

Tectonic geomorphology of the Ryukyu Trench-Arc-Backarc System: geological-geophysical exploration and mapping

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Abstract Based on an analysis of full-cover multi-beam bathymetric data, seismic and sub-bottom profiling data, and other geological-geophysical data sets, the geomorphologic features of the Ryukyu trench-arc-backarc (T-A-BA) system are delineated, and a geomorphologic map of the system is compiled. The results show that the evolution and spatial distribution patterns of the geomorphologic types of the Ryukyu T-A-BA system are controlled mainly by tectonic movements. The tectonic geomorphologic characteristics of the Ryukyu Arc (RA) differ distinctly from those of the East China Sea (ECS) continental shelf and slope. In term of geological structures, RA consists of the Tokara volcanic ridge, the Ryukyu folded ridge, the fore-arc accretion-wedge ridge and the Amami Depression and the fore-arc depressions between the ridges, which is composed of a complex of alternating island-slope ridges and fault basins. The slope of the ECS is a passive continental margin with stepwise faults. The Okinawa Trough (OT) is a backarc rift in which tectonic movements are intensive, with active volcanic and hydrothermal eruptions and sea floor spreading. The development of geomorphic features of the OT is controlled by the central en echelon spreading axes, the faults along the ECS slope and the marginal faults to the west of the Tokara volcanic ridge. The geomorphic complex of the OT is arranged in the following pattern: the en echelon grabens and volcanic chains formed by rifting and spreading lie in the central part of the trough, the turbidite plains inclining eastwards-south-eastwards from the slope foot of the ECS lie in the western-northwestern parts of the OT, and the volcanoclastic deposit plains inclining westward-northwestwards from the western slope foot of the RA lie in the eastern-southeastern parts of the OT. In term of tectonic geomorphology, the OT forms a natural division between the shelf of the ECS and

the RA.

Keywords: trench-arc-backarc system, tectonic geomorphology, geomorphologic classification, geomorphologic mapping.

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Submarine tectonic geomorphologic mapping provides a basic tool that systematically reflects the submarine topography, geomorphology, geology and geophysics, comprehensively represents the morphostructures, morphogenesis, distribution and evolution patterns of the geomorphic units in a sea area, and expresses the information on natural environments and resources in a graphic form. Modern geomorphologic classification and mapping of oceans and continental margins are generally carried out based on the concept of plate tectonics, with an emphasis on the study of the control of plate movements and plate tectonics on the evolution of geomorphic features and the geomorphic manifestations of plate tectonics. Such features within and in the marginal zones of the plates and their distribution patterns are significant indications of the mode of plate movements and the natures of the crustal structures. The International Geomorphologic Maps of Europe (1:2500000) compiled by IGUCGCM are based on tectonic geomorphologic classification^[1].

The continental margins of the west Pacific Ocean are composed of a series of plate collision zones, characterized by trench-arc-backarc (T-A-BA) systems. After the World War II, USA and the former Soviet Union conducted many large-scale topographic, geomorphologic, geologic and geophysical investigations in the Bering Sea including the Aleutian T-A-BA system, and compiled a series of small-scale bathymetric, geomorphologic, geological and geophysical maps. The US Geologic Survey kicked off a long-term marine investigation program in 1984. Since then, a series of geological, geomorphologic and gravitation maps have been compiled with the scale of 1:2500000. The former Soviet Union and Japan conducted many bathymetric surveys and geological and geophysical investigations in the Sea of Okhotsk (including the Kuril T-A-BA system) and the Sea of Japan, and compiled a series of bathymetric, geomorphologic, geologic and geophysical maps of these seas. The Far East Academy of Sciences published 1:2500000 geological maps of the Sea of Japan in 1985. Japanese scientists published 1:1000000 geological and geophysical maps of the eastern and central parts of the Sea of Japan in the 1980s^[2].

Many studies have been undertaken on the geology, geophysics and tectonic geomorphology of the Ryukyu T-A-BA system. Scientists from the former Soviet Union, France, USA, and Germany carried out geologic and geophysical investigations in the Okinawa Trough (OT), including full-cover multibeam bathymetric surveys in some areas. Japanese scientists carried out full-cover multibeam bathymetric survey and geologic, geophysical investiga-

tions in the OT and the Ryukyu Arc (RA), and compiled high-precision bathymetric, geological and geophysical maps. The Geomorphologic Map of the East China Sea (ECS) (1:1000000) was compiled by the Second Institute of Oceanography, State Oceanic Administration (China)¹⁾. Fu (1990) compiled a geomorphologic map of the eastern China Seas (1:5000000)^[3]. Chen (1993) compiled a geomorphologic map of China and the adjacent regions (1:4000000)^[4], and classified the geomorphologic types using information on tectonic geomorphology, climatic geomorphology and topographic structures^[5]. Liu et al. (1993) compiled a submarine geomorphologic map of China Seas and adjacent area (1:8600000)^[6], and discussed the methods of geomorphologic classification based on the concept of plate tectonics^[7], representative of the classification system of marine tectonic geomorphology in China. However, because the maps mentioned above are all of small scales, and only limited data were used in the maps, the classification of tectonic geomorphic features could not be discussed in details. The geomorphologic types of the Ryukyu T-A-BA system and the deepsea basins were compiled mainly based on low-accuracy bathymetric maps. During 1992–2001, large-scale bathymetric surveys and geomorphologic, geologic and geophysical investigations were conducted by the scientists from China in the Ryukyu T-A-BA system and in the northwest Philippine Sea; a large data set has been acquired, including full-cover multi-beam bathymetric survey and subbottom profiling and seismic data, with densely distributed survey lines. A series of topographic, geomorphologic, bottom sediment and geophysical maps of the region were compiled. Based on the above-mentioned data set and the research made by scientists both at home and abroad, a tectonic geomorphologic map of the Ryukyu T-A-BA system is compiled, and a systematic analysis of the tectonic geomorphic features of the system is conducted in the present contribution.

1 Regional geological background

The Ryukyu T-A-BA system consists of the Ryukyu Trench (RT), the Ryukyu Arc (RA) and the Okinawa Trough (OT). It is a plate-margin structural complex formed by the collision and subduction between the Philippine Sea plate and the Eurasia plate. The major regional geologic structures within the system and adjacent areas are the Taiwan-Sinzi upwarped belt, the OT rifting belt, the RA upwarped belt, the RT subduction belt and the western Philippine Sea deepsea basin (Fig. 1).

(一) Taiwan-Sinzi upwarped belt. The Taiwan-Sinzi upwarped belt is located at the margin of the shelf of ECS, with the water depth ranging between 130 and 170 m. It extends southwestward from the Goto Retto to the west of Kyushu in the north to the folded maintain in Tai-

wan Island in the south, passing Danzyo Gunto, Chiwei Islet (Sekibi syo), Diaoyudao Island (Uoturi Sima), Huangwei Islet (Lobi Syo), Mianhua Islet, Huapin Islet, etc. It has an old basement that separates the depression basins of the ECS from the OT and is composed of Mesozoic metamorphites and magmatites. The Miocene sequence on the belt is thin or even absent. The Pliocene and Quaternary sedimentary sequences with a thickness of around 1000 m overlap unconformably upon the older sequences and the basement. There are no morphologic expressions in seabed topography; in seismic profiles, this belt shows a basement upwarping feature.

(二) The backarc rifting belt of Okinawa Trough. This belt is located between the Taiwan-Sinzi upwarped belt and the Ryukyu Arc upwarped belt, including the slope of the ECS and the backarc basin of the OT.

The slope of the ECS to the west of OT is a newly formed passive continental margin. It extends in NE-SW direction with a fan-shaped outline widening from the south to the north. The major tectonic movement is extensional faulting. The faulted blocks cut by normal faults fall, tilt and roll down along the normal faults or plow faults, resulting in extension and thinning of the crust. The thickness of the crust decreases from 28 km at the margin of the shelf to 24–20 km at the ECS slope foot to the west of the OT. The major controlling faults on the slope are shelf-margin faults and slope-foot faults. The backarc basin of the OT is located between the slope foot of the ECS and the western island-slope foot of the RA. The general trend of the basin is NE-SW, with a trend of widening from the north to the south. Both sides of the rifting zone of the OT are zigzag-shaped, bounded by fault systems consisting of NNE- and NEE-trending faults. The Tokara and the Miyako fault zones divide the OT into three sections, i.e. the north, middle and south sections. In the geomagnetic map, the central OT shows a series of intensive-variation magnetic anomalies. While in seismic profiles, the axis of the central OT is composed of a series of grabens controlled by normal faults. Within the grabens, igneous and hydrothermal activities occur intensively. The central grabens in the northern OT are NE trending, whilst those in the middle and southern parts of the OT are NEE–E-W trending. The central grabens as a whole are arranged in an echelon patterns. Magnetic lineations formed by sea-floor spreading have been found^[8, 11], and fresh samples of tholeiite and dorgalite have been dredged in the grabens in the middle and southern OT. According to the characteristics of geophysical fields and the results of analysis of dredged rock samples, sea floor spreading has been taking place in the axial part of rifting belt of the OT, and the spreading movement weakens towards the north. There is an upwarped fault-block igneous belt in

1) Second Institute of Oceanography, SOA. The Geomorphologic Map of the East China Sea.

