Tectonophysics 817 (2021) 229047

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Active tectonics and volcanism in the southernmost Okinawa Trough back-arc basin derived from deep-towed sonar surveys

Ching-Hui Tsai [a], Shu-Kun Hsu [b,*], Song-Chuen Chen [c], Shiou-Ya Wang [a,b], Lien-Kai Lin [b], Pi-Chun Huang [b], Kuan-Ting Chen [b], Hsiao-Shan Lin [a], Chin-Wei Liang [a], Yen-Yu Cho [a]

[a] Center for Environmental Studies, National Central University, Taiwan
[b] Department of Earth Sciences, National Central University, Taiwan
[c] Central Geological Survey, Ministry of Economic Affairs, Taiwan

ARTICLE INFO

Keywords:
Taiwan
Okinawa Trough
Rifting
Active fault
Back-arc volcanism
Back-arc basin
Deep-tow sonar survey

ABSTRACT

The southernmost Okinawa Trough back-arc basin is an active and young basin formed just after the collision of the Philippine Sea Plate against the Eurasian continental margin. The back-arc extension occurs intensively because of the southward or southeastward migration of the southernmost Ryukyu Arc, or the roll-back of the Philippine Sea Plate. To better understand the active tectonics and volcanism of the southernmost Okinawa Trough, we have conducted deep-tow sub-bottom profiler and side-scan sonar surveys across the back-arc basin. Our results show that the volcanism of the southernmost Okinawa Trough is distributed in the southern half of the back-arc basin and occurs along some linear or branched zones roughly parallel to the trough axis. Volcanic seamounts are obviously located along the central depression of the basin and their sizes show lateral variation. On the other hand, the northern half of the southernmost Okinawa Trough back-arc basin has almost no volcanic activity, but contains more brittle normal faults. It is noted that gas plumes out of seafloor are generally associated with hydrothermal mounds or activities, instead of volcanic seamounts. We suggest that the more complete rifting of the southernmost Okinawa Trough back-arc is limited to the east of ~122°30′E. To the west of ~122°30’E, the back-arc extension could be still influenced by the inherited NE-SW trending structures of the continental crust created during the former Taiwan orogeny in this area.

1. Introduction

Along the eastern margin of the Eurasian Plate, the Okinawa Trough is an active back-arc basin of the Ryukyu subduction zone, that is caused by the subduction of the Philippine Sea Plate beneath the Eurasian Plate (Lee et al., 1980 ; Kimura, 1985 ; Letouzey and Kimura, 1986; Sibuet et al., 1987, 1995, 1998; Hsu et al., 2013). It extends from the Kyushu Island of southwest Japan to the Yilan Plain (IP) in northeast Taiwan and can be divided into three segments including the Southern Okinawa Trough (SOT), the Middle Okinawa Trough (MOT) and the Northern Okinawa Trough (NOT) by Tokara Fault and Kerama Gap tectono-morphological boundaries (Kodaira et al., 1996; Shinjo et al., 1999; Fabbri et al., 2004; Gungor et al., 2012) (Fig. 1). The width of the Okinawa Trough increases from 60 to 100 km in the south to 230 km in the north, and the water depth decreases from 2300 m to 200 m from south to north (Sibuet et al., 1987; Sibuet et al., 1998). The earliest rifting of the Okinawa Trough is suggested to be in the late Miocene (Hirata et al., 1991; Miki, 1995; Shinjo et al., 1999; Chung et al., 2000; Shinjo and Kato, 2000; Sibuet et al., 1987; Miki, 1995; Shinjo et al., 1999). However, the SOT started to rift in the Pleistocene (~2 Ma), because of the clockwise rotation of the southwestern Ryukyu Arc (Miki, 1995; Park et al., 1998; Shinjo et al., 1999). Hsu et al. (1996) demonstrated that the 30° clockwise bending of the southwestern RA and the former NW-SE trending strike-slip faults with block motions could be due to the collision of the Luzon arc with the former southern RA from 8 Ma to 3 Ma (Sibuet and Hsu, 2004). The crustal thickness along the trough axis varies from 27 to 30 km in the NOT to 15–18 km in the SOT (Lee et al., 1980; Sibuet et al., 1995). Currently, the deepest and hottest hydrothermal activity occurs in the SOT (Miyazaki et al., 2017; Okino et al. (2002); Matsumoto et al., 2001).

Morphologically, the Ryukyu Trench and Ryukyu Arc has changed their orientation from NE-SW to NW-SE to the west of longitude 123.5°E (Fig. 1). This change was due to the Luzon Arc collision (Hsu et al., 1996; Sibuet and Hsu, 2004). However, the Philippine Sea Plate has already

* Corresponding author.
E-mail address: hsu@ncu.edu.tw (S.-K. Hsu).

https://doi.org/10.1016/j.tecto.2021.229047
Received 6 April 2021; Received in revised form 10 August 2021; Accepted 29 August 2021
Available online 4 September 2021
0040-1951/© 2021 Elsevier B.V. All rights reserved.

