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Distribution, features, and influence factors of the submarine topographic boundaries of the Okinawa Trough

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Based on multiple types of data, the topographical features of the Okinawa Trough (OT) have been characterized and a computation method has been proposed to determine the break point of continental shelf (BOS), foot point of the continental slope (FOS), the central axial point, and the maximum depth point. A total of 48 topographical profiles that crosscut the continental slope have been used to determine the trends of the BOS and FOS (the BOS and FOS lines) in the East China Sea (ECS). The trend of central axial points in the OT has been similarly determined by analyzing 39 topographical profiles across the axis of the trough. The BOS line forms the boundary between the continental shelf and slope. In the ECS, the BOS line roughly follows the 200 m isobath, continuously in the northern and middle parts of the OT, but jumping about somewhat in the south. The FOS line is the boundary between the continental slope and the bottom of the trough. The depth of the FOS increases gradually from north to south in the OT. Intense incisions by canyons into the slope in the southern part of the trough have led to the complex distribution of FOS. Topographical profiles crosscutting the northern, middle, and southern parts of the OT exhibit features that include: a single W-shape, a composite W-shape, and a U-shape, respectively, which suggests that in the middle and northern parts of the trough the central axial points are always located on seamount peaks or ridges associated with linear seamounts, whereas in the south they are found in the center of *en echelon* depressions. The line formed by the central axial points is the east-west dividing line of the OT, which indicates that the trough is a natural gap that prevents the extension of ECS continental shelf to the east. The distributions of the BOS and FOS lines are influenced by fluctuation of sea levels and submarine canyons, whereas the distribution of axis lines is controlled by tectonics and deposition.

break point of continental shelf, foot point of continental slope, central axis, maximum depth point, topographical boundary, Okinawa Trough

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The region of the East China Sea (ECS) and Okinawa Trough (OT) has become a focal area for worldwide marine science in recent years. However, there are still many unsolved scientific questions in this region. The OT, a back-arc basin that is still in tension, is an important region for studying interactions between the Pacific and Eurasian plates, and also provides a window for understanding the features of the Pacific-type continental margins (Lee et al., 1980; Kimura, 1985; Sibuet, 1987; Qin et al., 1987; Xu et al., 1988; Jin et al., 1987, 1992; Liu, 1992; Li, 2008). In particular, it has shown its globally unique marginal sea basin characteristics through the “South China Sea Deep” project. Such research undertaken in the OT has revealed

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new information on the evolutionary pattern of marginal seas, and enabled the construction of an original evolutionary history of the marginal seas around the Pacific Rim.

Currently, the OT has attracted much attention because of the delimitation of the continental shelf beyond 200 nautical miles (http://www.un.org/Depts/los/clcs_new/submissions_files/submission_chn_63_2012.htm; http://www.un.org/Depts/los/clcs_new/submissions_files/submission_kor_65_2012.htm; http://www.un.org/Depts/los/clcs_new/submissions_files/jpn08/jpn_execsummary.pdf). Terrains and landforms provide important evidence for such delimitations. On one hand, submarine topography and geomorphology are needed to discuss the natural extension of continental crust; on the other hand, such data are essential to determine FOS, which is the starting point for assessing the line in the formula FOS+60 M (60 nautical miles extrapolates from FOS; M refers to nautical miles; this is the international delimitation of the continental shelf beyond 200 nautical miles and its unit) and the line of 1% sediment thickness (http://www.un.org/Depts/los/convention_agreements/texts/unclos/part6.htm; Lu et al., 2012). The break point of continental shelf (BOS) line and foot point of the continental slope (FOS) line are the natural boundaries between the continental shelf and slope, and the continental slope and trough, respectively. The central axis line, which is closely associated with the topographical features and tectonic evolution of the OT, is the natural boundary between its west and east.

All the above boundary lines (i.e., BOS, FOS, and central axis lines) are critical for maritime delimitation and submarine science research, because of their close relationship with the topographical and geomorphological features of the OT. Currently, extensive research has been undertaken concerning aspects of submarine terrains and tectonics in the ECS and OT (Fan et al., 2000; Yang et al., 2001, 2010; Wu et al., 2004; Liu et al., 2005; Luan et al., 2007; Zhao et al., 2011), but detailed descriptive data and studies concerning the BOS, FOS, and central axis lines are rare. Based on multiple sources of bathymetric data, we aim to finely analyze the submarine topographical characteristics of the OT and then identify and characterize these boundaries.

1 Data and methods

Bathymetric data were collected from multiple sources, including our own multi-beam bathymetric surveys, NGDC (NOAA National Geophysical Data Center), JODC (Japan Oceanographic Data Center), and GEBCO (General Bathymetric Chart of the Oceans). They were interfused into a water depth grid by the Kriging method and comprehensive mapping technology using our independently developed software "submarine topography electronic mapping system" (MBChart ver.1.0). All the results related to terrains in this paper are formed from the integrated computation of the above bathymetric data.

At present, there is no domestic independent software that can generate BOS, FOS, and central axial points automatically. International commercial software such as CARIS LOTS and others can generate FOS, but are not able to generate BOS, central axis points, and their corresponding boundaries. As a result, we designed and developed our own independent software "continental shelf boundary generating system" (CSChart ver.1.0) using C++. Typical crosscutting lines were constructed by a human-computer interaction method based on the bathymetric data mentioned above; the FOS and BOS of ECS shelf were subsequently automatically generated based on these crosscutting lines. The central axis points were determined by analysis of the terrains of the trough, and the boundary was determined by connecting these points in order. The boundary points were all mutually authenticated by multiple sources of bathymetric data to ensure consistency in the results.