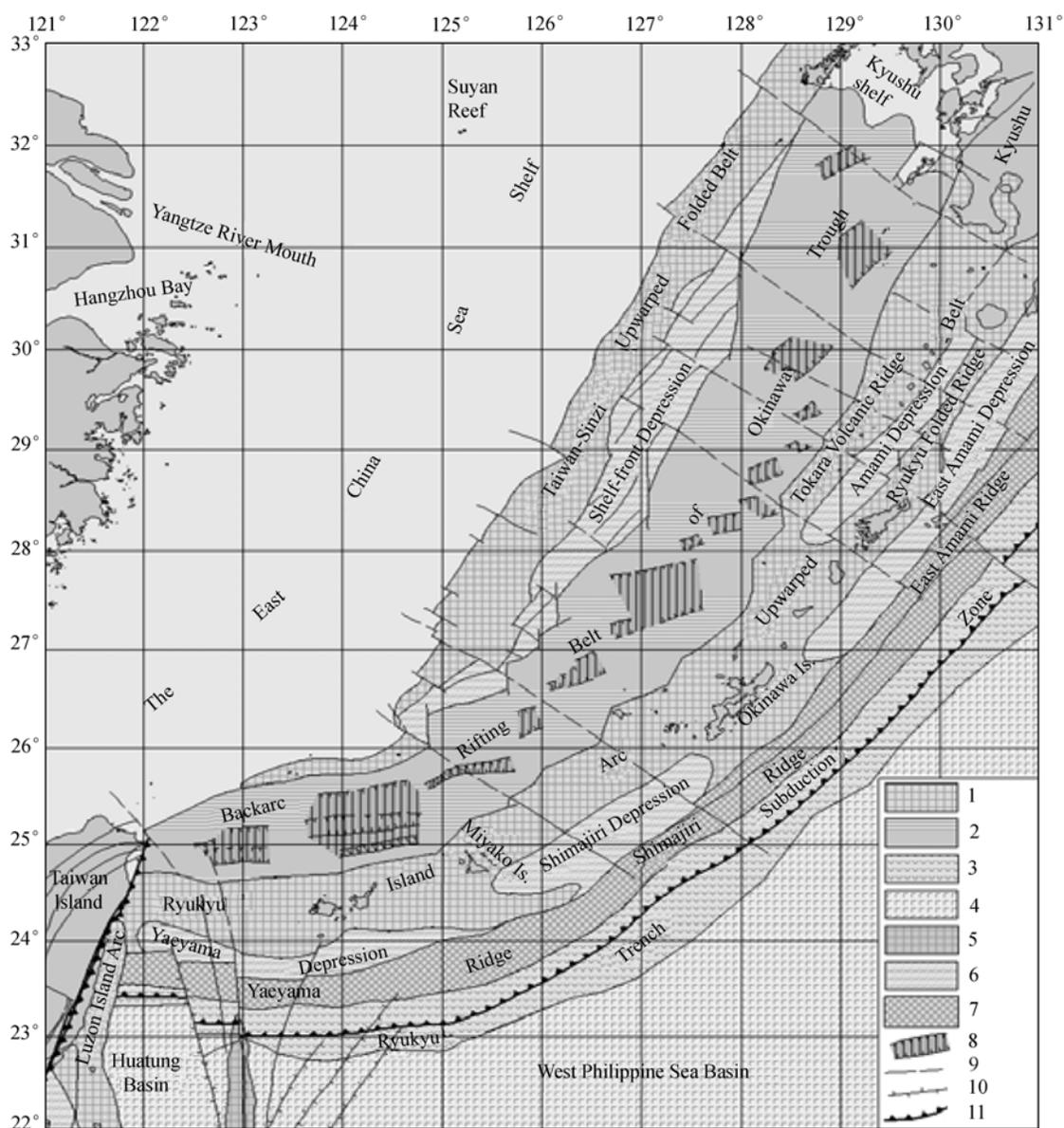


Fig. 1. Geologic structure map of the Ryukyu T-A-BA system. 1, Upwarped belt; 2, backarc rift belt; 3, trench subduction zone; 4, oceanic basin; 5, oceanic ridge; 6, secondary depression; 7, accretional ridge; 8, extensional graben; 9, fault; 10, transform fault; 11, subduction belt.

the east part of the middle OT.

(核) Ryukyu arc upwarped belt. This belt consists of three ridges and two depressions, i.e. the Tokara volcanic ridge, the Amami depression, the Ryukyu fold ridge, the forearc depression zone (the Eastern Amami, Shimajiri and Yaeyama depressions) and the forearc ridge zone (composed of accretion wedges, the Eastern Amami, Shimajiri and Yaeyama ridges). The Tokara volcanic ridge is a Quaternary volcanic ridge, representing a positive anomaly belt with a general NE-SW trending on the geomagnetic chart. The Amami depression separates the Tokara volcanic ridge from the Ryukyu fold ridge, being a

low quietly transitional anomaly zone with smooth variation on the geomagnetic chart. The Ryukyu fold ridge is the southwestward extension part of the Japanese Islands. The basement of this fold ridge is similar to that of the main body of the Japanese Islands, composed of metamorphic rocks of the late Paleozoic-early Cenozoic Eras. In the geomagnetic chart, the Ryukyu fold ridge shows as a positive anomaly zone. The forearc depression zone separates the forearc ridge zone from the Ryukyu fold ridge; in the geomagnetic chart, it shows low negative anomaly. Its northwestern side is characterized by extensional faults, while its southeast side is controlled by thrust faults. The forearc ridges are island-slope ridges

composed of accretion wedges formed in the subduction zone between the Philippine Sea plate and the Eurasia plate. In the geomagnetic chart, these ridges show anomalies with a gradient in the same direction as the bathymetric gradient of the ridges, and rapid decrease in the ΔT from the ridges to the Ryukyu Trench.

(烘) Ryukyu Trench subduction zone. The Ryukyu Trench (RT) is located in the collision zone between the Philippine Sea plate (PH) and the Eurasia plate (EA). The PH subducts under the EA via the axis of the RT, which extends from the south side of the connection between the Kyushu-Palau Ridge and Kyushu in the northeast to the northwest side of the Gagua Ridge 120 km east of Taiwan Island. The water depth in the RT is over 6000 m with a maximum of 7881 m. The seabed topography in the RT varies greatly, scattered with sea hills and seamounts.

(烙) Western Philippine Sea Basin. The PH is moving northwestwards at a speed of 10 cm/a. Its northwestern part is subducting under the EA. The PH is divided into the west and east basins by the Kyushu-Palau Ridge. The western PH has a significant effect on development of tectonic movements and geologic structures of the Ryukyu T-A-BA system and Taiwan-Luzon collision zone.

2 Classification and mapping of submarine geomorphologic features

(威) Classification of geomorphologic types. Classification of geomorphologic types forms a basis for the study and mapping of submarine geomorphologic features. There are inherent relationships between the geomorphology and its genesis, i.e. geomorphic forms reflect their genetic types. Based on the principles of "combining landforms with morphogenesis, combining endogenetic forces with exogenetic forces, and combining classification with grading"¹⁾, the submarine tectonic geomorphologic types are classified in 4 grades according to the dominant morphogenetic factors. Macro-scale geomorphic units are classified firstly, followed by smaller-scale ones; the grouped landforms are classified firstly, followed by individual ones. Grade Ⅳ consists of large tectonic geomorphic units. Three Grade I geomorphologic systems can be identified in the active continental marginal zones, including the continental-plate, the T-A-BA and the oceanic-plate geomorphologic systems. Grade Ⅲ consists of those developed under the control of regional geological structures. The Grade Ⅱ geomorphologic types within one geomorphologic system have the same crustal setting but are different in geologic structures. Grade Ⅰ consists of basic morphogenetic types formed by different endogenetic and exogenetic agents. Grade-Ⅱ are the lowest geomorphic units that can be found in the higher-grade units, classified mainly by geometric forms and the mate-

rials forming the strata. In general, Grade Ⅱ geomorphologic units are of a small size and mono-morphogenesis.

In the three Grade Ⅳ geomorphologic types identified, the shelf plain of the ECS belongs to the continental-crust geomorphologic system, the slope of the ECS and the Ryukyu T-A-BA system belong to the transitional-crust system, and the western Philippine Sea basin belongs to the oceanic-crust one (Table 1).