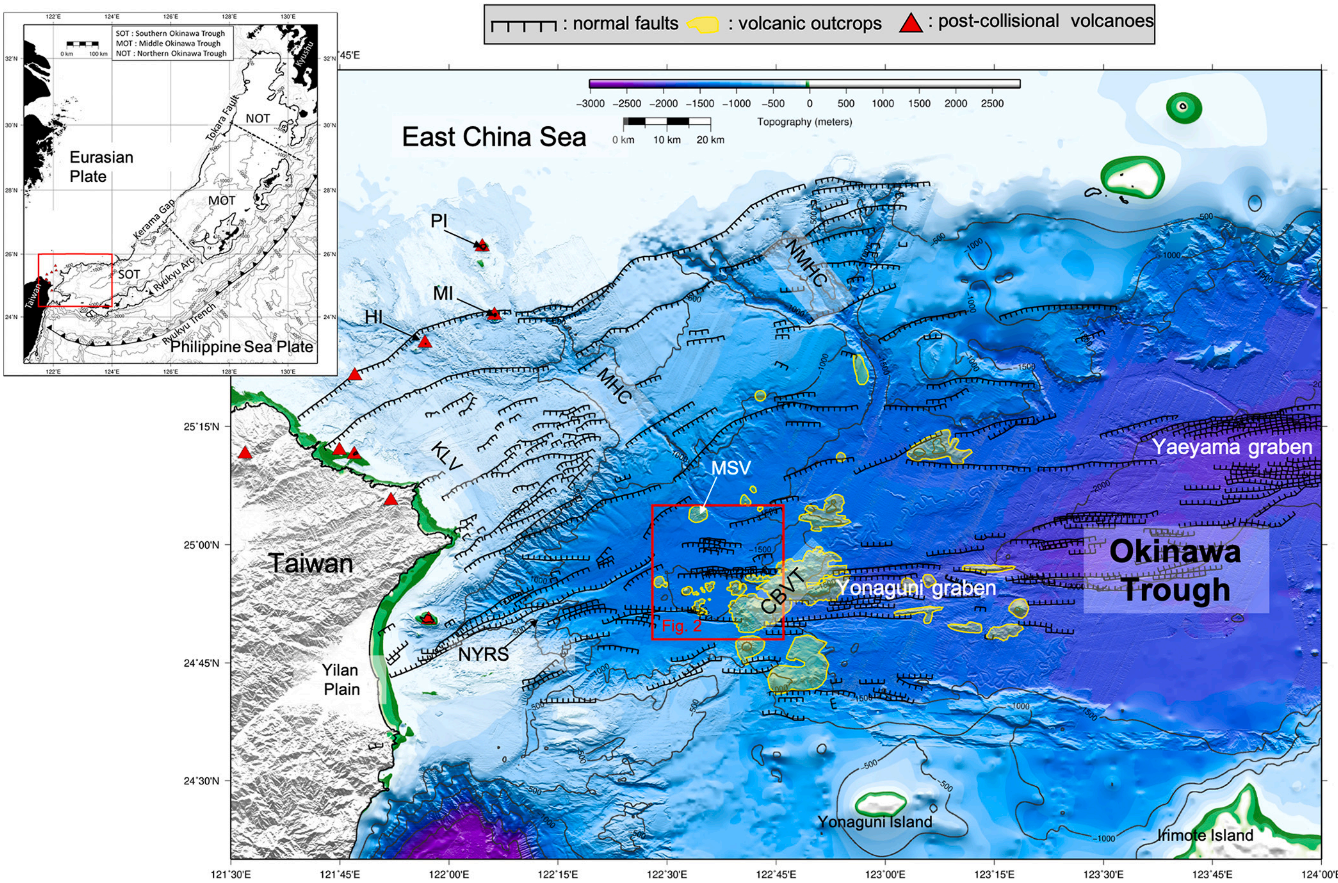

Fig. 1. Topography of the southernmost Okinawa Trough and the northeast Taiwan. The traces of the normal faults are generally based on the bathymetry and modified from the interpretations of Deffontaines et al. (1994), Sibuet et al. (1998) and Tsai et al. (2018). It is noted that the faults contain two main orientations: the NE-SW strike in the northern margin of the Okinawa Trough and the E-W strike around the central depression of the Okinawa Trough back-arc basin. CBVT: Cross Back-arc Volcanic Trail. NMHC: North Mienhua submarine canyon. MHC: Mienhua submarine canyon. KLV: Keelung Valley (submarine canyon). NOT: Northern Okinawa Trough. MOT: Middle Okinawa Trough. SOT: Southern Okinawa Trough. PI: Pengjia volcanic islet. MI: Mienhua volcanic islet. HI: Huaping volcanic islet. MSV: Mienhua submarine volcano. NYRS: North Yilan ridge spur.

extended westwardly its subduction beneath the northern Taiwan and the southernmost Okinawa Trough (Kao et al., 1998; Lallemand et al., 2001; Lin et al., 2004a, 2004b; Wu et al., 2009). In consequence, the southernmost Ryukyu Arc has migrated southward intensively (Hsu, 2001; Chen et al., 2018), and the rifting of the southernmost Okinawa Trough back-arc basin is very active with hydrothermal activities and numerous earthquakes (Matsumoto et al., 2001; Okino et al., 2002; Lin et al., 2007a, 2007b, 2009, 2019). The Yonaguni Graben is the westernmost depression of the Okinawa Trough back-arc basin and is bounded by roughly E-W trending normal faults (Fig. 1). The Yonaguni Graben is cut across obliquely by the NE-SW trending Cross-Back-arc-Volcanic-Trail (CBVT) (Sibuet et al., 1998). To the west of the CBVT, several submarine volcanoes emitting intensive gas plumes out of seafloor are distributed along the depression (Lee and Chung, 1998; Tsai, 1999; Lee et al., 2004; Tsai et al., 2019) (Fig. 1). In this study, we use deep-tow sonar data to understand the detailed tectonics and volcanism of the southwestern tip of the Okinawa Trough.

2. High-resolution deep-tow sonar data

The data used for this study was conducted during a 4-year project of “Geological Investigation of Mineral Resource Potential in the Offshore Area of Northeastern Taiwan” from 2016 to 2019 (Chen et al., 2019). The Deep-tow sonar surveys consist of sub-bottom profiler and side-scan sonar and magnetic data. In total, 36 sub-bottom profiler and side-scan sonar are used in in study (Fig. 2). The distance between every two survey lines is about 500 m and the deep-tow fish is generally kept at a distance of about 50 m to the seafloor. In order to stabilize the towed fish, we kept the survey vessel at speed range of 1.5 to 2 knots. Our data was collected from NE to SW in a direction against the strong surface Kuroshio current of northeastward flow. The frequency band of 1.5–6 kHz was used to collect sub-bottom profiler data and 120 kHz side-scan sonar was used simultaneously for each survey line (Fig. 2). In addition, the multi-beam bathymetry data was also collected for integrated interpretation.

The advantage of using the deep-tow sub-bottom profiler data is that we can have a very high-resolution of the seabed structures till about 50 m below the seafloor. The vertical resolution of the seabed structures is about 40 cm which is generally 25 times higher than the resolution from traditional air-gun source seismic profiles. This advantage allows us to clearly mark the active faults that outcrop seafloor and identify the subtle features in the seabed that are related to tectonic faulting, volcanism or hydrothermal activity. Therefore, we can much better understand the active tectonics and volcanism that is occurring in the southernmost Okinawa Trough bark-arc basin.

3. Results and discussion

3.1. *Active faulting in the southernmost Okinawa Trough*

As shown in Fig. 1, previous structural studies already indicate that the quasi-EW trending normal faults in the southern Okinawa Trough