2 Topographical characteristics of the Okinawa Trough

The OT, located at the eastern edge of the ECS, extends from the Yilan Plain of Taiwan in the southwest to the island of Kyushu in Japan in the northeast. The southern part of the middle section of the trough is slightly convex towards the southeast, and the central axis of the trough is parallel to the Ryukyu Island Arc (also called the Ryukyu Arc) and the Ryukyu Trench. The strike direction of the southern OT is nearly E-W, whereas it is NE-SW in the middle and NNE-SSW to the north (Figure 1). Bathymetric data show that the trough has relatively deeper water in the middle and southern parts, with the 2000 m isobath extending south of the Gonggu-Diaobei Fault and nearly reaching Jiumi Island and the Yushan Fault to its northwest (Jin et al., 1987, 1992; Liu, 1992). The deepest position is located in the E-W extended central depression in the southern part of the trough with a measured maximum depth over 2300 m (generally known as a "trough in trough" or "central graben") that gradually decreases towards the north (Wu et al., 2004; Luan et al., 2007; Li, 2008). The central graben shows relief and spatial distribution features that are similar to slow spreading ocean ridges (Luan et al., 2007). Inside the trough, isolated seamounts of different heights, linear seamount chains, and *en echelon* navicular depressions have developed. Profiles perpendicular to the OT have shown that the trough has a typical U-shape, with increasing depth from west to east. This is closely related to the abundant sedimentary supply from the ECS continental shelf, which suggests that the sediment source has a significant influence on sedimentary patterns and submarine terrain in the trough. The continental slope of the ECS is rugged. In the middle and southern parts of the slope, several well-developed incised submarine canyons extend upward to the outer margin

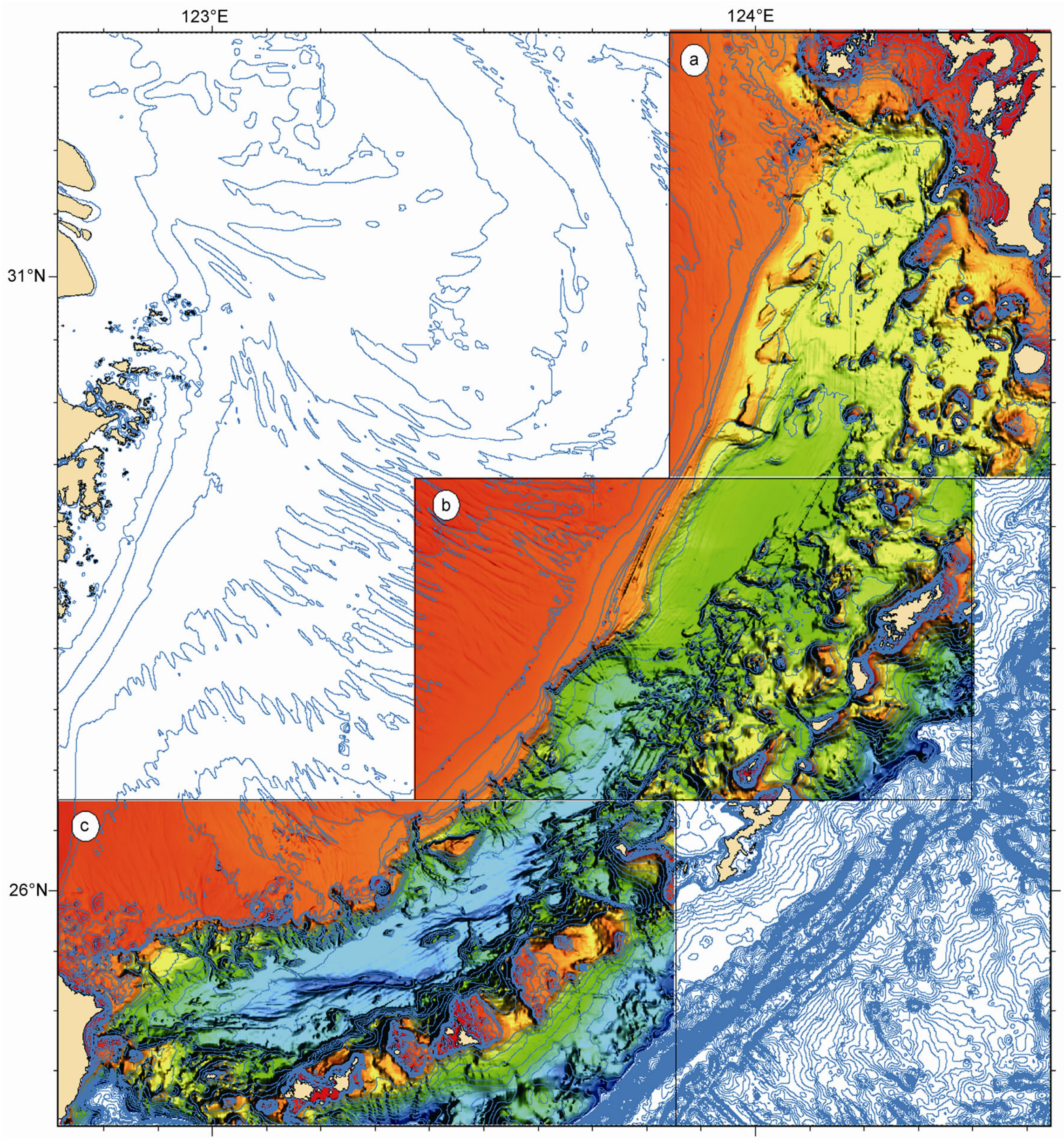

Figure 1 Submarine topography in the East China Sea. a–c, respectively refer to the approximate location of northern, middle, and southern parts of the Okinawa Trough.

of continental shelf and downward to the trough bottom. During glacial lowstands in sea level, these canyons were important channels connecting the shelf and the trough (Wu et al., 2004; Li, 2008; Zhao et al., 2011). Such topography not only molded the appearance of the ECS continental slope, but also affected the submarine topography in the western part of the OT. A series of fault blocks and ridges formed in the fore-slope area of the northern part of the ECS shelf, probably as a result of Miocene tectonic movements (Fan et al., 2000).

The ECS continental shelf and slope, and the OT, together form a typical continental margin (Figure 1). Water depth on the shelf differs greatly from the trough, and has totally different topographical features. The continental slope connecting the shelf and the trough is steep. Geological and geophysical evidence indicates that the crust in the southern part of the OT thins sharply to <13 km (Gao et al., 2004; Hao et al., 2004; Han et al., 2007) and new oceanic crust might have been generated locally (Li et al., 1997; Huang et al., 2006). Linear magnetic stripes have been identified in the middle and southern parts of the trough (Liang et al., 2001a, 2001b). Topographical, lithological, and geophysical evidence demonstrates that the OT is a back-arc basin in an early stage of expansion (Li et al., 1997; Wang et al., 1998; Liang et al., 2001a, 2001b; Gao et al., 2004; Hao et al., 2004; Huang et al., 2006; Han et al., 2007).

As the ECS continental shelf extends naturally to the east and terminates at the OT, the OT becomes the natural separation between the ECS continental shelf and Ryukyu Island Arc to its east.