Belonging to the Grade Ⅲ geomorphologic type, the ECS represents a wide fault-depression shelf with fault depressions of the Mesozoic-Cenozoic Eras. The Grade Ⅲ types within the shelf include modern subaqueous river deltas, depositional bay plain, depositional and erosional shelf plains, paleo-delta plain, modern and moribund tidal ridge fields, structural shelf platform, and structural and erosional shelf depressions.

The Grade Ⅲ types on the slope of the ECS (to the west of the OT) can be divided into three sub-types: the simple slope, the step-faulted slope and the transitional slope (turbidite slope). The Ryukyu T-A-BA geomorphologic system can be divided into three Grade Ⅲ types: the trench (RT), the island arc (RA) and the backarc basin (OT).

The Grade Ⅲ geomorphologic types in the RT include trench-bed plain, trench slope, sea ridge and fault grabens in the trench. The RA geomorphologic type can be divided into the island shelf and island slope. The Grade Ⅲ types in the island shelf consist of the nearshore slope, abrasion platform, coral reef, shoal in the island coastal zones, and the shelf slope, while those on the island slope consist of step-fault cliniform, the fault-block platform, sea ridge, fault depression and deep-water terrace.

The Grade Ⅲ geomorphologic types in the backarc basin of the OT include the bathyal turbidite plain (continental rise), bathyal volcanoclastic deposit plain, bathyal fault depression, central rift basin (graben), central volcanic chain, bathyal upwarped fault-block platform, bathyal sea ridge and bathyal step-faulted cliniform slope. The Grade Ⅲ types in the west Philippine Sea basin consist of deep-sea plain, deep-sea ridge, sea hill-seamount complex and deep-sea fault depression.

(裁) The submarine geomorphologic map. The 1:500,000 tectonic geomorphologic map is a middle-scale regional map. The basic graphic representations reflect the general pattern of large- and middle-scale tectonic geomorphologic units. Such a map emphatically represents various morphogenetic-morphologic types, geomorphologic structures and the major factors controlling the morphogenesis and dynamic processes, presents the di-

1) Institute of Marine Geology, Ministry of Land and Resources, 1999, The Professional Standard of Mineralogy: the Standards of 1:500,000 Submarine Geomorphologic Map.

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Table 1 Classification of geomorphologic types in the Ryukyu T-A-BA system and adjacent sea areas

Grade я (huge structural type)		Grade ё (regional structural type)		Grade — (morphogenetic-form type)	Grade (morphologic type)
Continental-Crust geomor- phologic System	coastal zone	intertidal zone		muddy tidal flat	
		nearshore zone		modern subaqueous river delta	
	continental shelf	wide fault-depression shelf (with fault depressions of Mesozoic-Cenozoic eras developed)		erosional nearshore slope	
				depositional bay plain	
				undulated paleo-delta plain	
				inclined paleo-delta plain	
				depositional paleo-tidal ridge field	tidal ridge
				erosional paleo-tidal ridge field	shoal
				inclined depositional shelf plain	erosional gully
				inclined depositional-erosional shelf plain	submerged reef
Transitional-crust geomor- phologic System	continental slope	simple slope		depositional simple clinoform belt	
		step-fault slope		erosion-depositional clinoform belt	canyon
		turbidite slope		erosional simple clinoform belt	structural valley
		island shelf		step-fault clinoform belt	sea hill
	T-A-BA system	island arc		fault-block platform	turbidite fan
		island slope		fault depression	land slide
		backarc basin V bathyal basin VI		gentle turbidite clinoform belt	fault gully
				incline island shelf	shoal
		trench		step-faulted island slope	canyon
				island-slope platform	structure valley
island-slope deepwater terrace	sea hill				
island-slope downwarped basin	submarine sill				
Oceanic-crust geomor- phologic system	deepsea plain	oceanic sea ridge		island-slope sea ridge	submarine depression
				trench-bed plain	canyon
				trench slope	sea hill, sea mount
				bathyal turbidite plain	
				bathyal volcanoclastic deposit plain	sea mount
	oceanic sea ridge	oceanic sea hill-seamount complex		bathyal sea ridge	sea hill
				bathyal upwarped fault-block platform	submarine sill
				bathyal step-faulted clinoform slope	submarine depression
				bathyal fault depression	shoal
				bathyal rift basin (graben)	
Oceanic-crust geomor- phologic system	oceanic sea ridge		undulated deepsea plain	seamount	
			inclined deepsea plain	sea hill	
			flat deepsea plain	submarine sill	
			deepsea fault depression	submarine depression	
			oceanic sea ridge	shoal	
oceanic sea ridge		oceanic sea hill-seamount complex		structural dyke	
				steep fault slope	

variation in spatial-temporal geomorphic development, and expresses the regional patterns of geomorphologic types. For the compilation of the map for the Ryukyu T-A-BA system, the data of topography, geomorphology, sedimentation, shallow acoustic profiling, seismic profiling, structural geology and geophysics, especially the data of multibeam surveys, are collated. For the areas outside the investigated areas by scientists in China, the data pub-

lished in foreign literatures are used, mainly including bathymetric charts, sediment maps and seismic profiles. The charts collated are of 1:200000 to 1:150000 in scale and almost cover the entire mapping area. For some deep parts in the western Philippine Sea, the global topographic data of 2'×2' grid are used. On such a basis, the morphologic features, structures, compositions, morphogenesis and modern dynamical processes of various geo-

geomorphic units in the study area are analyzed in detail. Finally, the geomorphic units are identified and classified, and the submarine tectonic geomorphologic map of the Ryukyu T-A-BA system is compiled (see Fig.2).

The geographic base map for the compilation is prepared using the bathymetric chart compiled by data of multibeam survey, the bathymetric charts collated and the positioning data of the survey lines of shallow profiling, seismic investigations, mono-beam bathymetric surveys, and sediment sampling. The mathematic basis of the base map is as follows: WGS-84 system; Mercator projection (non-deformation latitude: 30°N); Depth datum: local mean sea level; Scale: 1:500000.

In the graphic representation, the Grade — types are the basic cartographic units of the map. Each of the morphogenetic-form units is expressed as an independently isolated graphical patch filled with a specific color, indexed with a specific legend code. The Grade || types are expressed by form symbols (lines and patterns). A special line specifies the boundaries between Grade Ⅰ and Grade Ⅱ units. The boundary between the continental-crust geomorphologic system and the transitional-crust system (i.e. the Ryukyu T-A-BA system) is the same as the slope-break line of the ECS shelf. The actual boundary

between the transitional-crust system and the oceanic-crust system is the central axis of the RT, i.e. the subduction fault zone, while the geomorphologic boundary is the E-SE margin of the RT in the northeast part, and is the same as the foot line of the island slopes in the west part (Huatung Basin). The boundary between the OT and the RA and that between the RA and the RT are expressed by the foot lines of the island slopes at both sides of the RT, while that between the ECS slope and the OT is expressed by the foot line of the ECS continental slope.

Only the structural forms that control the development and overall distribution pattern of the regional geomorphologic complexes, and the formation of specific geomorphic units are presented on the map. The representative isobaths, special spot water depths and major sediment types are also shown on the map.

3 Characteristics and distribution patterns of the major geomorphologic types

(威) Continental-slope geomorphologic types. The geomorphic development of the ECS slope is controlled by fault structures. The slope can be divided into three clinoform belts: (1) the simple clinoform belt in the upper part; (2) the steep step-fault clinoform belt in the middle part; and (3) the gentle turbidite clinoform belt developed with turbidite fans.

(1) The simple clinoform. The upper boundary between this belt and the outer shelf relict-sediment plain of the ECS is the same as the slope-break line between the shelf and the slope, on which the water depth ranges from 150 to 170 m. The water depth on the lower boundary of

this belt varies from 250 to 350 m. Shelf-margin faults are developed near the slope break, which control the development of the shelf and the slope landforms. Fault furrows developed along the shelf-margin faults extend parallel to the isobaths below the slope break. The furrows are deep-cut in a V shape. In structural geology, the shelf-slope boundary is the shelf-margin faults. In term of geomorphology, this boundary is the line linking the inflection points at which the topographic slope becomes obviously steeper (Fig. 3). According to the geomorphic structures and dynamic processes, three sub-types can be classified i.e. the depositional, erosion-depositional and erosional clinoform belts.

The depositional clinoform belt is located to the north of the submarine canyon near 28°03'N, extending northwards to the southern side of the canyon near 31°35'N. The water depth along the lower boundary of this belt ranges from 250 to 355 m. It is 10 to 20 km in width, with a mean gradient ranging between 20% and 15%. The submarine sediment consists mainly of sandy silt and silty sand. Sand is found in local areas where the accretion is weak, and muddy sediment can be found where accretion is rapid. At low sea-level stages in the glacial periods in the late Pleistocene, the Paleo-Yangtze River and some other rivers flowed across the shelf plain of the ECS to enter the Okinawa Trough. They discharged a large amount of sediment into the sea and built a series of large delta systems at the margin of the shelf plain. The delta fronts covered the upper part of the ECS slope. The depositional clinoform belt is located where the buried river deltas are preserved.

