Hualian Canyon, RT: Ryukyu Trench, HB: Hoping Basin, NB: Nanao Basin, ENB: East Nanao Basin, HRB: Hateruma Basin.

Ryukyu Island Arc-Trench System

The Ryukyu Trench, Yaeyama Ridge, Nanao Basin, Ryukyu Arc and the Southern Okinawa Trough off eastern Taiwan progress towards the Asian continent, representing a typical morphological expression of a subduction-back arc extension system (Fig. 6). The Ryukyu Trench extends from Kyushu, Japan southwestward and ends at about 123 E where the northern tip of the Gauga Ridge intersects the Ryukyu Trench. Morphologically, the western end of the Ryukyu Trench changes into the Hualian Submarine Canyon that can be traced toward Taiwan to the northern end of the Longitudinal Valley (Yu and Song, 1999a). However, Kao *et al*. (1998) pointed out that the northward subducting Philippine Sea plate extends northwestward farther to 122 E beneath the northern Taiwan. In other words, the bathymetric expression of the subduction zone at sea floor is no longer the deep trench which is modified into the Hualian Canyon due to the collision between the arcs of western Ryukyu and northern Luzon near Taiwan.

The Yaeyama Ridge lies north of and parallel to the Hualian Canyon and Ryukyu Trench. This ridge has a rugged surface and is characterized by imbricated folds and thrust ramps (Liu *et al*., 1998). It is an accretionary wedge in terms of tectonic setting, structure and morphology. Its detailed structural descriptions can be referred to Lallemand *et al*. (1998) and Schurle *et al*. (1998).

Farther toward the Chinese continent, there are a series of forearc basins in front of the Ryukyu Arc (Fig. 6). Liu et al. (1998) pointed out that the forearc basin can be divided into four subbasins, namely, the Hoping, Nanao , East Nanao and Hateruma basins extending from west to east. The first one is the deepest basin (4600 m) and others become shallower toward Taiwan. Turbidites derived from eastern Taiwan are the main sediments filling these forearc basins (Liu *et al*., 1997). The crustal thickness beneath these basins ranges from 20 to 25 km (Shih et al., 1998), representing an attenuated continental crust of the Eurasian plate.

Using ocean bottom seismometer data, Meintosh and Nakamura (1998) and Tan and Chiang (1998) suggested that the oblique subduction of the Philippine Sea Plate beneath the Ryukyu Arc extends westward as far as at 122@E where the northern Luzon Arc collided with the western Ryukyu Arc. The interactions between arc-arc collision and subduction of the Philippine Sea Plate in the western Ryukyu forearc area result in a complex system of morpho/tectonic features with high seismicity.

North of the Ryukyu Arc is the Southern Okinawa Trough that has long been recognized to be a typical backarc basin (Lee et al., 1980). Recently, progress in geophysical understanding of the trough has been brought to light by scientists from Taiwan and France through international cooperation. For example, Sibuet et al. (1995) presented structural and kinematic evolution of the Okinawa Trough. Lately, Sibuet et al. (1998) gave an account of the tectonic and magmatic evolution of this basin.

East China Sea Slope

The East China Sea Slope extends from the shelf edge of the East China Sea Shelf to the basin floor of the southern Okinawa Trough (Fig. 7). The depth of this slope is generally shallower than 2,000 m, ranging from 1,700 to 2030 m. Structurally, the slope is the northern flank of the Okinawa Trough. Extension and faulting of this young backarc basin produce morphology and size of the slope different from that of a mature continental slope.