3 Determination of Okinawa Trough terrain boundaries

3.1 FOS and BOS lines

3.1.1 Determination method

The FOS is the starting point used to determine national continental shelf boundaries lying beyond the 200 nautical miles limit. As prescribed in article 76 of the "United Nations Convention on the Law of the Sea" (UNCLOS) (http://www.un.org/Depts/los/convention_agreements/texts/unclos/part6.htm), in the absence of evidence to the contrary, the foot points of the continental slope shall be determined as the points of maximum change of gradient at its base. Determination of FOS can be divided into two steps (Lu et al., 2012): (1) the identification of the region defined as the base of the continental slope, and (2) the positioning of the point of maximum change in gradient at the base of the continental slope. As submarine topography is complicated on the continental slope, the base region of the continental slope, which is the possible area where the FOS should be constrained, must be determined before determination of the FOS. The FOS is always located in the transitional zone between continental crust and oceanic crust (COB, Continent Ocean Boundary), whereas the determination of the continental slope base region needs to be supported by topographical, geophysical, and geological evidence.

The most direct way to determine the FOS line is to construct a series of topographical profiles vertical to the strike of continental slope. By automatic analysis, the FOS can be determined, and the FOS line is formed by connecting these FOS in order. A method that integrates the use of topography, gradient, second derivative of the terrain and the D-P algorithm fitting profile (Douglas et al., 1973) (TSDPIA, Topography, Slope and 2nd Derivative Profile Integrated Analysis) was proposed to determine the FOS point (Figure 2). Firstly, simplification of the original topographical profile was carried out using second derivative extreme points and the D-P algorithm. Then, the derivation of the original profile and simplified D-P profile was executed. Finally, automatic identification of the FOS was realized by programming based on a comprehensive judging method that combines analyses of the gradient, water depth, concavity and convexity of the profile, segmentation and continuity.

The BOS line can be considered as the boundary between the continental shelf and slope. There presently is no readily available method or software for quantitatively calculating the FOS or FOS line. However, there are similarities in the features of the BOS and FOS that can be observed in the integrated profile in which FOS was identified carefully (Figure 2). The FOS is at the position where the continental slope transitions into ocean basin, with the terrain rapidly changing from a steep slope to a gentle incline. It is observed to have a convex hull shape on topographical profiles. Although the BOS marks the transition from continental shelf to slope, it is shown as a concave envelope on topographical profiles. The BOS can be determined in a similar way to that of the FOS, but with several specific constraints including the concave features and segmentation that differ from an FOS point. The underlying programming is able to automatically recognize the BOS (see BOS in Figure 2).

3.1.2 BOS and FOS lines and their characteristics

A total of 48 topographical profiles crosscutting the ECS continental slope were constructed (Figures 3, 4) and 48 BOS were determined using the above method (Figure 3). The average water depth for the BOS points is about 200 m (Figure 5), with 19 of them having a water depth <200 m (mostly distributed at the northern and middle parts of ECS continental slope), 23 of them with water depths between

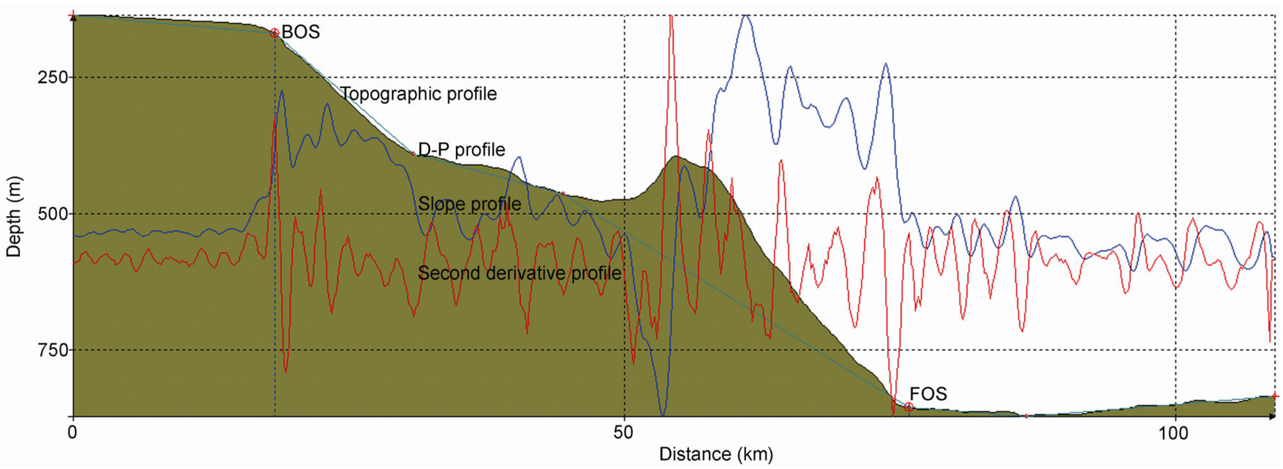

Figure 2 Integrated profile for FOS determination.