The erosion-depositional clinoform belt is located between 28°03'N and 25°45'N. The water depth of lower boundary of this belt is about 250 m. A number of submarine canyons extend upstream, cutting into the clinoform belt. Erosion is intensive near large canyons, forming rugged seabed and steep slope. The clinoform belts near the large canyons are narrow, generally 2.5 to 3.5 km in width, with the gradient of 30% and 40%. However, in the clinoform zones between the large canyons, deposition takes place, and the slope surface is quite smooth. The clinoform belts are 7 to 10 km in width, with the topographic gradient of 15% and 10%.

The erosional clinoform belt is located in the northern ECS slope (to the north of 31°35'N) and the upper part of the island slope to the south and southeast of the Goto Retto (128°21.87'E to 129°25.30'E, 32°17.87'N to 32°42.63'N). This clinoform belt is bounded by the erosional depression in the north part of the ECS shelf via the slope break line. Due to erosion induced by the Kuroshio bottom currents and the tidal currents, this clinoform belt has a rugged and rough seabed with gullies. The seabed sediment consists mainly of shelly sand, probably deposited by the paleo-rivers at low sea-level stage in the

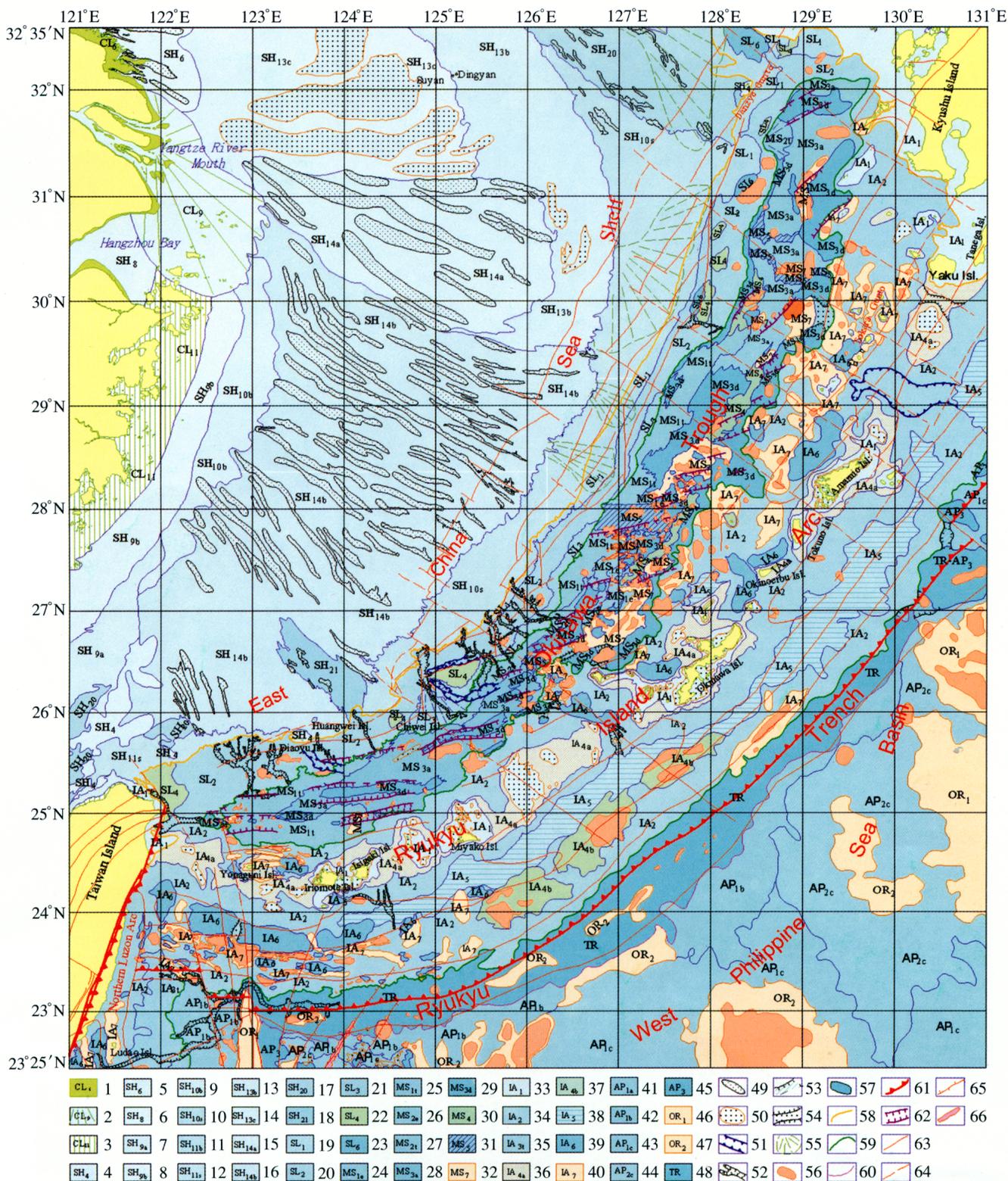


Fig. 2. The geomorphologic map of the Ryukyu trench-arc-backarc system. 1, Tidal flat; 2, subaqueous delta; 3, nearshore zone; 4, structural shelf (SH) platform; 5, modern tidal ridge field; 6, depositional bay plain; 7, flat depositional SH plain; 8, inclined depositional SH plain; 9, inclined erosion-deposition SH plain; 10, outer SH relict deposit plain; 11, inclined erosional SH plain; 12, erosional outer SH plain; 13, inclined paleo-delta plain; 14, undulating paleo-delta plain; 15, depositional moribund tidal ridge field; 16, erosional moribund tidal ridge field; 17, erosional SH depression; 18, structural SH depression; 19, simple slope (SL) clinoform; 20, faulted step SL clinoform; 21, turbidite SL clinoform; 22, SL fault-block platform; 23, SL fault basin; 24, pyroclastic plain; 25, turbidite plain; 26, inclined pyroclastic plain; 27, inclined turbidite plain; 28, flat bathyal basin; 29, bathyal fault basin; 30, bathyal fault-block platform; 31, bathyal fault-step clinoform; 32, bathyal sea ridge; 33, island-shelf clinoform; 34, fault-step island-slope (IS) clinoform; 35, turbidite IS clinoform; 36, folded fault-block IS platform; 37, fault-block IS platform; 38, IS deepwater terrace; 39, IS fault basin; 40, IS sea ridge; 41, flat deepsea plain; 42, inclined deepsea plain; 43, lowly-undulated deepsea plain; 44, highly-undulated plain; 45, deepsea fault basin; 46, oceanic ridge; 47, oceanic sea ridge & sea hill-seamount group; 48, trench; 49, tidal ridge; 50, shoal; 51, structural valley; 52, submarine canyon; 53, deepsea channel; 54, sea sill; 55, buried delta; 56, sea hill & seamount; 57, depression; 58, slope-break line; 59, slope-foot line; 60, boundary between the oceanic- and transitional-crust geomorphologic systems; 61, subduction belt; 62, extensional rift; 63, fault; 64, inferred fault; 65, transform fault; 66, structural dike.

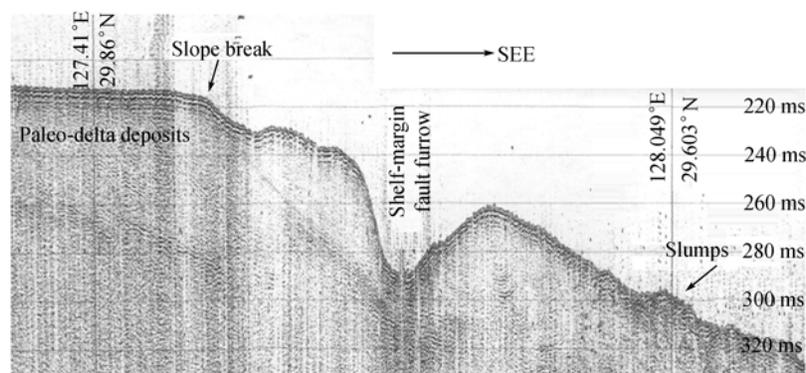


Fig. 3. A subbottom profile record near the slope break and shelf-margin fault furrow (ORE Geopulse 5000, frequency: 500–3000 Hz).

Pleistocene glacial periods. Since the postglacial sea-level rise, terrestrial sediment supply has decreased, and the strong currents on the shelves of the Yellow Sea, ECS and in the Korea Strait have caused seabed erosion.