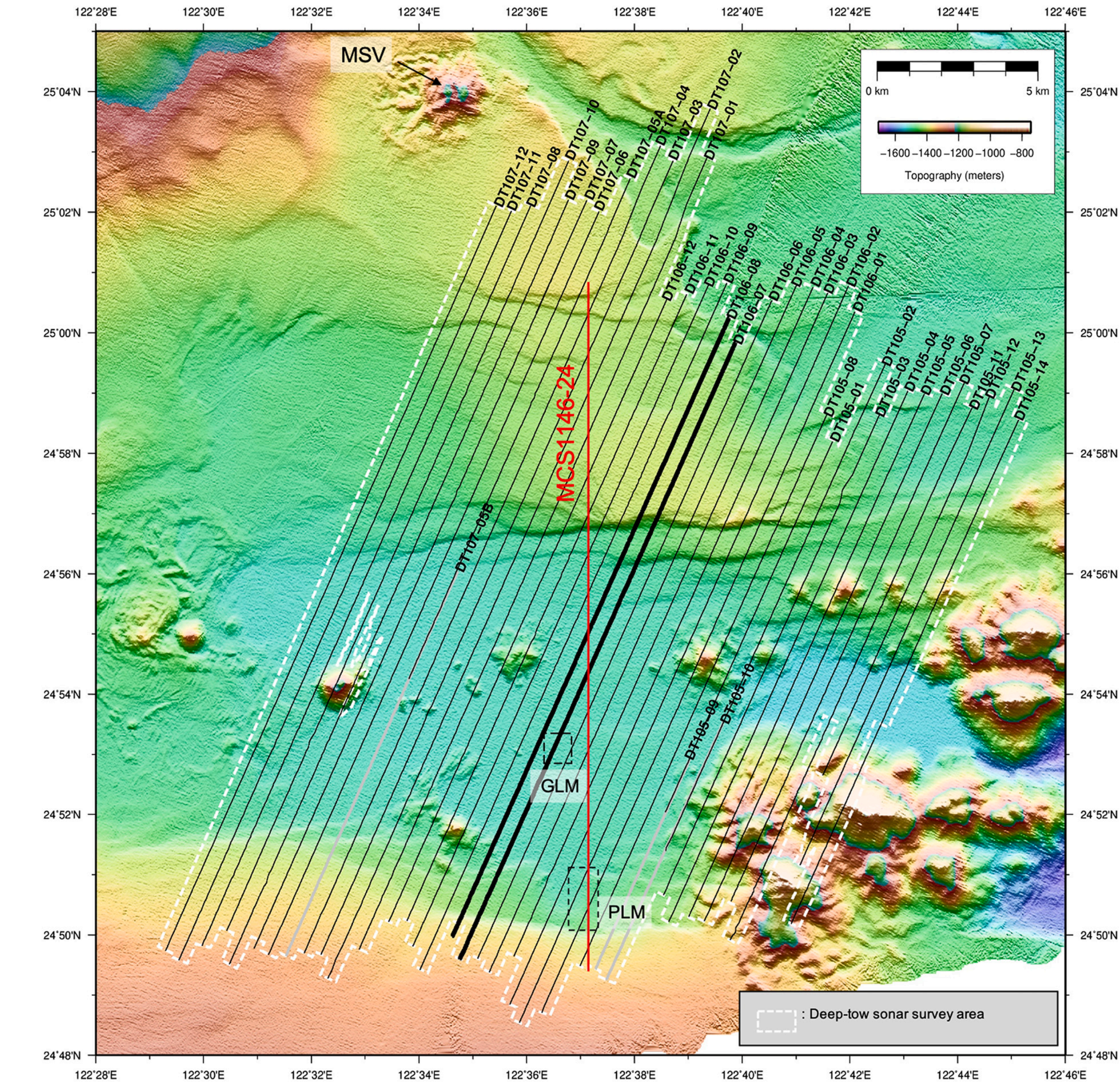

Fig. 2. The ship tracks of our deep-tow sonar surveys, superposed on the multi-beam bathymetry. The distance between every two survey lines is about 500 m. Two heavy lines of sub-bottom profiler are shown in Figs. 3 and 4, respectively. Twelve sections sub-bottom profiler are lined up in Fig. 6. The air-gun seismic reflection profile MCS1146–24 is shown in Fig. 5. GLM: hydrothermal site of the Geolin mounds. PLM: hydrothermal site of the Penglai mounds.

mainly concentrate along the central grabens and terminate in the west near 122° 30′E. To the west or northwest, the faults generally follow the of N*E*-SW orientation. The NE-SW trending faults could have reactivated along the inherited structural trend of the former Taiwan mountain belt (e.g. Sibuet et al., 1998; Tsai et al., 2018). Based on the multi-beam bathymetric data that we collected in the southernmost Okinawa Trough (Fig. 2), the roughly E-W trending features are particularly obvious to the north of the central depression (or graben) of the southernmost Okinawa Trough. These "linear" bathymetric features are active normal fault as evidenced by deep-tow sub-bottom profiler data DT1–06-08 and DT106–07 (Figs. 3 and 4), showing that the faults outcrop the seafloor. Figs. 3 and 4 also show that the northern margin of the Okinawa Trough contains more active normal faults than in the southern margin. In contrast, the back-arc volcanic intrusions are mainly distributed in the middle of the Okinawa Trough or in the southern margin of the basin. Based on air-gun source reflection seismic profile (Fig. 5), the active faults in the southernmost Okinawa Trough can be traced down to about 2 km deep. Profile by profile sub-bottom profiler data show that the crustal faulting in the northern margin exhibits not only the normal faulting component, but also the strike-slip component (Fig. 6). The brittle behavior of the crustal deformation is much clear in the northern margin.

3.2. Active volcanism in the southernmost Okinawa Trough

The most prominent feature of seamount in the southern Okinawa Trough is the CBVT that is obliquely distributed across the central back-arc basin depression (Fig. 1) (Sibuet et al., 1998). The abnormally voluminous seamounts of CBVT might be linked to the subduction of the Gagua Ridge (Sibuet et al., 1998). In contrast, the back-arc volcanism in the southernmost Okinawa Trough is mainly distributed along the central depression of the back-arc basin (Figs. 1, 2 and 5), where seamounts have emerged seafloor several to tens of meters (Fig. 6). Some volcanoes or submarine volcanoes (including the Mienhua submarine