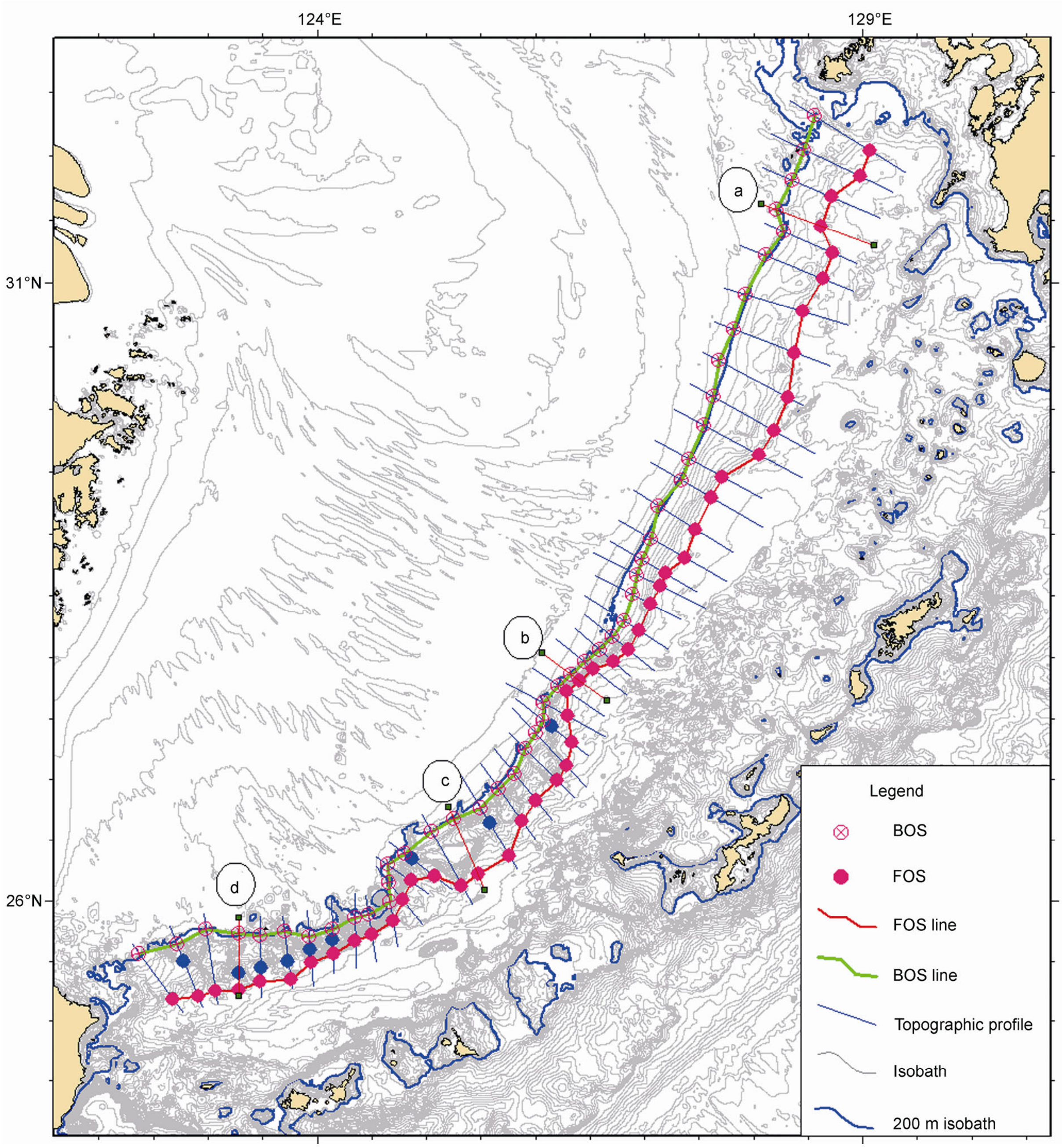

Figure 3 Okinawa Trough and the profiles that determine the BOS and FOS lines. a–d are typical topographic profiles; MDP: maximum depth points; CAP: central axis points; SDP: secondary depth points.

200 and 250 m, and six of them >250 m. Collectively, most of these points are concentrated at a water depth of 200 m, with a deepening tendency from north to south and more 'jumpy' transitions in the south. The BOS line (the green line in Figure 3) interlaces with the 200 m isobath (the blue line in Figure 3); they nearly merge together at the northern part of continental shelf but the BOS locally extends outboard of the 200 m isobath in the middle and southern parts of the margin.

This distribution pattern of the BOS is closely related to the submarine terrain between the continental shelf and slope. In the northern part of the trough, even though some fault blocks and ridges have developed (Fan et al., 2000), the terrain of the continental slope is relatively smooth and the isobaths are generally parallel to the strike of the slope. Thus the BOS line generally is parallel to the isobaths. In the middle and southern parts of the trough, many canyons are found on the slope (Wu et al., 2004; Li, 2008; Zhao et al., 2011) that have strongly incised the continental slope and altered the original relief of the continental shelf. This has led to a cracked marginal terrain on the outer shelf and frequent fluctuations in the BOS, but basically in water

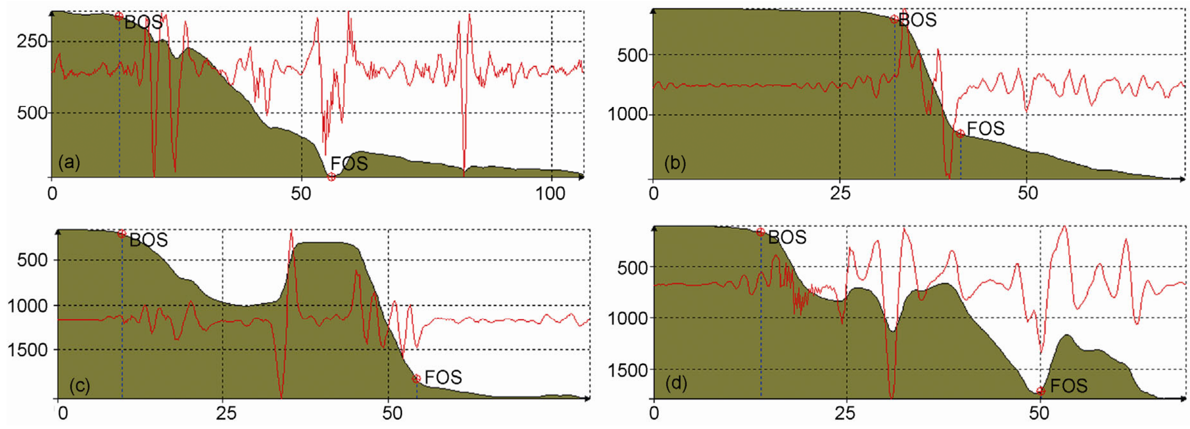

Figure 4 Typical profiles with recognized BOS and FOS. (a) a profile from the northern trough; (b) a profile from the middle part of the trough crosscutting the narrow continental slope; (c) a profile from the middle part of the trough crosscutting a fault block on continental slope; (d) a profile from the southern trough across a submarine canyon. Black curve is topographical profile, and red curve is second derivative to the terrain; positions of these profiles are shown in Figure 3.