(2) Step-faulted clinoform belt. This belt is located in the middle-lower parts of the ECS slope. Its northern part (to the north of 28°28'N) is a fault-controlled stepped slope with small relief and quite flat seabed. In geomorphology, this belt is characterized by alternating steep fault scarps and gentle narrow platforms. Submarine canyons are seldom present. The surface sediment is clayey silt. Its southern part (to the south of 28°28'N) is relatively steep, and the seabed is rugged and rough, with submarine canyons densely distributed. The modern submarine sediment layer is thin, consisting mainly of fine-grained materials. The sediment type is clayey silt. Bedrock is exposed on the seabed in some areas.

In term of tectonics, the northern part of the belt represents a horst-graben structural system composed of alternating fault depressions and fault-block rises. The landforms of the slope consist of alternating elongated fault basins and fault-block platforms or hills. Seismic subbottom profiles revealed two fault-block rises and two fault depressions in the middle and lower ECS slope. The fault-block rise on the middle slope is referred to as “the faulted shelf rise”, while that on the lower slope is called “the Dragon Rise”. Fault basins are developed at the landward sides of the fault-block rises. The slope zone between the two horst-graben systems and that below the

“Dragon Rise” is shaped in stepped clinoform due to the movement of faulting (Fig. 4).

The southern part of the step-faulted clinoform belt of the ECS slope is very steep, with a slope angle being as high as 6°40'. Hundreds of submarine canyons are densely developed in the slope zone.

(3) Gentle turbidite clinoform belt. This belt is located below the step-faulted clinoform belt of the ECS slope to the south of 29°11'N. The seabed here is obviously gentler than the step-faulted clinoform belt. A series of turbidite fans with relatively steep surface slope are developed. The topographic slope of this belt is also steep as compared with that of the bathyal turbidite plain in the OT. Hence, it can be classified as a continental slope geomorphic system. There are narrow fault depressions or fault furrows at the foot of the turbidite clinoform belt, forming the evident division between this belt and the backarc basin of the OT.

(裁) Backarc basin geomorphologic types. The OT is one of the backarc basins in the T-A-BA systems in the continent-margin structural zone of the western Pacific Ocean. The planar configuration of the OT has a shape of an arc with the convex edge facing towards the Pacific Ocean. The cross-sections of the OT are U-shaped with steep slopes at both flanks and relatively flat bottom. Tectonic geomorphic types such as the central graben valleys, fault depressions, volcanic chains and upwarped fault-block platforms, are developed in the backarc basin, which are the distinct geomorphologic features of the OT

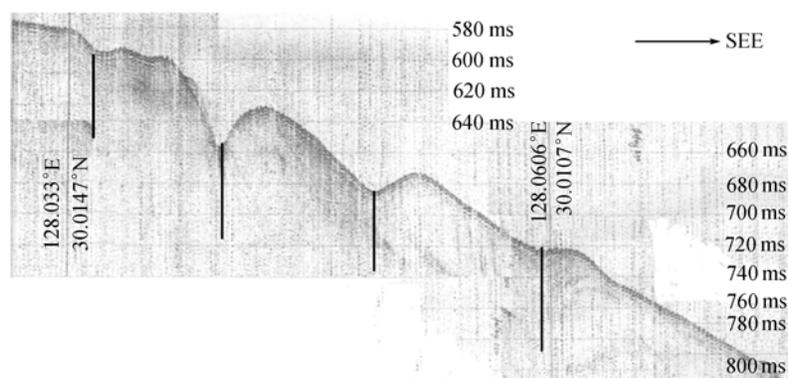


Fig. 4. A subbottom profile record of the typical step-faulted cliniform slope (ORE Geopulse 5000, frequency: 500–3000 Hz).

that differ from common slope troughs.

The geomorphic configuration of the OT is mainly controlled by the ECS slope and the west Tokara marginal fault systems. The general trend of the OT is in NE–NNE direction. The development of the morphology is controlled mainly by the movements of the en echelon central rifting grabens. The central OT is composed of the central rifting basins and volcanic chains that are developed along the en echelon spreading axes. Fault furrows developed at the foot of the ECS slope to the western OT, while narrow fault depressions formed at the foot of the island slope of the RA to the east of the OT. The major geomorphologic type in the western-northwestern OT is the bathyal turbidite plain composed mainly of terrestrial deposits and inclining from west-northwest to east-southeastwards, while that in the eastern-southeastern OT is the bathyal volcanoclastic deposit plain consisting mainly of volcanoclastic deposits and inclining west-northwestwards. In the eastern part of the middle OT, upwarped fault-block platforms and sea ridges are developed.

(1) Bathyal turbidite plains. The bathyal turbidite plains are located between the ECS slope and the central rift basins (grabens). In geomorphology, the turbidite plains are composed of bathyal turbidite fans and the depositional plains between the fans. To the north of 27°36'N, narrow fault depressions and/or fault furrows are present between the bathyal turbidite plains and the ECS slope. The bathyal turbidite fans are the most significant geomorphic features. Due to the movements of the extensional slope-foot faults on the ECS slope, the OT backarc basin subsides as faulted blocks; the turbidite plains are compressed by the westward pressure in response to the spreading of the central rifting grabens, leading to the formation of a series of derivative compressive faults, which cuts the turbidite plains into small faulted blocks and forms secondary horst-graben structures. These secondary structures are expressed as upwarped mound shoals and furrows alternately distributed in the turbidite plains, which are composed mainly of terrestrial sedi-

ments carried from ECS shelf and slope by turbidity and gravity currents via the canyons and over the slope, with a small amount of biogenic and volcanoclastic deposits. The content of terrestrial sediment accounts for more than 70%. The major sediment type in the turbidite plain is clayey silt. The sediment at the top of the bathyal turbidite fans is composed mainly of sandy silt and silty sand.

(2) Bathyal volcanoclastic deposit plains. The plains are distributed in the eastern-southeastern OT and around the central volcanic chains. Their sedimentary sequences are thin, representing basin-filling facies. The sedimentary structures differ from that of the bathyal turbidite plains in the western OT. Analysis of the submarine sediments indicates that the sediment here is mainly originated from the nearby volcanic clast, with low contents of terrestrial debris.

(3) Bathyal rifting basins (grabens). Extensional rift basins (grabens) and central volcanic chains developed along the extensional axes of the OT. As the trend of extensional axes change gradually from E–W direction in the southwest to NEE, NE and NNE in the northeast, the extending directions of the central rift basins and volcanic chains change accordingly. The central rift basins to the south of 26°N extend in E–W to NEE directions. To the south of the Diaoyudao Islands and Chiwei Islet is the deepest and largest one, with a maximum water depth of 2302 m. This rift basin is elongated in shape, extending in the E–W direction. It is 133 km long and 10–13 km wide, with an area of 1272.95 km². A volcanic ridge is developed along the axis of the graben. This ridge is parallel to the axis of the rift basin, with a minimum water depth of 2120 m.

The central rift basins in the middle OT (28°N–26°35'N) are large in size, with the one located between 27°10'N and 27°50'N being the largest. This basin is 58 km wide on average, with a maximum of 65 km. Volcanoes and rift depressions are alternately distributed in the rift. Maximum water depths in the depressions reach 1770 m. Volcanic activities are intensive, accompanied with intensive hydrothermal activities^[12]. Fresh labradoritic

basalt (Station 134, at $27^{\circ}31'N$ $126^{\circ}58'E$, with an age of 0.3 MaBP on the basis of K-Ar dating) and olivine basalt (Station 133, at $27^{\circ}32'N$, $127^{\circ}02'E$) were dredged from the volcanic province in the rift basin in 1995^[13]. The unconsolidated sediment layer here is very thin, composed mainly of volcanoclastic debris. Bedrock is exposed on the seabed with volcanoes. The intermontane depressions are merely filled with a thin layer of volcanic detritus.

(4) Bathyal fault depressions. The bathyal fault depressions are those developed under control of extensional faults outside the central rift basins in the OT. This type of depressions is widely distributed in the entire OT. The elongated fault depression off the ECS slope extends along the slope foot. Normal faults are present on both sides of the depression. The depression shows as a U-shaped channel or V-shaped deep-cut gully. The acoustic reflectors in subbottom profiles are characterized by downwarped concave arcs (Fig. 5). The sedimentary sequences in the depression are composed mainly of terrestrial debris eroded from the ECS slope. The fault depressions off the western RA, the northern OT, are much wider than those at the ECS slope foot. However, the depressions here are separated by saddle-shaped sea sills, forming stringed-bead depressions discontinuously distributed along the island slope foot. The fault depression on the eastern side of the middle OT extends continuously along the western RA, forming a natural division between the Tokara volcanic ridge and the OT (Fig. 6).