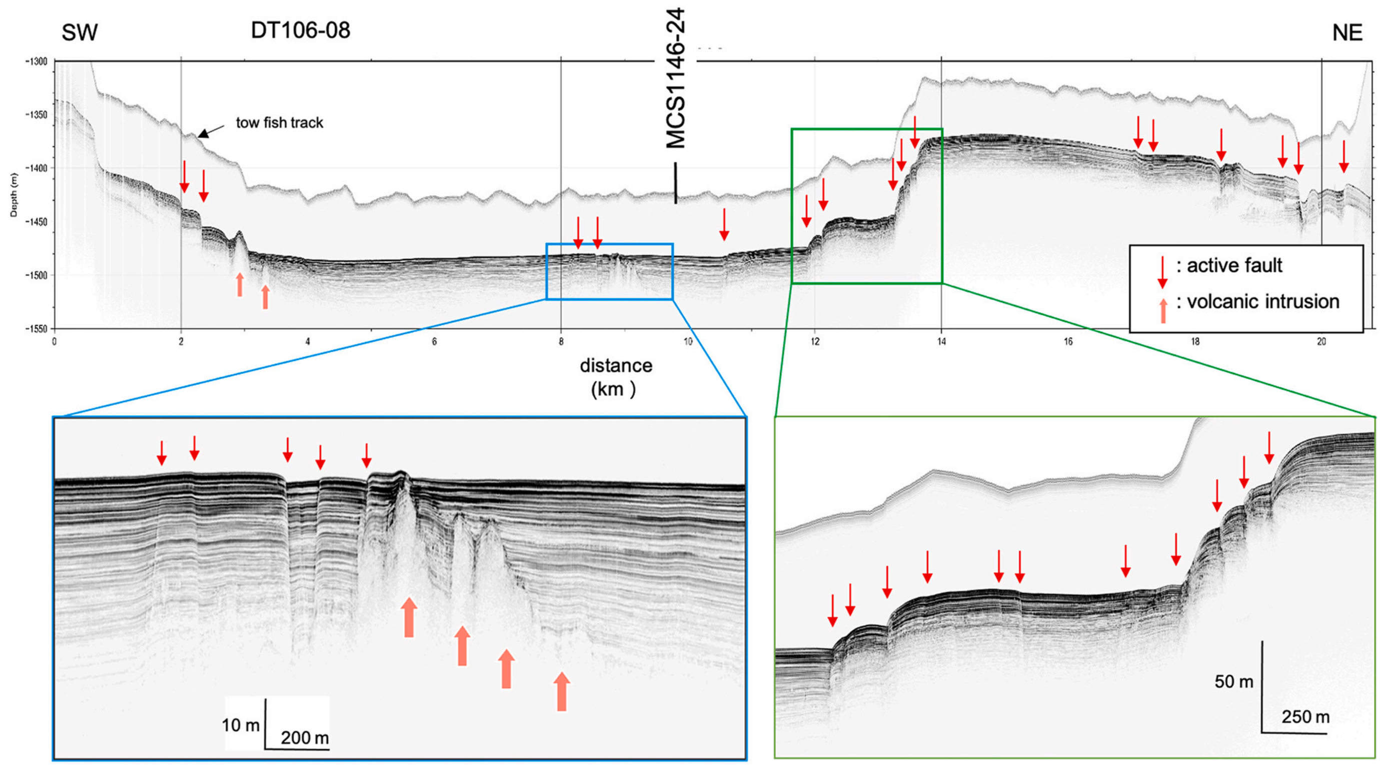

Fig. 3. The section and interpretation of sub-bottom profiler DT106–08. It is noted that the active faults have intensively ruptured the seabed and exposed on the seafloor. Volcanic intrusions have blanked the stratification of the seabed. See profile DT106–08 location in Fig. 2.

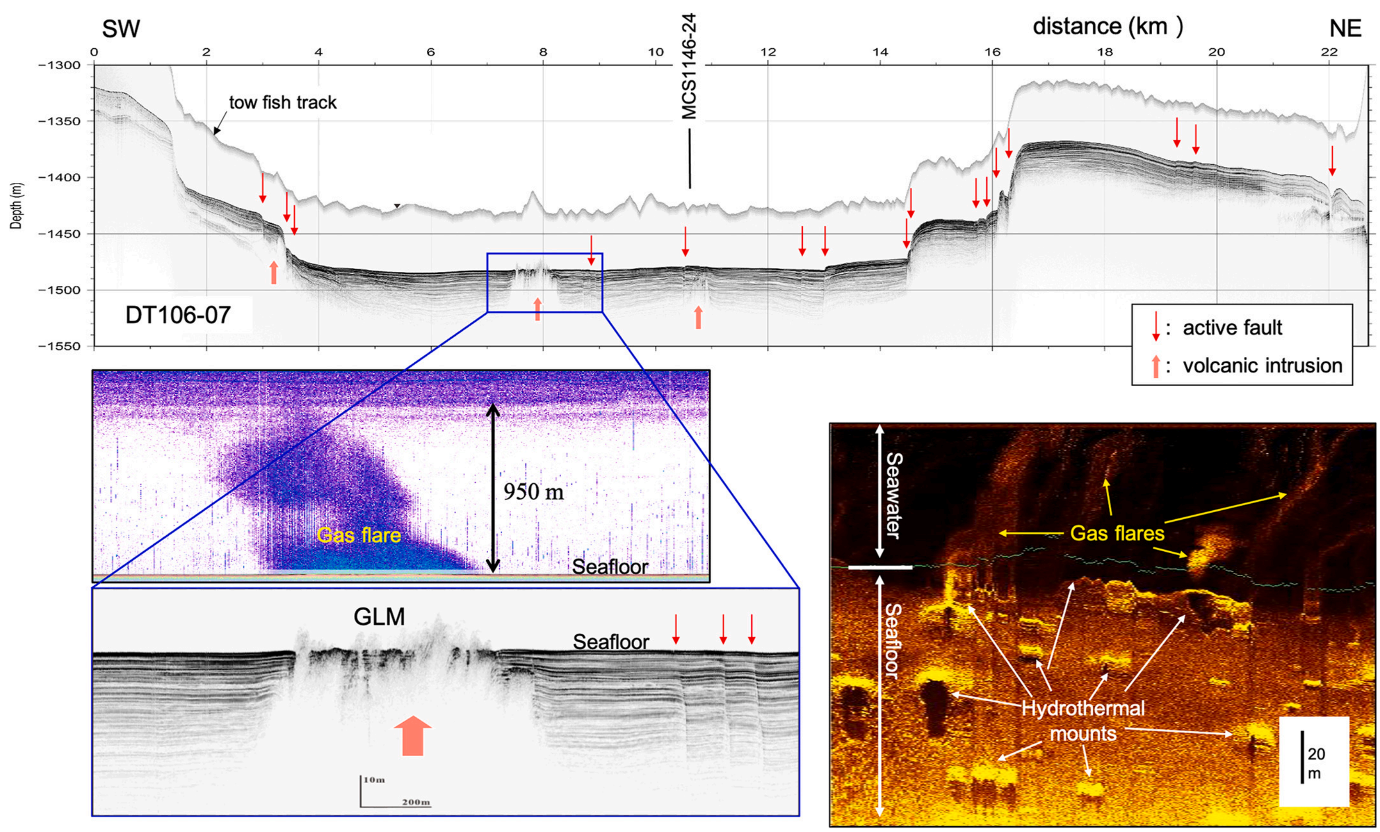

Fig. 4. The section and interpretation of sub-bottom profiler DT106–07. The lower left panel shows the close-up of the section where the hydrothermal site of the Geolin mounds exists. The middle left panel show the gas flare above the Geolin mounds, imaged by the EK38 echo sounder. The lower right panel shows the side-scan sonar image of gas flares and hydrothermal mounds in the western portion of the Geolin mounds. See profile DT106–07 location in Fig. 2.

