Balanced Cross Section for Restoration of Tectonic Evolution in the Southwest Okinawa Trough

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ABSTRACT: On the basis of the multi-channel seismic data and the other data, using 2DMove software, the tectonic evolution in three seismic profiles was restored since Pliocene. The tectonic restoration results show that: (1) the initial active center lay in the west slope and then was transferred to east and south via trough center during the evolution process; (2) several main normal faults controlled the evolution of the southern Okinawa Trough; (3) since Late Pliocene, the southern Okinawa Trough has experienced two spreading stages. The early is depression in Early-Middle Pleistocene and the late is back-arc spreading in Late Pleistocene and Holocene, which is in primary oceanic crust spreading stage.

KEY WORDS: balanced cross section, tectonic evolution, back-arc basin, Okinawa Trough.

INTRODUCTION
The Okinawa Trough (OT) lays the boundary between Eurasian plate and Philippine Sea plate (PSP). It is a nascent back-arc basin of the trench-arc-basin system in West Pacific margin. It is a key spot for continental margin rifting, especially for the Chinese continent and its adjoining areas. Many scholars have paid much attention to it (Liu et al., 2005; Zeng et al., 2003; Jin and Yu, 1987; Kimura, 1985; Lee et al., 1980; Herman et al., 1978).

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The OT tends NE in whole, and is divided into three parts by Tokara fracture zone and Miyako fracture zone (Fig. 1). The north part tends NNE, with depth about 600–800 m. The middle part is NE tending, with 1 000–1 200 m deep, and the south part NEE, mostly over 2 000 m deep (Fig. 2). In this area, the crust is thinned, with strong tectonic movements and high heat flux (Fan and Yang, 2004; Li et al., 2001; Jin and Yu, 1987). The Miyako fracture zone is similar to transformation fault. To its north, the faults are right-strike slip, whereas in the south are left-strike slip (Jin and Yu, 1987; Fig. 1).

There remains dispute on the rifting stage. Depending on seismic strata, bore data, and the strata development features in this area, the OT mainly experienced three tectonic periods: Late Miocene, Late Pliocene–Early Pleistocene, and Late Pleistocene–Holocene. Late Miocene is the rifting stage of OT (Jiang et al., 2003; Zeng et al., 2003; Herman et al. (1978) thought the rifting occurred
between Late Miocene and Early Pleistocene, when the Ryukyu islands broke from the continent, based on the nonconformity between upper and lower sediment layers. Kimura (1985) suggest that the opening of OT began 6–4 Ma BP, based on the sedimentary sequences in middle OT. However, Park et al. (1998) thought that during 6–2 Ma BP there was no spreading, it began about 2 Ma BP; whereas Miki (1995) thought it began spreading since 10–6 Ma BP. There are also different opinions on the structural property of present OT: some scholars thought the south and middle parts of OT are on “oceanic-crust” spreading (Yang et al., 2004; Jiang et al., 2003; Jin and Yu, 1987), whereas others thought there is no spreading (Liu, 2001). Therefore, further study about the formation and evolution of OT is necessary. On the basis of seismic interpretation and geological analysis of OT (Guo, 2004), the quantity described on the formation and evolution process using balanced cross section technique is discussed in this article.

Figure 1. Geological map of East China Sea (modified after Jin and Yu, 1987). 1. Hupijiao rise; 2. Haijiao rise; 3. Yushan rise; 4. Wuyishan low rise. ① Fujiang depression; ② Yangtze depression; ③ Qiantang depression; ④ Oujiang depression; ⑤ Xihu depression; ⑥ Taipei depression.
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Figure 2. Map of water depth in Okinawa Trough with seismic lines. A, B, C are the seismic lines.

SEISMIC SEQUENCES

The data used were collected by R/V “KEXUE I” Cruises during 1982–1984. After Jin and Yu (1987), Park et al. (1998) and Liu et al. (2005), five seismic sequences, which have various velocity models (Table 1), were identified and modified.

Three seismic profiles in southwest OT (Fig. 2) were chosen to restore by further process and interpretation. The profiles show no fold, and all strata are disconformity contact or conformity contact. This means that in the whole trough, there is no compression, and the OT is extensional structural environment. Several main faults controlled sedimentary development in the OT. During Late Pleistocene, many small contemporaneous faults developed. So this period had strong tectonic activity with high deposition rate (Fig. 5). Some diapirs also developed, which may have been formed by magma upwelling (Fig. 3).