A large-scale fault basin developed between the bathyal turbidite plain and the upwarped fault-block platforms and ridges in the middle OT (between $28^{\circ}09.25'N$ and $29^{\circ}23.27'N$). This large fault basin extends in the NNE-SSW direction, 165 km long and 20–40 km wide, with an average width of 25 km. Both the western and eastern sides of the basin are controlled by normal faults. The western margin of the basin is a series of fault banks and/or steep slopes that divide the turbidite from the basin, while the eastern margin of the basin is composed of fault scarps and step-faulted slopes that divide the basin from

the upwarped platform-sea ridge zone. The bottom of the basin is relatively flat; the water depth increases gradually from the northeast to the southwest, with a maximum of over 1200 m. Acoustic reflectors in the basin show downwarped concave arcs, representing the stratigraphic structure of typical fault basin-filling facies (Fig. 7). The bathyal fault depressions in the southern OT are distributed mainly to the southeast of the central rift zone, especially clustered near the southern Miyako fault zone. The geomorphic characteristics of depressions are similar to those of the fault depressions in the middle and northern OT.

(5) Bathyal upwarped fault-block platforms. These platforms are distributed mainly in the middle and northern OT. A major one in the northern OT is located to the east of a fault depression, at the foot of the ECS slope. It manifests as an elongated submarine mound along the slope-foot depression, with the relative relief decreasing towards the north. Some small upwarped fault-block platforms and/or shoals are distributed in the middle northern OT.

The platforms located in the middle OT are developed mainly in the upwarped fault-block igneous belt in the east. This belt extends from the south of the Tokara fault zone in the north (about $29^{\circ}32'N$) to the north of the Miyako fault zone (about $26^{\circ}32'N$). This upwarped belt is composed of a series of sea ridges and platforms. The magnetic characteristics indicate that this belt is an igneous belt. Controlled by the intersection of the faults of the extensional rifts with the upwarped igneous belt, the geomorphologic complex of upwarped belt is aligned with alternating sea ridges and platforms. The platforms have a shape of slightly upward convex mounds. The platform top is relatively flat, geomorphologically referred to as shoals, shallow fault depressions and furrows. There are isolated volcanoes on some of the platforms. Seismic profiles reveal that the unconsolidated sediment layers on the platforms are very thin, and the acoustic reflectors show the form of upwarped arcs (Fig. 6).

(6) Bathyal sea ridges (volcanic chains). Most of the sea ridges in the OT are associated with volcanoes,

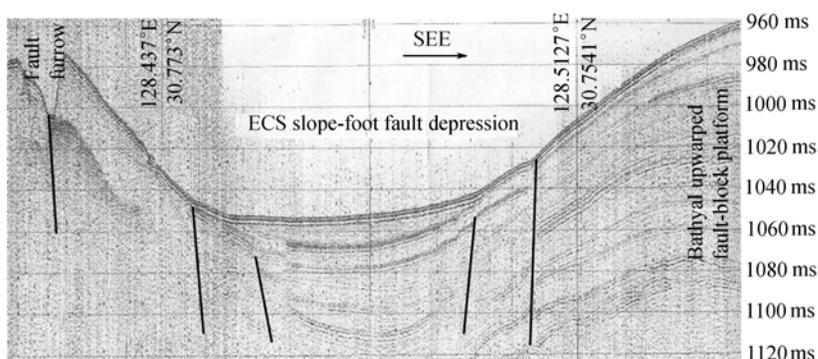


Fig. 5. Subbottom profile record of the slope-foot fault-block depression at the west side of the Okinawa Trough (ORE Geopulse 5000, Frequency: 500–3000 Hz).

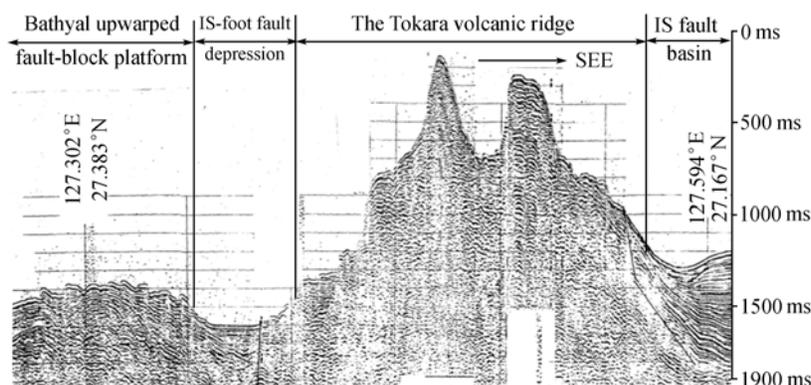


Fig. 6. A seismic profile transecting the upwarped igneous fault-block platform, the slope-foot fault depression, the Tokara volcanic ridge and the island-slope fault basin of RA (DELPH1, frequency: 1 to 32 kHz) (IS: island slope).

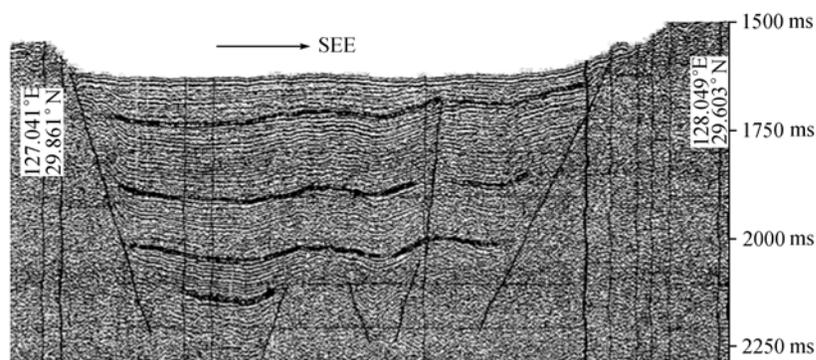


Fig. 7. Seismic profile record of the large fault basin in the north part of middle OT (DELPH 1, frequency: 1 to 32 kHz).

hence the term “volcanic chains”. Two types of sea ridges have been identified: 威) those composed of volcanoes and igneous rock erupted in the upwarped fault-block igneous belt and along the large and deep trans-trough faults; and 裁) those formed in the extensional rifts. Volcanoes stand on the sea ridges, and the intermontane fault depressions are scattered. The seabed is rugged and rough. It appears that the northward extension of the upwarped fault-block igneous belt can be traced through the Tokara fault zone to the volcanic hill in the northern OT to the west of the Kosikizima Retto (about 31°39'N), which is composed of discontinuous sea hills and sea ridges. The southward extension of the upwarped belt can be traced through the Miyako fault zone to about 25°47'N. The volcanic hills to the south of the Miyako fault zone in the southern OT may be an indication of the southward extension of the igneous belt.

Most of the volcanic chains formed in the central extensional rift basins (grabens) in the OT consist of small volcanoes. These are the most recent volcanoes in the OT. The volcanic hills are lofty in stereovision, without sediment cover. Volcano eruptions have taken place almost over the entire central extensional rifts. The volcanoes and

volcanic chains extend parallel to the extensional axes. However, the large volcanoes in the OT are outside the modern extensional rifts. Two large volcanoes have been identified by multibeam sounding outside the extensional rifts in the northern OT. One of them, located to the west of Gazya Island (124°44.34'E, 30°04.53'N), is the largest in northern OT. With a minimum water depth of 132 m at its top, the volcano is over 800 m high above the turbidite plain to the west. The relative elevations of most of the volcanoes in the OT do not exceed 1000 m. As a result, they are classified as sea hills. Only the NE-SW elongated volcano in the middle OT (around 70 km to the west of Iheya Island) and the Onodera Seamount in the southern OT can be classified as sea mounts as their relative elevations exceed 1000 m. The famous Onodera Seamount in the southern OT (in the range of 25°31.51' to 25°41.77'N, 124°55.06' to 125°16.67'E) extends in the NEE-SWW direction for around 35 km, with widths ranging from 9 to 12 km. The sea mount uprises from the flat seabed (water depth 2050 m), with a minimum water depth at its top of less than 950 m and the relative elevation more than 1100 m.

No typical volcanic chains are present in the south-

ern OT. The volcanoes near the Miyako fault zone and those near the southwestern end of the OT are all isolated and scattered, or clustered to form volcanic groups.

(核) Geomorphologic types of the island arc. The Ryukyu island arc (RA) extends from the south end of Kyushu Island to the northeast Taiwan Island, with a length of 1200 km and a shape of a southeastward convex arch. The geomorphologic development of the island arc is mainly controlled by tectonics and geological structures. The major geomorphologic units include (from the west to the east) the island-slope sea ridge zone formed on the Tokara volcanic ridge, the string-bead island-slope fault basins developed in the Amami depression zone, the island-slope platforms, island-shelf shoals and reefs formed on the Ryukyu folded ridge, the island-slope fault basins and deepwater terraces developed in the forearc depression zone, and the island-slope sea ridges, platforms and intermontane depressions formed on the forearc accretional ridges. These positive and negative landform units are linked with the step-faulted island slope. The RA geomorphologic system can be divided into two sub-types: the island shelf and the island slope.