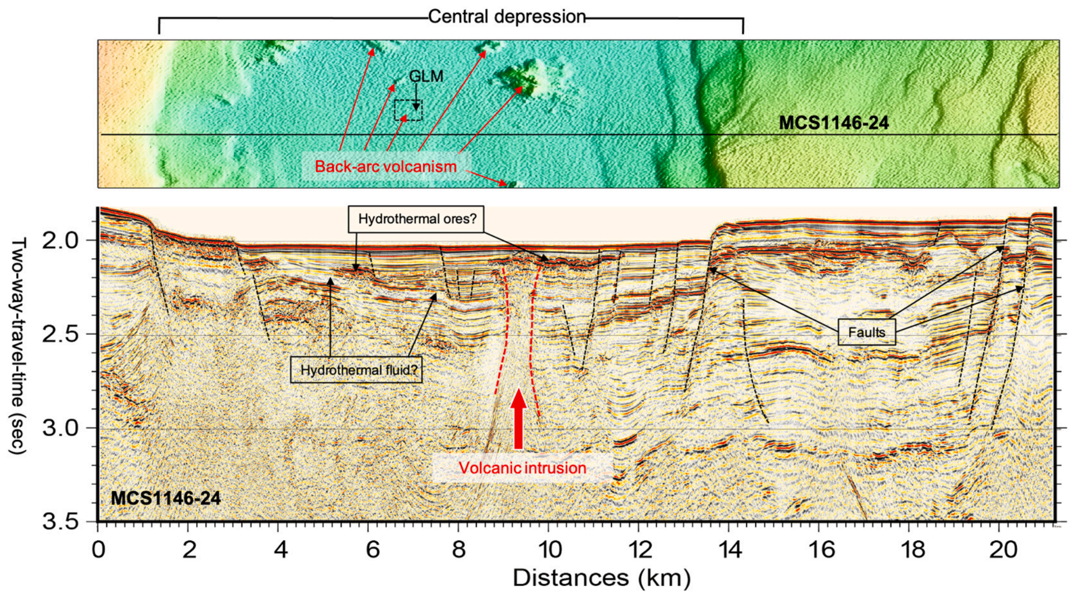

Fig. 5. Multi-channel seismic reflection profile MCS1146–24 and its interpretation. It is noted that the volcanic intrusion is particularly intensive in the middle of the central depression of the back-arc basin. GLM: Geolin mounds.

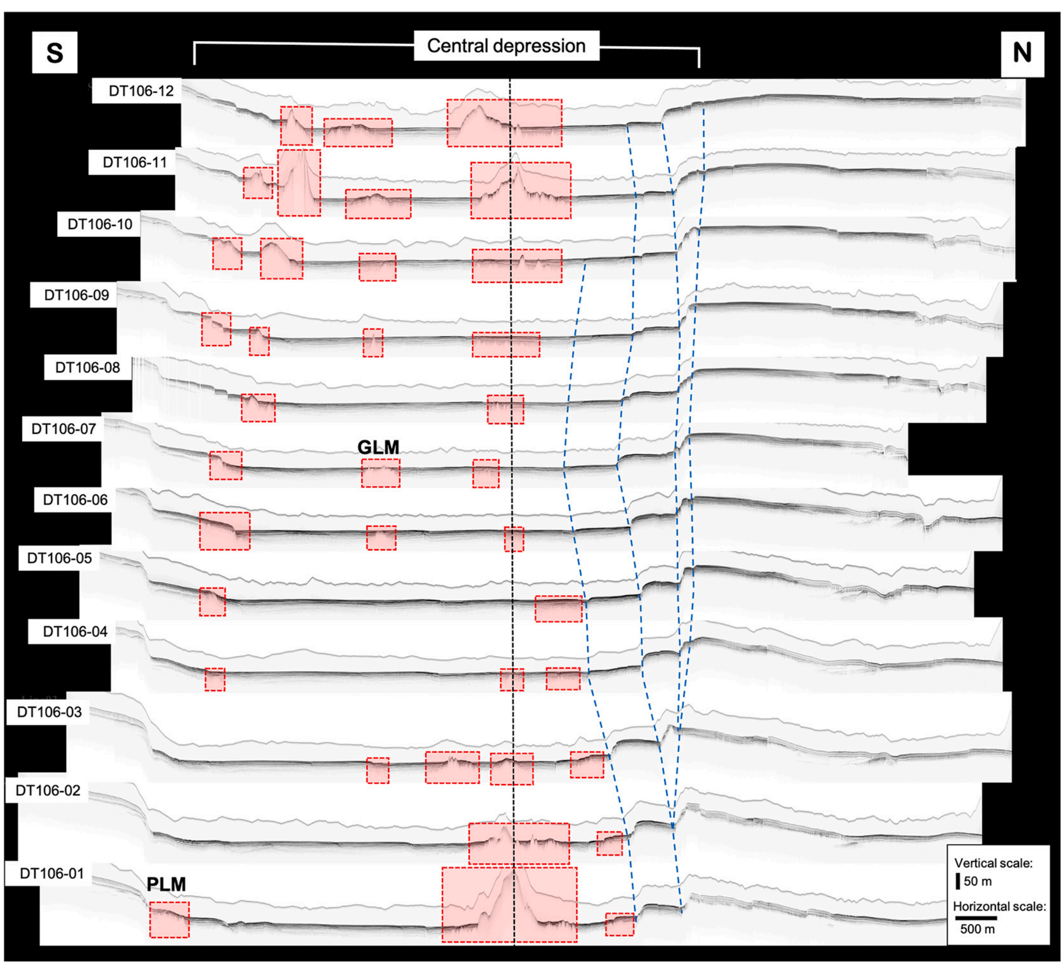

Fig. 6. The sections of sub-bottom profiler from DT106–01 to DT106–12 in the middle of the deep-tow survey area. The red zones indicate the locations of volcanic activities in either volcanic seamounts or volcanic intrusions. The blue dashed lines indicate some major active normal faults that exposed on the seafloor. It is noted that the sizes of volcanism display lateral variation and the volcanism occurs in some linear or branched pattern. The black dashed line indicates the axis of the central depression of the back-arc basin. GLM: Geolin mounds. PLM: Penglai mounds. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