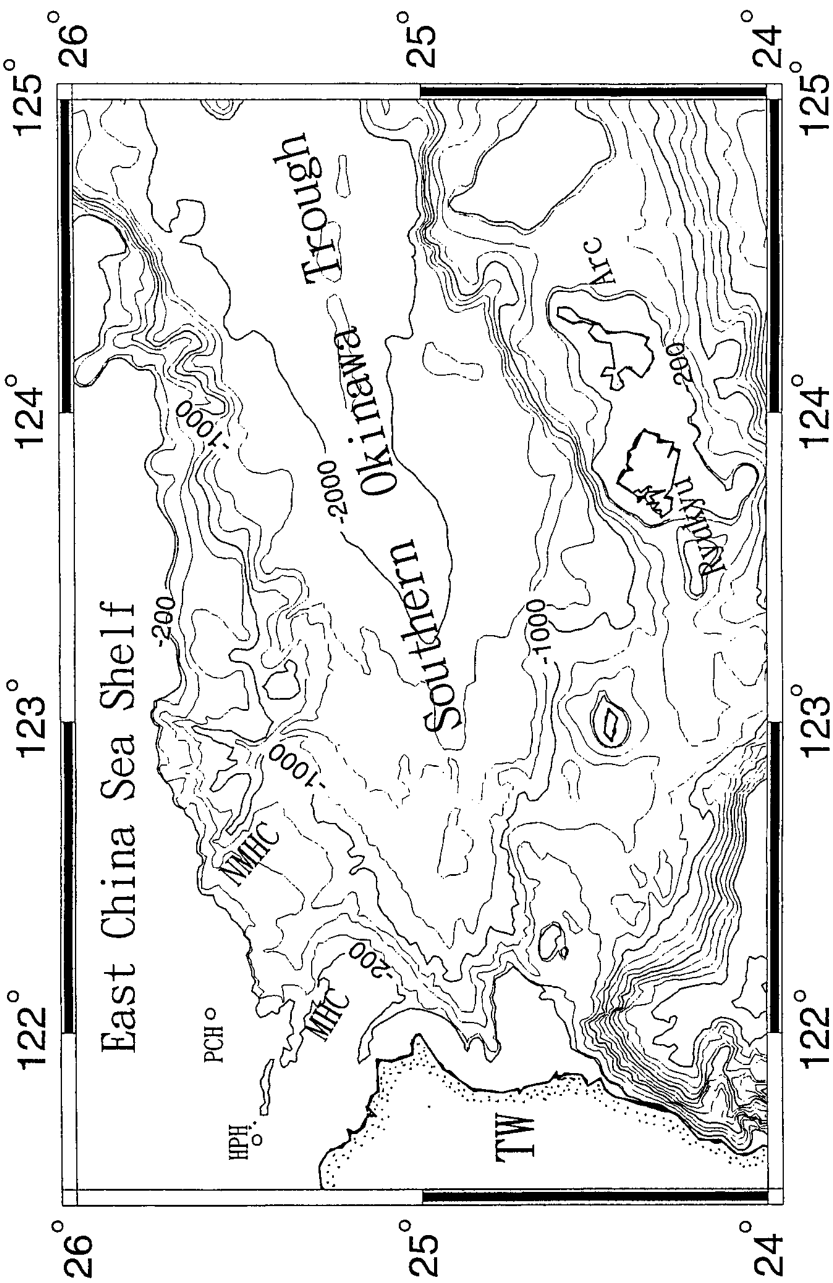

Figure 7. Bathymetric map shows the East China Sea Slope at the northern flank of the southern Okinawa Trough. This soipe is characterized by its irregular sloping surface produced by erosion of numerous gullies and canyons and mass-wasting movements. MHC: Mien-Hua Canyon, NMHC: North Mien-Hua Canyon, PCH: Pengchiahsu Island, HPH: Huapinghsu Island.

The slope is transversely dissected by submarine gullies and canyons among which the North Mien-Hua Canyon is the most prominent one (Fig.7). This slope is characterized by irregular topography and shows moderately lateral variations in gradients with an average slope angle of about 1.31 degrees (Yu and Song, 1999b). Tilted normal faults formed by backarc extension of the southern Okinawa Trough during late Miocene-Quaternary and subsequent deposition of sediments from the nearby shelf have formed the present-day East China Sea Slope.

DISCUSSIONS AND CONCLUSIONS

The marine geology in Taiwan region reflects a transition from a passive margin to an active margin during last five million years in general. Prior to the collision with the Luzon Arc, the Chinese continental margin in Taiwan region was characterized by a bathymetric setting with shelf, slope, basin and trench with increasing depth and by a NE-SW regional trend. After collision with the Luzon Arc and rising of the mountain belt of Taiwan, the Chinese margin in Taiwan region became an active margin where is characterized by a paired thrust-belt and foreland basin, bounded by two remnant marginal ocean basins and transitional subduction systems.