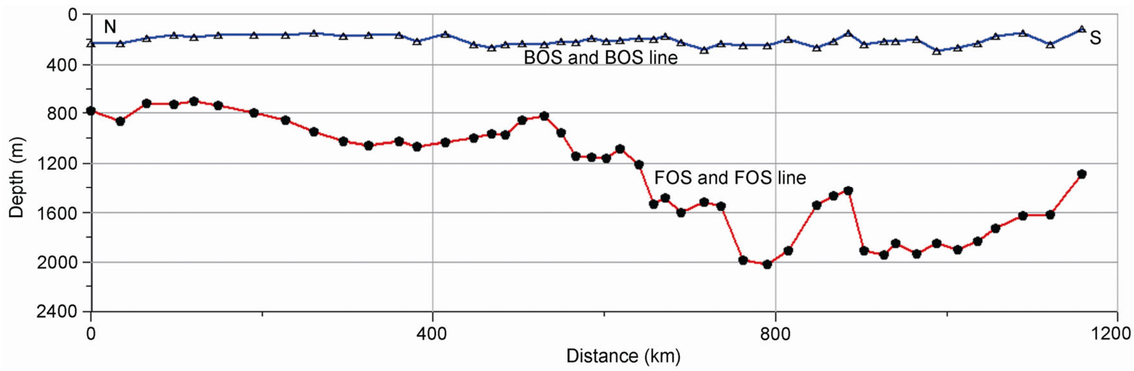

Figure 5 Water depth profile of connecting line between BOS and FOS. Spatial distribution is shown in Figure 3, and two points with the same distance are related to the same profile.

depths of around 200 m (Figure 5). Therefore, we take the 200 m depth contour to be the BOS line for the ECS, instead of 160 m as previously used (Liu et al., 2005).

From the 48 topographical profiles used above, we obtained 57 FOS (Figure 3). For nine profiles, foot points on both the upper and lower continental slope were obtained (shown as blue and red solid circles in Figure 3, respectively). An analysis of these FOS points shows that the water depth of the FOS increases gradually from north to south (Figure 5), with a value at about 800 m in the northern trough (Figure 4(a)) increasing to 1000 m or more in the middle section of the trough (Figure 4(b)). In the southern part of the middle trough, the water depth of the FOS is near 2000 m (Figure 4(c)) and is generally >1500 m in the southern trough (Figure 4(d)). In the middle part of southern trough, the water depth of the FOS tends to fluctuate with localized values decreasing to 1400 m (Figure 5) and with even more reduction near the island of Taiwan. In the southern part of the trough, submarine canyons are extensively developed and interrupt the terrain of the continental slope. Turbidity currents flow along the canyons and form turbidite fans inside of the trough (Wu et al., 2004; Li, 2008; Zhao et al., 2011). The canyons and turbidite fans change not only the terrain of the sea floor but also the position of FOS. Both the upper and lower continental slope can be identified in most profiles in the southern trough (Figures 3, 4(d)), together with their FOS.

If we define the continental slope as the region lying between the BOS and FOS, then the continental slope of the ECS can be characterized by wide features in the north and south, and narrow features in the middle (Figure 3). The northern continental slope is about 40–70 km wide (Figure 4(a)) with a water depth drop from 600 to 800 m (Figure 5) from BOS to FOS. The middle continental slope has a minimum width about 10 km at the narrowest position (Figure 4(b)) and a depth drop of 600–1800 m from BOS to FOS (Figure 5). However, the width of the southern continental slope gradually increases to a range of 30–50 km (Figure 4(c), (d)) accompanied by a depth drop of 1000–1800 m (Figure 5). Connecting the points of slope, the position of the continental slope follows a broad S-shape that is relatively flat in the middle part of the trough. In the northern part of the trough, a similar slope shape is also seen, but overall it is slightly broken with some small terrain fluctuations (Figure 4(a)). In the southern part of the trough, the continental slope is severely incised by many canyons and has the appearance of being totally smashed (Figure 4(d)).

3.2 Central axis of the Okinawa Trough

3.2.1 Determination method

The OT has an overall U-shaped groove appearance (Figure 1) with the continental slope of the ECS to its west and the Ryukyu Arc slope to its east. The continental slope of the ECS has a regular FOS, which is generally distributed at the lower part of the continental slope (Figure 3). Although locally cut and disconnected by channels, the Ryukyu Arc is continuous on the whole; the FOS along its west side can be readily traced. Therefore, we can use the method discussed in the previous section to determine the FOS at both the eastern and western sides of the OT; the boundary of the OT axis area can be formed by connecting these FOS in order (Figure 6).

The determination of a trough axis is based on 3D submarine topographical maps. Some typical tectonic units, such as the central axis of *en echelon* depressions at the bottom of the trough, or a ridgeline associated with linear ocean mountains, can be considered as basic evidence for the determination of a trough axis (Figure 1). By analyzing the topographical profile in the axial area, and combining this with the 3D topographical features, we can confirm the positions of central axial points quantitatively. If linearly oriented seamounts are mapped in 3D, they can be used as the central axis for the profile. If there are obvious linear depressions in such a 3D map, the points with maximum depth should be used to select central axial points in the trough. In addition, geological and geophysical evidence is also critical for the determination of central axes, e.g., the shallow or deep tectonic features of the trough revealed by single- or multi-channel seismic profiles can sometimes directly determine the position of central axial (Sibuet, 1987; Yang et al., 2001, 2010; Luan et al., 2007).

3.2.2 Central axial point and central axis

The axial region of the OT has been characterized by the construction of 39 typical topographical profiles perpendicular to the axis (Figure 6) using the method discussed above. After analyzing the topographical characteristics of each profile, a series of topographical feature points on each profile has been determined quantitatively, such as the minimum, maximum, and secondary depth points. Comprehensive analysis of these topographic profiles and maps has led to the positioning of a central axial point on each profile; then, after connecting all these points in order, the central axis in OT axial region is formed.

From the analysis of the 3D map and typical topographical profiles (Figures 1, 7), we find the general appearance of the trough is similar at the northern, middle, and southern parts of the trough with a U-shaped groove terrain. However, there are significant differences in detail that control the position of the central axial points.

In the northern OT (Figure 1(a)), the continental slope of the ECS is not flat and has developed numerous fault blocks (Fan et al., 2000). In contrast, on the eastern side of the trough, numerous islands exist, which makes the west flank of the Ryukyu Island Arc relatively broken. There are many low sea-knolls and depressions developed in the trough. The terrain in the axial region of the trough is characterized by the features of that high relief in the middle and deep water along the two sides, and most profiles are W-shaped features of symmetry (Figure 7(a)). The maximum and secondary depth points are always distributed on the two sides of the W-shaped profile. As a result, the maximum depth point in a few profiles jumps between the eastern and western sides of the axis, with most of the maximum depth points distributed east of the axis but a few to the west (Figure 6). The maximum water depth ranges from 800 to 1200 m (red line in Figure 8). This distribution pattern of maximum depth points in the northern OT is consistent with that of boundary points defined in the submission to CLCS (the Commission on the Limits of the Continental Shelf) (http://www.un.org/Depts/los/clcs_new/submissions_files/submission_chn_63_2012.htm). For this type of topography, the shallow point should be chosen as the central axial point, i.e., the middle shallow point on a W-shaped profile. In summary, the central axial points in northern OT are essentially located in the middle part of the axial region with a fluctuating water depth. The shallowest water depth of the point is only 200 m but this point has a large depth drop of 400 m on the same profile, and even to 1000 m locally (Figure 8).