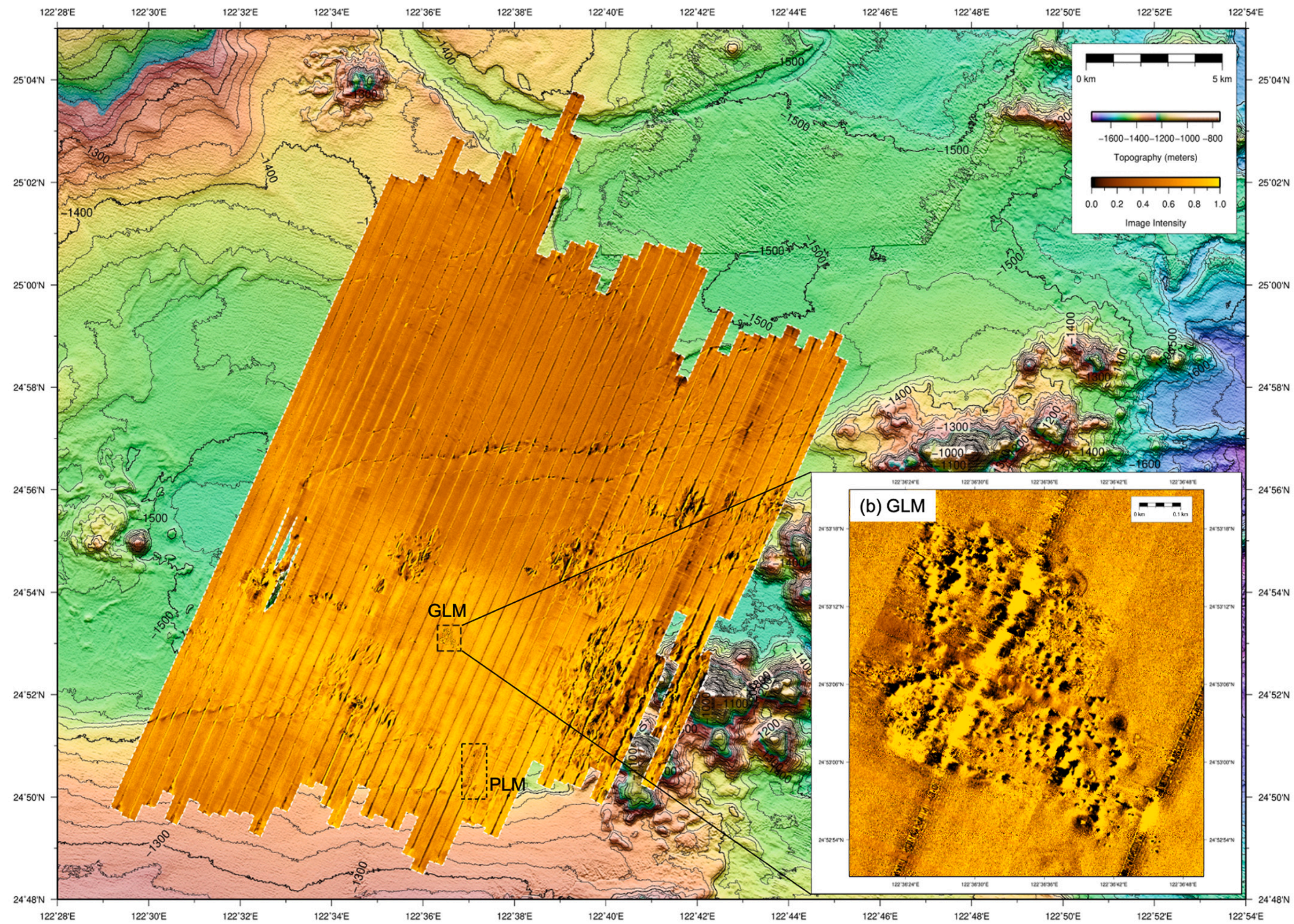

Fig. 7. A mosaic map of the deep-tow side-scan sonar images. The hydrothermal site of the Geolin mounds is enlarged.

volcano, located offshore northeastern Taiwan or in the northern margin of the southernmost Okinawa Trough may be related to the post-collision of early Taiwan orogeny (Figs. 1 and 2) (Wang et al., 1999); they are not considered as the back-arc basin volcanism.

In fact, some submarine mounds less than 10 m are scarcely detected by onboard multi-beam echo sounders; nevertheless, they can be detected by our deep-tow sonar surveys. These small volcanic or hydrothermal mounds are highly related to strong hydrothermal activity, showing vigorous venting of gases out of seafloor. For instance, the Geolin mounds and Penglai mounds are two hydrothermal sites containing numerous small mounds (Hsu, 2017; Tsai et al., 2019) (Figs. 4 and 7). On top of the Geolin or Penglai mounds, the gas flare almost reaches the sea surface (Figs. 2, 4, 6, 7 and 8). The sub-bottom profiler section across the Geolin mounds shows that the seabed has seismic blanking phenomenon beneath the Geolin mounds, indicating that upward gases related to volcanic activity has disturbed the strata at the site of the Geolin mounds (Hsu, 2017; Tsai et al., 2019; Hsu et al., 2019). Furthermore, some volcanic activities have intruded the back-arc basin seabed and disturbed the seabed stratification, but do not emerge from the seafloor (see examples in Figs. 3, 4 or 6). Those features are delicate and can be detected by our deep-tow sub-bottom profilers, but hardly detected by research vessel onboard sonar equipment. Taking into account all the volcanic activities (extrusions and intrusions), the southernmost Okinawa Trough back-arc volcanism is not only distributed along the central depression or the axis of the back-arc basin but also occurs in the southern half of the back-arc basin (Fig. 6). It suggests that the southernmost Ryukyu Arc has migrated southward and the southern half of the southernmost Okinawa Trough basin has also migrated southward. It is coherent with the fast and southward roll-back of the Philippine Sea Plate to the south of the southernmost Ryukyu Arc (Hsu, 2001). However, the back-arc volcanism does not happen everywhere but occur along some linear or branched zones (Figs. 6 and 8). The most obvious one is the volcanism along the central depression of the back-arc basin (Fig. 6). It implies that the volcanism has probably occurred along some existing weak zones of crust that were sheared prior to back-arc basin opening. Secondly, the sizes of volcanism along the central depression seem not equally distributed, as indicated by the emerged seamounts along the central depression do not have same sizes (Fig. 6). The gradual change of the volcanic volumes along the central depression implies that the back-arc basin magmatism may have propagated both perpendicular and parallel to the trough orientation. As mentioned previously, the actively normal faults are mainly distributed in the northern half of the back-arc basin, while the volcanism occurs mainly in the southern half of the back-arc basin. It suggests that the back-arc basin rifting has incurred more brittle deformation in the northern half of the southernmost Okinawa Trough crust and more ductile deformation in the southern half of the crust.

Volcanic gases emitted out of seafloor can be detected by onboard high-frequency echo sounders and seen as gas flares or gas plumes in the sea water column. Tsai et al. (2019) have completely identified all the gas plumes in the southernmost Okinawa Trough by using 38 kHz echo sounder (Fig. 8). As shown in Fig. 8, not all the volcanic activities are accompanied by the gas plumes. It is particularly interesting to see that almost no gas plume exists along the central depression of the back-arc