The rock materials of continental slope, deep basin and trench of the Chinese margin and a part of Luzon Arc were deformed into the fold-and-thrust belt of Taiwan. The topographic and tectonic loads of Taiwan orogen at the edge of the Chinese margin downflex the crust of the Eurasian plate to form a foredeep west of Taiwan orogen. After sediment infilling the western Taiwan foredeep close to the sea level, the foredeep becomes the present-day Taiwan Strait Shelf (i.e., a foreland shelf). On the other hand, the East China Sea Shelf north of Taiwan is little affected by lithospheric downflexing and maintains a passive margin.

The Kaoping Shelf off southwestern Taiwan coast represents an early stage of the development of a foreland basin with a narrow shelf and an underfilled submarine slope (i.e., Kaoping Slope). The variation from a passive margin shelf (East China Sea Shelf), a foreland shelf (Taiwan Strait Shelf) to an island shelf (Kaoping Shelf) along the strike of the mountain belt of Taiwan mainly reflects the oblique collision between the Luzon Arc and the Chinese margin from Pliocene to the present. The uplift of Taiwan orogen, accompanying foreland-basin sedimentation, surface processes and sea level changes are responsible for the formation of the varying shelves near Taiwan. The detailed descriptions of the foreland basin in relation to the forming of Taiwan orogen was given by Yu and Chou (1999).

The area north of 21 ° 30'N off southeastern Taiwan represents initial arc-continent collision and the northern Luzon forearc region is deformed into N-S trending troughs and ridges. Similarly, the western part of Ryukyu Arc System near Taiwan is deformed into a series of complex W-E trending morpho/tectonic features, resulting from interactions between arc-arc collision, oblique subduction, submarine ridge indentation, and backarc extension near Taiwan.

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臺灣區域海底地形及其地質意義

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摘　　要

環繞臺灣海底地形的特徵是其不對稱性，西部是相當淺而平坦的大陸棚，而東部及南部出現顯著的深海盆地，海溝和起伏大的海槽與海脊。地體構造與沉積作用是其形成約主要因素。

三個上新世至第四紀大陸棚分佈在臺灣的北部和西部海域，由北向南沿著臺灣的走向依次為東海大陸棚(被動邊緣大陸棚)，臺灣海峽大陸棚(前陸大陸棚)及高屏大陸棚(島嶼大陸棚)。臺灣東北海域的地形主要有東西走向的耶亞瑪增積岩體，琉球島弧，四個錯動的弧前盆地，花蓮海底峽谷，琉球海溝和活躍的南沖繩海槽。東部海域的花東深海盆地位於北呂宋島弧與加瓜海脊之間，其底部相當平坦，雖然有幾條大型海底峽谷侵蝕盆底。源自臺灣造山帶的沉積物經由海底峽谷堆積在花東盆地底部。

廣闊的高屏大陸斜坡是西南海域最主要的地形，它以澎湖海底峽谷與南海大陸斜坡為界，澎湖海底峽谷的下游在北緯二十一度三十分逐漸併入馬尼拉海溝。東南海域北呂宋島弧的弧前區域經過初期弧陸碰撞變成南北走向的海槽與海脊，其中恆春半島向海延伸的恆春海脊是最顯著的地形。

臺灣區域的海洋地質反映了過去五百萬年由一個被動大陸邊緣轉變成一個活動大陸邊緣。與呂宋島弧碰撞之前，當時在臺灣區域的大陸邊緣具有向東逐漸增加深度的大陸棚，大陸斜坡，深海盆地及海溝，其區域構造為東北—西南向。弧陸碰撞之後以及臺灣造山帶的隆起，被動大陸邊緣變為活躍，並形成成對的逆衝斷層帶與前陸盆地，其邊界為兩個殘留邊緣海盆地與過渡隱沒—碰撞體系。

關鍵詞：海底、地形、地體構造、沉積作用、臺灣