In the middle part of the OT (Figure 1(b)), the continental slope of the ECS is narrow and flat. By contrast, the western slope of the Ryukyu Island Arc is quite uneven, and there are linear seamount chains, conical seamounts and hills distributed from the eastern part of the trough to the Ryukyu Arc (Wu et al., 2004; Li, 2008). Influenced by linear seamounts, the trough as a whole shows the characteristics of composite W-shaped topography (Figure 7(b)). The maximum depth points are distributed in the strap-like depression area among linear seamounts, and additionally, this occurs mostly in the central area of the trough axial region. Given the combined features of the topographical profile, a ridge of the linear seamounts is distributed regularly in the middle of the axial region, which can be used as the central axial line of the trough axial region. In contrast, in the region where these amounts are not linear, the maximum depth points in the central depression can be taken as the central axial points. In the middle part of the trough, the maximum depth points and the central axial points gradual-

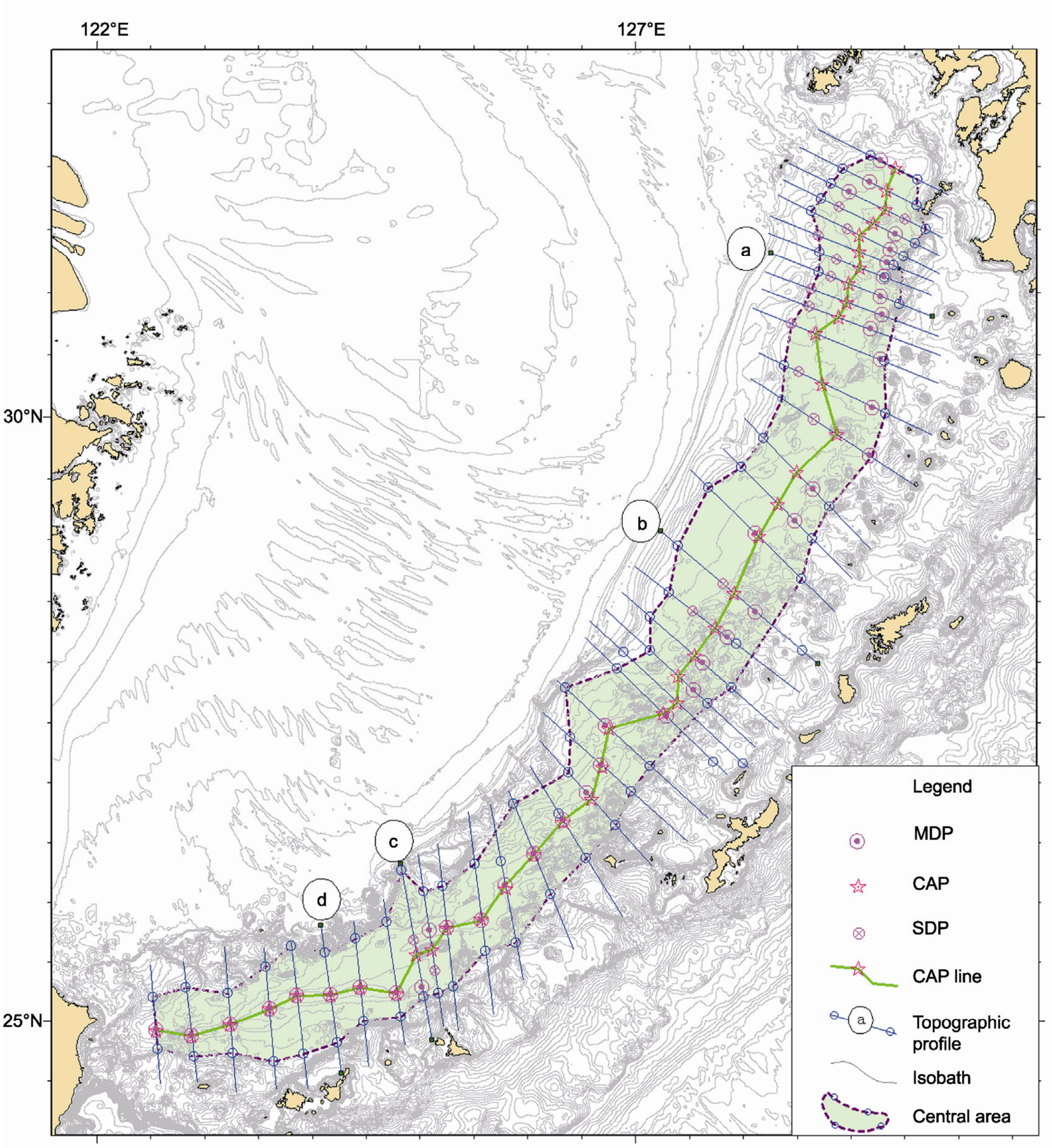

Figure 6 Topographical profiles to determine the central axial points. a–d are typical topographic profiles.

ly gather together in spatial distribution, and even overlap each other in southern part of the middle trough (Figure 6), which is distinct from dispersion in northern part of the trough. The maximum depth in the middle section gradually increases from 1200 to 2000 m or more (Figure 8). The water depths of axial points have a small-amplitude fluctuation in northern part of the middle section and coincide with the maximum depth points in the south.