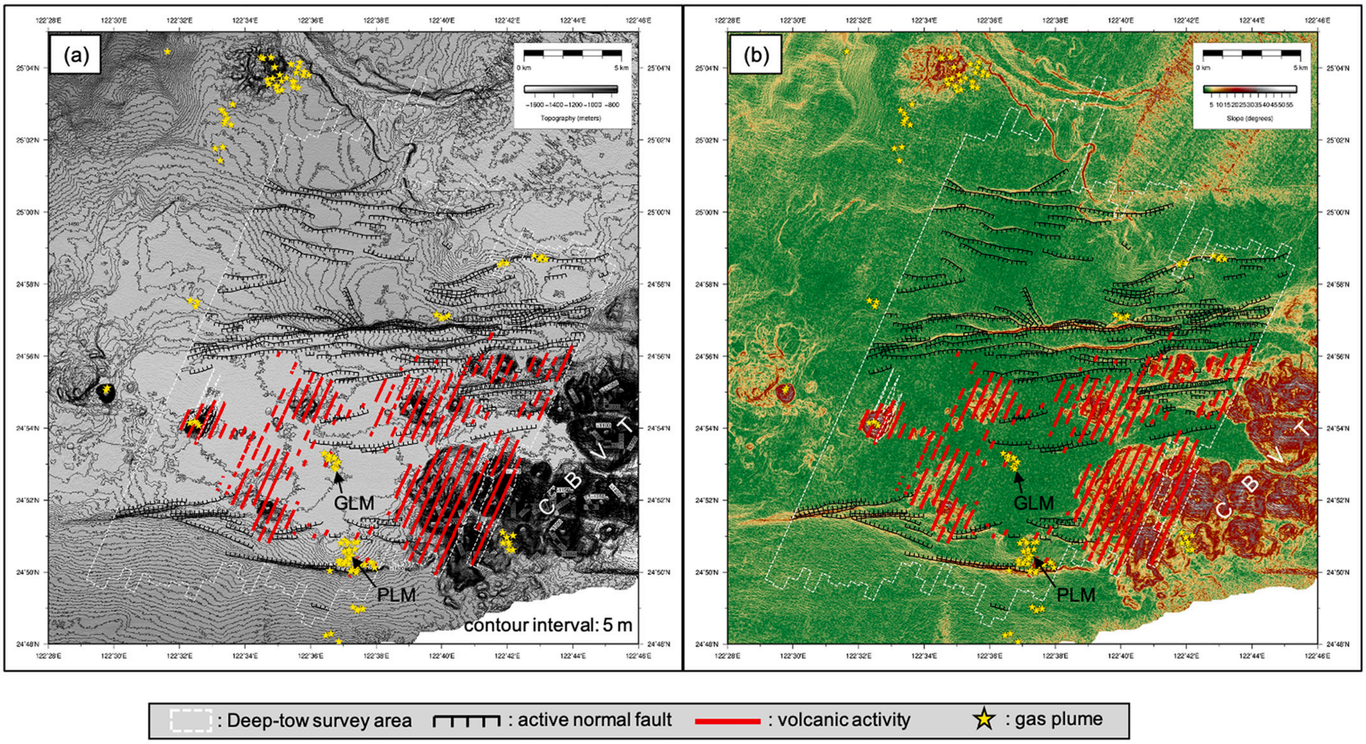

Fig. 8. A synthetic interpretation of the active faults, volcanism, and gas plumes superposed on (a) bathymetry and (b) the slope of the bathymetry. It is remarked that the brittle deformation of crust generally occurs in the northern half of the back-arc basin, while the volcanism is mainly distributed in the southern half of the back-arc basin. The gas plumes appear mainly in hydrothermal sites. GLM: Geolin mounds. PLM: Penglai mounds. CBVT: Cross Back-arc Volcanic Trail.

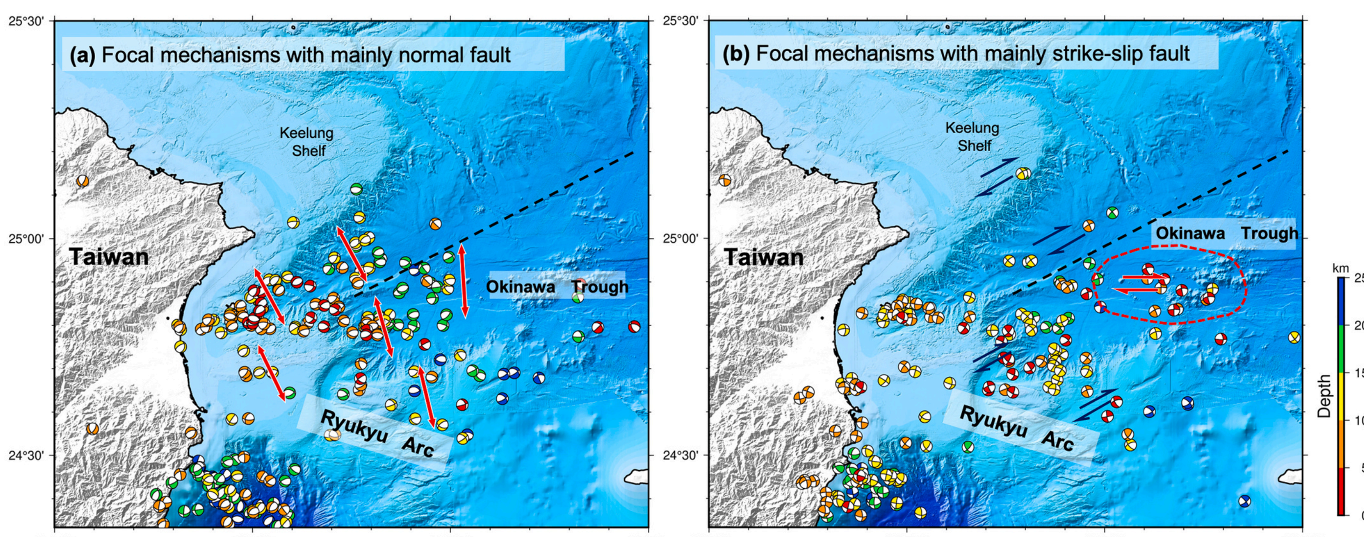

Fig. 9. The distribution and focal mechanism of the crustal earthquakes (shallower than 25 km) with magnitude greater than 3.5. It is noted that our study area is under an extensional regime of normal and with strike-slip components. The crustal extension is generally NW-SE or N-S oriented. The strike-slip faulting is generally right lateral. (Dataset is from BATS of Academic Sinica, from 1963 to 2021 March).

basin, though its volcanic seamounts are prominent (Figs. 6 and 8). Except the gas plume emitting from the top of the seamount located in the western end of our deep-tow survey area, the rest of gas plumes in the southernmost Okinawa Trough back-arc basin occur mainly in the Geolin mounds, Penglai mounds, or at the places where normal faults exist but no seamounts (Fig. 8). However, the volcanic seamounts and intensive gas plumes are present in the southern half of the back-arc basin (Fig. 8).