Figure 3. Interpretation map of section A (position in Fig. 2).
METHOD AND RESULTS OF BALANCED CROSS SECTION

Balanced cross-section technique is a quantifying tool for geological structures. Dahlstrom (1969) first advanced the concept, and also made some applications. From then on, it developed and improved continuously. At present, it is mainly applied for checking result of seismic interpretation, quantity study on tectonic deformation, and tectonic evolution of basin (Zhou, 2005; Diao and Cheng, 2004; Mao et al., 1998).

Section keeping balance is a base geological rule. On the basis of the law of conservation of matter, the balanced cross-section technique is advanced, following the laws of conservation, the agreement of layers’ length, displacement, and shortening. Zhang and Chen (1998), and Diao and Cheng (2004) concluded the steps by applying this technique: firstly, construct proper geologic column model; secondly, establish the structural setting, this technique is more suitable for simple compaction or extension area; thirdly, collect aspect of profiles, the optimum aspects parallel the greatest structure migratory direction, for it can evade sliding movement; finally, recover the tectonic compaction.

Table 1  Seismic sequences in the Okinawa Trough
Following the above steps, the profiles A, B, and C (Fig. 2) were restored by 2Dmove software. Because of shortage of data, the Pliocene and Miocene strata were not restored. So, Early Pleistocene, Middle–Late Pleistocene, Holocene and the present of the above three seismic profiles were restored and the results are shown in Figs. 6–8.
The restoration maps of line A in four periods are in Fig. 6. The Pliocene strata developed at the northern continent slope (Fig. 6). Old Miocene strata only occurred in the shelf. Normal faults developed on shelf, and a big normal fault controlled the sedimentations. Two subsequence stages can be divided in the profile. The early extension occurred in Early Pleistocene and accepted 1 000 m sediment, and the late stage was in the Middle–Late Pleistocene, whereas the Holocene was about 2 000 m, with 4% extension rate. The whole extension rate was 7% greater. Depocenter transferred from the shelf in
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Pliocene to the island slope in Holocene, completing the south transference of depocenter.

The tectonic restoration of line B is on Fig. 7. Four sediment layers overlaid basement. A few inverse faults developed on the continent slope. But many normal faults developed mainly on the continental slope, trough center, and the islands slope. And the faults were active in the trough floor. So the remainder of Miocene was conserved. The active faults controlled two depocenters in Early Pleistocene. The two depocenters had 1 700 m and 2 050 m thick sediments, respectively. During Middle–Late Pleistocene the depocenter migrated to the trough. And the depocenters accepted 1 700 m and 2 050 m respectively. Ascribing to sedimentary compaction, the Early Pleistocene became 750 m and 1 500 m thick in the two depocenters respectively. And compaction amplitude in center was bigger than in east. This may be because the Middle–Late Pleistocene sediments in center were heavier than in east. During Holocene, the sediments deposited in center and east part with thickness of 1 600 m. The compaction of Early Pleistocene was small, changing into 700 m and 1 450 m. Whereas the Middle–Late Pleistocene became big, from 2 200 m and 1 600 m, changing into about 1 200 m and 900 m. But the extension rate was very small, only about 3%.

The tectonic restoration of line C is on Fig. 8. The sedimentary feature is the same as Fig. 7. There also were two depocenters, trough center and off islands slope. By Middle–Late Pleistocene, the Early Pleistocene deposited 3 050 m and 1 900 m separately in two depocenters. Whereas by Late Pleistocene, Middle–Late Pleistocene deposited about 1 900 m and 1400 m, making the Early Pleistocene sediment compact to 3 000 m and 1 590 m. Obviously, the compaction was not big, so regional subsidence might have been intense. The Holocene depositing into this area was the same as the line B, with 1 300–1 500 m thickness. Ascribing to sedimentary compaction, the Early Pleistocene became 2 750 m in west slope and 1 550 m in middle part, whereas the Middle–Late Pleistocene became 1 600 m and 900 m. From the map, the stretching rate of line C was about 4%, amounting to 3 000 m.

From the above, the stretching rate and compaction rate are different in different stages, and mainly in Early Pleistocene and Late Pleistocene to Holocene, the two spreading stage of OT. The line A is the biggest in stretching rate among the three lines. Maybe in the southwestern OT there appears oceanic-crust spreading. That is to say, OT is at the initial stage of oceanic-crust spreading.