(1) Island-shelf geomorphologic types. 威) Fault-step island-shelf clinoform. This type is distributed around the islands of the Ryukyu Islands. The water depths at the island-shelf slope vary (20–200 m). The seabed is rugged and rough with relatively large slope gradient, although it is not as steep as those associated with the fault-step island slope. 裁) Island-shelf shoals and reefs. These are distributed mainly in the middle and southern Ryukyu fold ridge. The major shoals include the Okinawa-Kerama-Kume, Miyako Reef, Miyako-Irabu, Minna-Tarama and Iriomote-Isigaki shoals. The water depths in the shoals and reef fields vary from 20 to 200 m (less than 20 m on the top of some reefs). The sea floor is highly rugged and rough with reefs being clustered. The shoals and reef fields are composed mainly of coral reefs, shells and sandy gravels.

(2) Island-slope geomorphologic types. 威) Island-slope platforms. These platforms are upwarped structural platforms. The surface of the platforms are relatively flat or slightly upward convex in topography. They are developed on three structural ridges of the RA. Among them, the structural platforms on the top of the Ryukyu folded ridge are distributed almost continuously from the Sandiao Headland-Guishan Island to the northeast of Taiwan Island to the southern end of the Kyushu Island, which is a protruding geomorphologic representation of the Ryukyu fold ridge. The platforms are composed of upwarped fault-block Mesozoic metamorphites and Cenozoic flysch sandstones, slates and volcanoclastic stones. The water depths along the lower boundaries of the platforms vary between 500 and 600 m. All the islands, island-shelf shoals and reefs in the Ryukyu Islands are situated on the platforms. The platforms on the Tokara volcanic ridge are

composed of volcanic rocks. Their geomorphologic characteristics are similar to those of the platforms on the Ryukyu fold ridge, but are smaller in size. The platforms on the Shimajiri ridge and East Amami ridge are composed of folded accretional prisms. The water depths on the top of the platforms are 1500–2000 m. 裁) Island-slope sea ridges. These ridges are a major geomorphologic type of the Tokara volcanic ridge and the forearc accretional ridges. The development of such ridges is mainly controlled by tectonics. The extension of the sea ridges is basically parallel to the structural lines of the structural zones where the sea ridges formed. Most of the sea ridges in the Tokara volcanic ridge trend in the direction of NNE-SSW or N-S. Some of the ridges are controlled by NW-SE trending faults; hence, their crests extend in the direction of NW-SE (e.g. the Takara-Sima sea ridge near the Tokara fault zone). The sea ridges and the sea hills on them are composed mainly of igneous rocks. A typical geomorphologic characteristic of the sea ridges in the Tokara volcanic ridge is that there are numerous volcanoes and volcanic islands on the sea ridges (Fig. 6). The sea ridges formed on the Shimajiri ridge trend in the NE-SW direction, whilst those on the Yaeyama ridges trend mainly in the E-W direction. The sea ridges in the forearc ridges are composed of the accretional wedge (mainly flysch formation) formed at the marginal zone of the collision plates. There are no volcanoes on the forearc ridges, while sea hills, small or large, are widely developed. 核) Island-slope fault basins. These basins are distributed mainly in the Amami depression zone and the forearc depression zone. There are small-scale intermontane fault depressions in the three upwarped ridge belts. The fault basins in the Amami depression zone are distributed in a string-bead pattern. The sediments filling in the basins are composed mainly of sand. The water depths of the basins increase from the north to the south. Maximum water depths reach ~900 m in the East-Akuseki Basin, 970 m in the Amami Basin, over 1000 m in the Okinoerabu Basin, and up to 1230 m in the Yoron Basin, larger than those in the western-RA island-slope foot depression at the same latitude. The fault basins in the forearc depression zone are mainly formed in the Yaeyama depression. The major fault basins include (from the west to the east) the Hoping basin, the Nanao Basin, the East Nanao Basin and the Iriomote Basin. The Nanao Basin and the East Nanao Basin are the deepest ones. The bottoms of these two basins are 1000–1600 m lower than the sea hill peaks on the Yaeyama ridge to the south of the basins. The margins of the basins are composed of steep fault cliffs, while the bottoms of them are quite flat. The sediment layers in the basins are of typical depression-filling facies, with the acoustic reflectors with a shape of downward concave arcs. The fault basins in the west and east island-slope depressions are typical island-slope troughs; the geomorphologic structures and

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stratigraphic properties are apparently different from those of the backarc basin of the OT. iv) Island-slope deepwater terraces. The island-slope deepwater terraces are distributed mainly in the eastern part of the forearc depression zone. The fault basins in the forearc depression zone to the east of the Iriomote Island are filled with sediment. The shape of basins disappears gradually and the basins are replaced by gentle deepwater terraces which have a gentle slope in the middle island slope. The slope gradient of the deepwater terraces is smaller than that of the steep step-faulted island slope belt. The deepwater terrace to the east of the Iriomoto Basin is gentlest in topography. The topographic gradient and water depth of the terraces increase slightly from the southwest to the northeast. v) Step-faulted island slope. Both the northwestern and southeastern slopes of the RA are steep step-faulted cliniform belts that link the island-slope sea ridges, platforms and basins, etc. The northwestern slope of the RA is rugged and rough, with sea ridges, sea hills, volcanic islands, and fault basins and intermontane depressions. The middle and northern parts of the southeast slope of the RA (to the northeast of the Miyako Island) are simple fault-steeped cliniform slopes, whilst the southeastern slope of the RA to the southwest of the Miyako Island undulates roughly with alternating sea ridges, sea hills and fault basins. The relative elevation of relief is even larger than that of the northwestern slope.

The bottom sediment types on the northwestern slope of the RA, which consist mainly of sand and sandy gravel, are different from those on the southeastern slope, which consist of clayey ooze. The difference in sediment types between the two slopes reflects the different tectonic environments and physical oceanographic conditions.

(烘) Trench geomorphologic type. The Ryukyu Trench is where the Philippine Sea plate collides with the Eurasia plate, subducts and consumes beneath EA. The trench has a shape of a deep valley at the southeastern slope foot of the RA. In geomorphology, it forms a natural division between the Ryukyu T-A-BA system and the oceanic basin of the Philippine Sea.

The northeastern RT (to the east of $\sim 125^{\circ}\text{E}$) extends in the NE-SW direction. The western RT (to the west of $\sim 125^{\circ}\text{E}$) extends in the E-W direction, with a water depth of ~ 5900 m at its margin and a maximum of ~ 6700 m at its bottom. The transverse profiles of the eastern part of the western RT (to the east of 124°E) are U-shaped, with a flat bottom and steep slopes on both sides. On the northern side the slope is steeper than on the southern side. The width of the trench varies between 50 and 60 km. Some sea hills and seamounts scatter inside the trench and at its southern edges. The seamount at the southern edge of the trench (with a peak at $\sim 124^{\circ}25'\text{E}$, $22^{\circ}50'\text{N}$) is relatively high. The water depth at its peak is less than 4300 m, while it is 5875 m at its foot. The relative elevation of the seamount is 1575 m. A part of the western RT (to the west

of 124°E) is V-shaped in the transverse profile, with a canyon extending eastwards in the central trench. The width and water depth of the trench decreases gradually from the east to the west. At around 123°E , the Gagua Ridge subducts northwards beneath the EA via the RT, causing the RT to become narrow suddenly and disappear gradually. To the west of $\sim 122^{\circ}40'\text{E}$, the subduction zone shows no topographic form of a trench.

Seismic profiles reveal that the ocean-crust basements at the east-southeast-south sides of the RT are cut into small stepped fault blocks by dense faults as they subduct westwards, northwestwards and northwards. The ocean-crust basements and the oceanward slope of the RA constitute the V-shaped trench configuration of the RT in transverse profiles. The oceanic deposit over the basement is very thin. In the RT, the oceanic sequence is overlapped by the sedimentary sequences in the region. The sequences of the RT are very thick and quite uniformly distributed; the acoustically reflected sequences can be divided into four major layers that can be traced continuously, indicating that the trench has been subsiding along with the plate subduction since it was formed. The filling of thick Cenozoic deposits has changed the configuration of transverse profiles of the RT from the original V-shaped valley into a U-shaped valley.

4 Discussion and conclusions

(威) Tectonic geomorphologic patterns of the Ryukyu T-A-BA system. The distribution of geomorphologic types of the Ryukyu T-A-BA system is mainly controlled by plate movement and the resultant structural stress field and regional geological structures. In the plate subduction zone, as the oceanic-crust plate (PH) subducts beneath the continental-crust plate (EA), the Ryukyu Trench was formed as an asymmetric V-shaped valley. After being filled by consequent deposition, the trench became a U-shaped valley with a flat bottom and two steep sides.