In the southern Okinawa Trough (Figure 1(c)), the continental slope of the ECS is fragmented, whereas the west slope of the Ryukyu Arc is relatively flat. Topography inside the trough is relatively simple with most *en echelon* depressions (half grabens) located along the trough (Wu et al., 2004; Luan et al., 2007; Li, 2008) along with some local linear seamounts. Most of the topographical profiles cross-cutting the trough have a standard U-shape (Figure 7(d)), with some occasionally exhibiting a W-shape (Figure 7(c)). The maximum depth points of U-shaped profiles are coincided with the central axial points, whereas those of the W-shaped profiles are in the linear depressions and the central axial points are always located at central shallow position of the profiles (Figure 7(d)). Spatially, all of the maximum depth points were located inside the linear depressions (Figure 6), where they coincided with the majority of central axial points. However, where there is a linear seamount, the central axial point exists on the ridge of the seamount, and the water depth drop can exceed 1000 m between a central axial point and the corresponding maximum depth point. Generally, in the southern OT, the depth of maximum depth points is between 1600 and 2400 m, whereas the

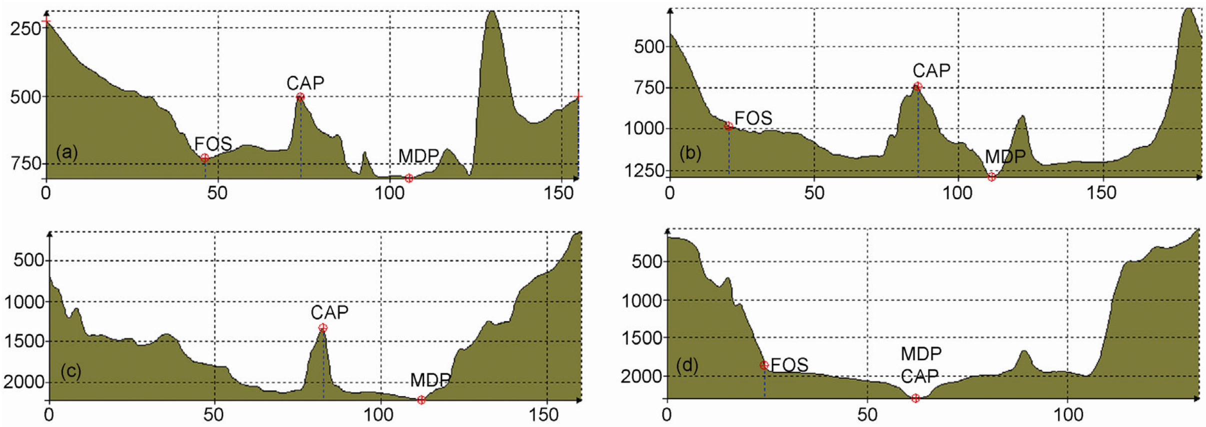

Figure 7 Typical profiles and their central axial points. (a) a profile in the northern trough; (b) a profile in middle trough; (c) a profile in southern trough; (d) a profile in southern trough. FOS: foot point of the slope; MDP: maximum depth points; CAP: central axial points ; positions of the four profiles are shown in Figure 6.

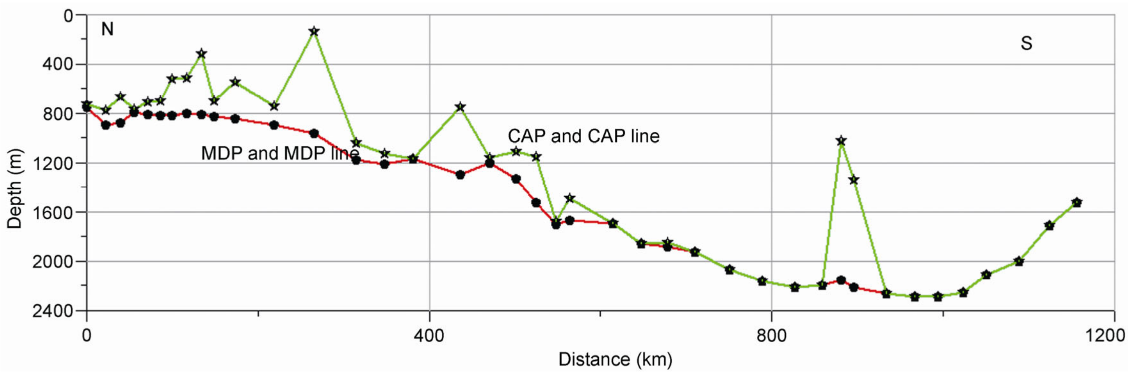

Figure 8 Connecting line of central axial points and that of the maximum depth points in the Okinawa Trough. Spatial distribution is shown in Figure 3, and two points with same distance are corresponding to a same profile.

minimum water depth of the central axial point is about 1000 m (Figure 8).

4 Factors influencing boundary distributions

4.1 Influence of sea-level fluctuation on boundary characteristics

Significant sea-level fluctuation is the most important factor affecting continental shelf deposition and seafloor topography. Milankovich cycles, with a main cycle interval of 100 thousand years, lead to the global cycle of glacial and interglacial stages (Lin et al., 1987). The growth and decay of continental ice sheet leads to regionally significant sea-level change with a range of over 100 m. During the last glacial stage, sea level fell to a position 140 m lower than the present level (Zhu, 1979), causing the transgression and regression of the ECS continental shelf. Sea-level changes control the development of sediment accumulation patterns on the ECS shelf, and form sequence stratigraphic relationships that include Forced Regression Systems Tracts, Lowstand Systems Tracts, continental sedimentation, Transgressive Systems Tracts, and Highstand Systems Tracts, respectively, during the following stages of sea-level change: regression, lowstand, drought, transgression and highstand. Multiple stages of comparable strata are imaged by high-resolution single-channel seismic data (Wu et al., 2002). Additionally, changes in hydrodynamic environmental conditions, brought about by sea-level change, also are a major factor in the development of relief on the continental shelf. Overland rivers that crosscut the shelf during lowstands (Li et al., 2004; Li, 2008) flow into the ocean directly at the front of the continental slope, or alternatively into canyons on the continental slope (Wu et al., 2004; Li, 2008; Zhao et al., 2011), providing the source and dynamics for changes in the relief of shelf outer margins and the continental slope of the ECS.

Sea-level fluctuations, because of their role in promoting changes in sedimentary sequences and the dynamic environment during very low sea levels, play a critical role in shaping the form of the BOS. This in turn affects the shape of the slope and the position of the FOS from place to place on the margin.

4.2 Influence of tectonic movements on the boundary distributions

The Ryukyu Trench, Ryukyu Arc, and OT make up a typical "trench-arc-basin" system. This specific tectonic pattern is the result of the interaction between the Eurasian and Pacific plates (Lee et al., 1980; Kimura, 1985; Sibuet, 1987; Qin et al., 1987; Xu et al., 1988; Jin et al., 1987, 1992; Liu, 1992; Li, 2008). Three stages of tectonic movements have been identified as being important for the evolution of the OT.