DISCUSSION

The faults develop widely in this area (Fig. 1), and most are normal faults with high angle (Figs. 3–5). The north subduction of Philippine Sea plate and Huatong basin makes tensional stress flow back to the Ryukyu Islands. Then the upwelling of materials from mantle forms the OT. In this tensional environment, normal faults develop widely, whereas some inverse faults develop locally because of compression. It is easier to see the formation and the controlling of faults in this area from the restoration maps.

Most of the faults in this region formed before Early Pleistocene. The faults are mostly normal faults and they control the development of sedimentary strata in OT. Only a few inverse faults occur in the west slope of OT. So, the southern part of OT is in tensional environment in this period. The basement is composed of Pliocene and Miocene sedimentary layers and volcanic rocks. It is thus evident that the southern OT began to form and accept sediments. During Pleistocene, there are two depocenters in the trough floor and off island slope, which accumulated thick sediments. But to continent shelf and slope, there is no Pleistocene sediment, maybe because the sea level decreased, the slope was steep and tectonic activity was strong. During this period, many normal faults dipping to trough are formed in the slope induced by subduction of Philippine Sea plate. The dip angle is high and sediment distorts very intensely. Holocene sediments cover the whole area, and are thick in the two depocenters. Few faults can be discerned from the profiles. It means that, the tectonic movement was not active during Holocene.

From the above analyses, the development of faults controlled the migration of depocenters. The depocenter migrated the continent slope to off island slope. Since the Pliocene, the profiles are stretching (Table 2). Especially on Fig. 7, the extension arrives to
4000 m, with stretching rate up to 7%. On Figs. 8–9, this phenomenon is not obvious, with rate of 3%–4%, eroding excluded. The difference in rate may be caused by their places. Line A lies in most southern of OT, whereas lines B and C lie off Miyako fracture zone. The OT rotates clockwise during spreading, and rotation axis is Miyako fracture zone. Comparing rates, this rotation may have happened in Holocene.

Table 2  Stretching rate of the section along seismic lines

<table>
<thead>
<tr>
<th>Seismic line</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension amount (m)/rate (%) in Holocene</td>
<td>2 000/3.33</td>
<td>1 000/1.32</td>
<td>1 000/1.32</td>
</tr>
<tr>
<td>Extension amount (m)/rate(%) in Middle–Late Pleistocene</td>
<td>1 000/1.67</td>
<td>1 600/2.10</td>
<td>1 400/1.84</td>
</tr>
<tr>
<td>Extension amount (m)/rate(%) in Early Pleistocene</td>
<td>1 000/1.67</td>
<td>700/0.92</td>
<td>900/1.18</td>
</tr>
<tr>
<td>Total extension amount (m)/rate (%)</td>
<td>4 000/6.67</td>
<td>3 300/4.34</td>
<td>3 300/4.34</td>
</tr>
</tbody>
</table>

Figure 9. Evolution model of Okinawa Trough in Cenozoic.

The evolution model of OT can be constructed as shown in Fig. 9, according to the seismic interpretation, which includes depositing, uplift and erosion, rifting, and initial spreading. During the Miocene the southern OT accepted the huge thickness of sediments (Fig. 9a), Pliocene strata were distributed in both slopes, but absent in the trough basin. It is inferred that, the Pliocene originated from the Chinese mainland deposited in this region, and the trough did not open. In the Late Pliocene the southern OT started
to rise, and thinning in the center subducted by Gagua Ridge. So the region uplifted and the Pliocene and the early deposits were eroded because of this movement. The Pliocene in the trough area were nearly eroded and Miocene remained only a little as the residual deposition. The acoustic basement was exposed in some areas. Then nonconformity occurred. From the seismic profiles, the Miocene pinched out northwestward probably because of subsidence. After the last movement, the trough area began to rift. The Early Pleistocene concentrated into the trough area and filled the depressions. With the sea level ascending, the Middle and Late Pleistocene and Quaternary deposited. The neonatal submarine volcanoes suggest that the southern OT is in the initial seafloor spreading stage. This agreed with the preceding studies (Yang et al., 2004; Jiang et al., 2003; Jin and Yu, 1987).

CONCLUSIONS
The results of balanced cross-section restoration and seismic interpretation show that, since Pleistocene the depocenters have migrated to east; several large faults controlled the development of minor faults and strata; the OT has experienced two spreadings since Pliocene, the early was fault depression in Early–Middle Pleistocene, the late was back-arc spreading from Late Pleistocene to Holocene. And at present, it is in the initial stage of oceanic crust spreading.

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REFERENCES CITED