On the side of the continental plate, the Ryukyu arc was folded and upwarped to form the fault-folded platforms at the central part of the island arc and the Ryukyu Islands upon the platforms. The Tokara fault zone and the Miyako fault zone cut the Ryukyu arc into three sections, i.e. the northern, middle and southern Ryukyu arcs. In the forearc zone, the oceanic deposition and oceanic-crust stripped off from the oceanic plate were accreted in the forearc zone of the RA. Under the compression stress field, the forearc accretional deposits were intensively compressed, deformed and upwarped to form the forearc accretional wedges, which are present as a series of sea ridges and upwarped fault-block platforms. The western part of the forearc depressions between the Ryukyu folded ridge and the forearc accretional ridges (to the west of $\sim 125^{\circ}\text{E}$) was transformed into a series of downwarped basins, while its northeast part (to the east of 125°E) was

filled with deposits and developed into island-slope deepwater terraces. The difference in geomorphologic development between the western and northeastern parts of the forearc zones is due to the regional difference in plate subduction movement, structural compression and uplifting.

The extensional stress field derived from the backarc extension led to the rifting and subsidence of the OT and the formation of the Tokara volcanic ridge. Igneous sea ridges, sea hills and volcanic islands are formed on the Tokara volcanic ridge in the western RA. A series of downwarped island-slope basins are formed in the Amami depression between the Tokara volcanic ridge and the Ryukyu folded ridge. The geomorphologic types in the OT are distributed in a distinct pattern. Taking the extensional axes as the reference, the bathyal turbidite plains that incline to eastward-southeastward are developed in the western-northwestern OT, the bathyal volcanoclastic deposit plains that incline to westward-northwestward are developed in the eastern-southeastern OT, and the central OT is occupied by the rift basins (grabens) formed along the successively distributed en echelon extensional axes of the backarc basin. Volcanic chains and isolated volcanoes are formed in large rift basins. In addition, the Tokara and the Miyako fault zones also cut the OT backarc basin into three sections, i.e. the northern, middle and southern OTs. The north OT is bounded by marginal fault depressions on both sides, and is the shallowest section of the OT. An E-W trending step-faulted cliniform belt ($28^{\circ}02.5'N$ – $27^{\circ}47.5'N$) separates the middle OT into two parts, with the northern part being shallow (water depth 1000–1200 m) and simple in geomorphologic structure and the southern part being deep (water depth 1500–1900 m) and complex in geomorphologic structure. An upwarped fault-block belt, formed by igneous intrusion, extends in NNE-SSW directions in the eastern part of the middle OT, which is characterized by a series of sea ridges and upwarped fault-block platforms. Sea floor spreading has taken place in the central rift basins in the southern part of the middle OT and in the southern OT [8, 11]. The sea floor spreading in the southern OT is the most intensive where the rift grabens are the largest in size and depth.

(裁) Tectonic geomorphologic characteristics. In geochronology, the ECS shelf is older than the Ryukyu Islands in age. The evolution of the ECS shelf depression zone is different from that of the RA, with the former being characterized with the evolutionary processes of the continental rift basins, while the latter being closely related to the collision between EA and PH since the mid Tertiary. The crust properties of the ECS shelf are different from those of the OT and the RA. The crust of the ECS shelf is continental crust, with a thickness of 30–33 km. The crust of the ECS slope thins rapidly eastwards from ~30 km at the shelf margin to ~20 km at the slope foot.

The thickness of the crust in the north OT is 20–24 km, while it is 15–18 km in the middle and southern OTs, indicating that the transitional crust in the OT is similar to oceanic crust. The crust thickens eastwards in the Ryukyu arc.

The ECS shelf represents a natural extension of the mainland of China in terms of geologic structures, geomorphologic characteristics, sediment properties and paleo-geographic environments. At the low sea-level stages in the last glacial period (the late Pleistocene), the ECS shelf was exposed and became a vast plain in the eastern part of mainland China. At 15000 aBP, sea level reached its lowest position, whence the coastline of the ECS was located along the shelf margin where the water depth is 150–160 m at present. Coastline indicators such as relict shell beaches, cheniers, and other coastal landforms were found near the ECS slope-break line, and paleo-river channels and relict coastal lagoon-barrier complexes were found on the shelf. Buried delta deposits were found in several places in the outer shelf zone of the ECS and the simple cliniform belt in the upper part of the ECS slope (Fig. 3). Nevertheless, the Ryukyu arc has been always separated from mainland China because of the presence of the Okinawa Trough.

The ECS slope is distinctive from the RA in geomorphology and tectonics. The ECS slope is the transitional zone between the ECS shelf and the backarc basin of the OT. The ECS slope is characterized by the typical geomorphologic pattern, i.e. with the relatively gentle simple cliniform slope in the upper part, the step-faulted cliniform slope controlled by faults in the middle-lower part, and the transitional gentle slope formed by turbidite fans in the lowest part. The seabed sediments are characterized by normal bathyal deposits. The composition of terrigenous clastic minerals in the sediments is in good accordance with those on the shallow ECS shelf and the weathering products of the igneous, sedimentary and metamorphic rocks in the eastern part of mainland China. The clayey materials of the ECS slope contain quartz and there is a high content of Si and low content of Fe in the sediments, indicating that the ECS slope sediments have affinity with the weathering products of the intermediate and acid rocks in eastern China. The sediments of the ECS slope are mainly originated from the ECS shelf, the Taiwan Island and eastern mainland China. Further, bathyal turbidite fans are developed at the outlets of large canyons in the middle OT. Integrated turbidite sequences have been revealed in the turbidite fans. The mineral composition of turbidite sequences is in accordance with the sediments on the ECS shelf. Generally, the turbidite sequences also contain nearshore-neritic shelf species of foraminifera and Ostracoda. Even fresh diatoms can be seen in the turbidite deposits. Hence, the turbidite sediments are originated from the ECS shelf. The ECS slope is a result of the natural development of the ECS shelf, and is the natural

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extension of the ECS shelf toward the OT.

The western-northwestern slope of the RA has a series of volcanic ridges separated by fault depressions. Here, the tectonic geomorphologic pattern is characterized by the alternately distributed igneous sea ridges and island-slope fault basins, without similarities to the ECS slope. The bottom sediment types of this region are mainly sand and sandy gravel originated from volcanic debris, which contrasts sharply with the fine-grained terrigenous sediments of the ECS slope.

The results of comparative analysis of the ECS shelf and slope with the Ryukyu island arc in crustal properties, geologic structures, geomorphologic characteristics and distribution patterns, submarine sediment types, mineral assemblages, geochemical compositions and microfossil assemblages indicate that the Ryukyu Islands does not represent a natural extension of the continental shelf associated with mainland China.

(核) Tectono-geomorphologic characteristics and geographical significances of the Okinawa Trough. The Okinawa Trough is the backarc basin of the Ryukyu T-A-BA system. The extensional rift basins in the OT are elongated narrow depression landforms associated with the backarc extensional structural grabens. These landforms are prominently seen to the south of 28°N in the OT. The trend of the rift basins to the northeast of the Miyako Seamount is in the NE-SW direction, while that of the graben basins to the west of the Miyako Seamount is in the E-W direction. Among these basins, the Yaeyama Graben basin is 133 km long and 8–13 km wide (~10 km on average), with a maximum water depth of 2302 m and the relative depth of 100–200 m. The geophysical evidence shows that the sea floor spreading along the central extensional axes of the OT began at least 2 MaBP. The semi-spreading velocity in the southern OT is 1.2 cm/a. New oceanic crust has been formed at the spreading centers of the grabens in the middle and southern OT. The thin crust, high crustal hydrothermal values, widespread young faults, frequent earthquakes and volcanic eruptions in the middle and southern OT reflect the properties of secondary sea floor spreading of the region. The elongated narrow bathyal basins are the graben depressions formed by sea floor spreading in the central OT. The sea floor spreading has also led to the deepening towards the centers of the graben basins and the development of narrow and deeply-cut V-shaped gullies. In addition, seismic profiles have revealed that the stratigraphic structures in the southern OT incline in flexure towards the central graben basins from both the northern and southern sides, which not only indicates the origin of the sediments from the ECS shelf and the RA, but also verifies the central rift basins in the OT as a natural geomorphologic division separating the ECS shelf from the RA.

In term of geomorphology, the central spreading zone of the OT is composed of a series of en echelon rift basins; within most of these systems volcanic chains or

isolated volcanoes are developed. The depositional sequences in the volcanic fields are very thin. Igneous rocks are exposed at the seabed where there are volcanoes. The intermontane depressions are filled only by a thin layer of volcanic ash or volcanic detritus. The geomorphic features and sedimentary structures of the bathyal plains on the two sides of the central spreading zone are apparently different from each other. The bathyal plains to the west-northwest are eastwards-southeastwards inclined turbidite plains composed mainly of terrigenous sediments, whilst those to the east-southeast are westwards-northwestwards inclined volcanoclastic deposit plains consisting mainly of volcanic debris. The geomorphic pattern of the OT also indicates that the OT central rift zone represents a natural geomorphic division between the ECS shelf and the Ryukyu island arc.

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