During the late stage of the Early Miocene, the Philippine Sea plate subducted eastward along the eastern side of the Diaoyu Islands folding zone, and initiated the Ryukyu Trench, Ryukyu Arc and OT basin system (Xu et al., 1988). A series of beaded rift basins formed along the normal fault because of the extensively developed rifts in the OT and Ryukyu Island region (Jin et al., 1987, 1992). The expansion direction during this stage was 135°N–155°N (Sibuet, 1987). The second episode of OT tectonic movement started in the Pliocene/Pleistocene. This stage was characterized by the tilting of fault blocks and formation of normal faults with a rough strike of 45°N and approximate displacements of 50 m (Wu et al., 2004). The expansion direction during this stage was 155°N–170°N (Sibuet, 1987). The OT evolved into a unique trough from this rift basin, which tended to expand preferentially at its southern end (Jin et al., 1987, 1992). In the Late Pleistocene, the third episode started. A number of normal faults with vertical displacements >10 m and newly developed linear seamounts in the central deep depressions formed during this period (Wu et al., 2004). The expansion direction during this stage was around 175°N (Sibuet, 1987).

These three stages of tectonic movements formed not only the U-shaped groove terrain of the OT, but also other various forms of relief in the trough, such as: several *en echelon* central depressions along the axis in the middle and southern parts of the trough (Wu et al., 2004; Li, 2008), normal faults with displacements of a few meters to tens of meters along the two sides of linear depressions, and new seamounts with apparent linear features in the southern part of the central depression (Wu et al., 2004). Fresh olivine tholeiite samples obtained from the central depressions show geochemical characteristics similar to those of mid-ocean ridge basalts from mantle plume sources (Li et al., 1997). Additionally, there are several linear seamounts scattered through the trough, such as the Ono Temple seamount in the southern part of the trough and other multiple linear seamounts chains aligned in parallel in the middle and northern parts of the trough. All of these linear seamounts are the product of trough expansion (Wu et al., 2004; Li, 2008). The seismic profile across the trough has confirmed the existence of a spreading center with a spreading axis extending along the trough axis (Sibuet, 1987; Yang et al., 2001).

Morphotectonic (Fan et al., 2000; Wu et al., 2004; Liu et al., 2005; Luan et al., 2007; Li, 2008), petrologic (Li et al., 1997; Huang et al., 2006) and geophysical (Liang et al., 2001a, 2001b; Gao et al., 2004; Hao et al., 2004; Han et al., 2007) evidence has proven that the southern OT came into the spreading stage as a result of rifting and subsidence. The linear seamounts and the central depressions in the center of the OT are the results of seafloor rifting and expansion, whereas the seamount ridge and depression axis are the central axis of OT. The three stages of tectonic movements have not only shaped the appearance of the trough but also controlled the distribution of its central axis.

As the apparent central axial point in the OT can be traced from north to south, this suggests that the OT is a natural boundary for the eastward extension of the ECS continental shelf. This reasoning is consistent with the submission made to the CLCS by the Chinese government (http://www.un.org/Depts/los/clcs_new/submissions_files/submission_chn_63_2012.htm).

4.3 Influence of submarine canyons on boundary characteristics

On the ECS slope, especially to the south, there are numerous variably sized submarine canyons that incise the continental slope and divide it into segments (Figure 1). On the north-central continental slope of the ECS, the submarine canyons are relatively small and streamlined, whereas on the middle and southern continental slope they are usually large. Canyons in the south are generally 10–50 km long, 1–15 km wide and have a gradient of 5°–15° with an incised depth of 100–500 m. Many canyons have three or four branches resembling, in plan view, a goose-claw or tree (Li, 2008). These canyons extend upward to the shelf, downward to the bottom of the trough and show visible turbidite accumulation along their extent. These deposits indicate that the submarine canyons act as channels for turbidity currents flowing down slope; i.e., the ECS shelf provides sediment sources for deposition on the western side of the OT (Wu et al., 2002; Li, 2008; Zhao et al., 2011). During the Last Glacial Maximum, the sea level of the ECS had dropped to 140 m beneath the present level (Zhu, 1979) with the continental shelf completely exposed with widespread desertification (Zhao et al., 1996). The ancient rivers of the ECS flowed directly across the continental shelf (Wu et al., 2002; Li, 2004) into the submarine canyons, which means that the submarine canyons probably acted as the direct channel for sediment flowing from the ECS continental shelf into the OT. The heads of the submarine canyons extending into the continental shelf not only changed the position of the BOS, but also transformed the original shape of the BOS line. In short, the submarine canyons that incised the slope had changed the slope shape. The sediments they carried also changed the relief between the lower continental slope and the trough bottom. They also changed the position of the

FOS and FOS line for the ECS shelf. On the southern continental slope, multiple FOS are even available for a single profile.

5 Conclusions

(1) Based on multiple sources of bathymetric data, the submarine topography of the OT has been investigated. The trough has an overall U-shape, with the central axial depth gradually increasing from 500 m in the north to 2300 m or so in the south. The maximum water depth is located within a "trough in trough" in the south. Linear seamounts and navicular depressions are especially well developed in the middle and southern trough, whereas a large number of other submarine features exist on the western slope of the trough. The continental shelf of the ECS extends eastwards naturally and terminates at the OT, i.e., the OT forms a natural boundary between the ECS continental shelf and the Ryukyu Arc.

(2) Quantitative determination methods have been proposed to constrain the positions of the BOS, FOS, and central axial points. The analysis of 48 topographical profiles crosscutting the continental shelf of the ECS has enabled the systematic determination of BOS and FOS lines for the ECS continental shelf for the first time. Additionally, the analysis of 39 topographical profiles cutting through the trough axial region has also enabled a systematic and quantitative determination of the central axis of the OT for the first time.

(3) The BOS line is the boundary between the continental shelf and slope. In the ECS, the BOS line generally follows the 200 m isobath. It is relatively continuous in the northern and middle parts of the OT but jumps about slightly in the south. In comparison, the FOS line is the boundary between the continental slope and trough. Its position deepens gradually from north to south. The continental slope in the southern part of the trough is intensively incised by submarine canyons, leading to a complex distribution for the FOS. Submarine canyons have greatly influenced the distribution of BOS and FOS in the southern part of the trough.

(4) The central axis is the dividing line between east and west in the trough axial region. Tectonic processes and sedimentary features are the main controls on the distribution of maximum depth points and the central axial points. We have proven that the trough is the natural boundary for the eastward extension of ECS continental shelf. Topographical profiles crosscutting the northern, middle and southern parts of the trough take on the form of a single W, a composite W, and a U, respectively. As a result, the central axial points are mostly positioned on the tops of seamounts or along the ridges of linear seamounts in the middle and northern parts of the trough, whereas they are always in the center of *en echelon* depressions in the southern part of the trough.

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