3.3. Where is the western end of the Okinawa Trough back-arc basin rifting?

The trends of the structural faults off northeast Taiwan or in the southernmost Okinawa Trough mainly show NE-SW or E-W orientations (Fig. 1) (e.g. Deffontaines et al., 1994; Sibuet et al., 1998; Tsai et al., 2018). The NE-SW trending faults are distributed in the northern continental margin of the southern Okinawa Trough, which could be inherited structures formed during the compression in early Taiwan

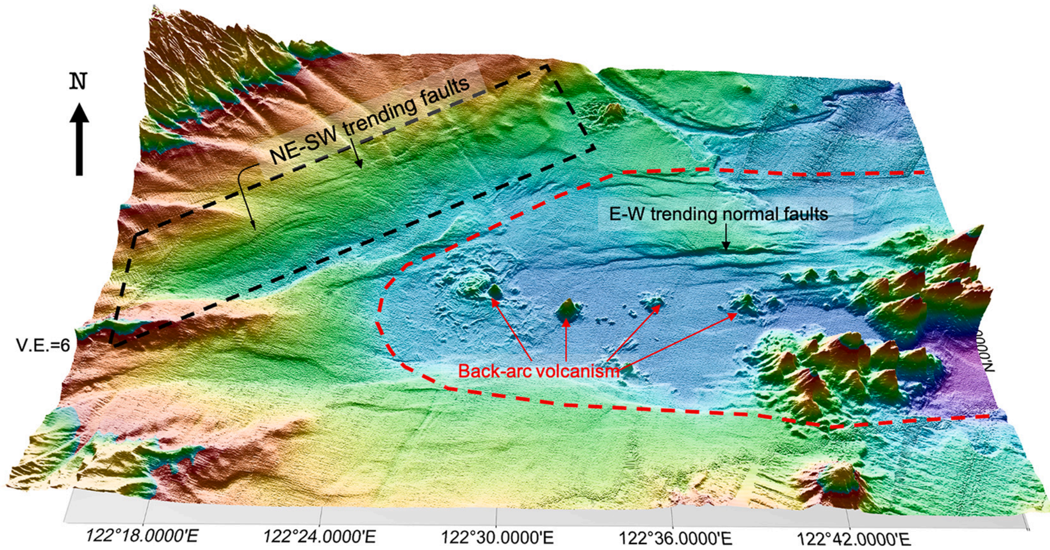

Fig. 10. A 3D view of the southernmost Okinawa Trough. It is noted the existence of NE-SW trending faults in the northern margin of the basin and the E-W trending faults parallel to the central depression of the back-arc basin.

orogen (Sibuet and Hsu, 2004). Now, these structures have inverted from thrusts to normal faults after the collision of the Luzon Arc had passed the area off northeast Taiwan (Sibuet and Hsu, 2004). On the other hand, the roughly E-W trending faults are distributed along the axial zone of the southernmost Okinawa Trough back-arc basin (Figs. 1 and 2).

Sibuet et al. (1998) interpreted that the NE-SW trending faults are associated with the extension of the southernmost Okinawa Trough back-arc basin at the period from 2 to 0.1 Ma, and the E-W trending faults with the back-arc extension after 0.1 Ma. Looking at the focal mechanisms of crustal earthquakes in our study area, we may find the southernmost Okinawa Trough is under an extensional regime and the extensional axis is generally in a direction of NW-SE (Fig. 9a). The NW-SE extension of the southernmost Ryukyu Arc, southernmost Okinawa Trough and the Keelung Shelf could be associated with the northwestward subduction and roll-back of the Philippine Sea Plate (Hsu, 2001; Chen et al., 2018; Lo et al., 2019). However, right lateral strike-slip faulting earthquakes are also frequent in our study area (Fig. 9b). Almost all the strike-slip earthquakes follow the NE-SW orientation which is the same as the generally structural trend in northern Taiwan (Fig. 9b), except the E-W trending strike-slip faulting earthquakes distributed along the axial zone of the southernmost Okinawa Trough back-arc basin (inside the red dashed circle zone in Fig. 9b). Our interpretation is that a more complete and younger rifting (opening) of the Okinawa Trough is limited to the east of ~122°30'E; the back-arc extension to the west of ~122°30'E is influenced by the inherited NE-SW trending structures. Therefore, the NE-SW trending structures are still predominant to the west of ~122°30'E, and the actively volcanic seamounts or hydrothermal activities are distributed to the east of ~122°30'E, especially along the central depression or the southern margin of the southernmost Okinawa Trough back-arc basin (Fig. 10).

4. Conclusion

Our near-seafloor and deep-tow sub-bottom profiler and side-scan sonar data provide a detailed information about the volcanism in the southernmost Okinawa Trough back-arc basin. The volcanism, including volcanic seamounts, volcanic intrusions and hydrothermal activities, is mainly occurring in the southern half of the back-arc basin. However, they are distributed along the central back-arc basin depression or along some linear or branched zones. It indicates that the back-arc volcanism together with the southernmost Ryukyu Arc are migrating southward. Volcanic gases emitting out of seafloor in terms of gas flares or gas plumes are generally associated with structural faults or hydrothermal activities, but seldom with seamounts. A more complete rifting of the southernmost Okinawa Trough back-arc basin is occurring to the east of ~122°30'E, especially along the central depression of the back-arc basin. To the west of ~122°30'E the crust is generally dominated by NE-SW trending structures, which implies that the back-arc extension is still influenced by the inherited NE-SW trending structures of the former Taiwan orogen.

Declaration of Competing Interest

None.

Acknowledgments

This study was supported by the Central Geological Survey (CGS), Ministry of Economic Affairs, Taiwan, and the Ministry of Science and Technology (MOST), Taiwan. We are appreciated the crew of R/V Legend, R/V Ocean Researcher I and R/V Ocean Researcher II for the help of collecting data. We acknowledge the comments from two anonymous reviewers.

References

Chen, H.Y., Ikuta, R., Lin, C.H., Hsu, Y.J., Kohmi, T., Wang, C.C., Ando, M., 2018. Back-arc opening in the western end of the Okinawa Trough revealed from GNSS/acoustic measurements. Geophys. Res. Lett. 45 (1), 137–145.

Chen, S.-C., Lin, J.-Y., Su, C.-C., Doo, W.-B., 2019. Introduction to the special issue on tectonic environment and seabed resources of the southern Okinawa Trough. Terr. Atmos. Ocean. Sci. 30, 605–611.

Chung, S.-L., Wang, S.-L., Shinjo, R., Lee, C.-S., Chen, C.-H., 2000. Initiation of arc magmatism in an embryonic continental rifting zone of the southernmost part of Okinawa Trough. Terra Nova 12, 225–230.

Deffontaines, B., Lee, J.C., Angelier, J., Carvalho, J., Rudant, J.P., 1994. New geomorphic data on the active Taiwan orogen: a multisource approach. J. Geophys. Res. Solid Earth 99 (B10), 20243–20266.

Fabbri, O., Monié, P., Fournier, M., 2004. Transtensional deformation at the junction between the Okinawa trough back-arc basin and the SW Japan island arc. Geol. Soc. Lond. Spec. Publ. 227 (1), 297–312.

Gungor, A., Lee, G.-H., Kim, H.-J., et al., 2012. Structural characteristics of the northern Okinawa Trough and adjacent areas from regional seismic reflection data: geologic and tectonic implications. Tectonophysics 522, 198–207.

Hirata, N., Kinoshita, H., Katao, H., Baba, H., Kaiho, Y., Koresawa, S., Ono, Y., Hayashi, K., 1991. Report on DELP 1988 cruises in the Okinawa Trough: part 3. Crustal structure of the southern Okinawa Trough. Bull. Earthq. Res. Inst., Univ. Tokyo 66, 37–70.

Hsu, S.-K., 2001. Lithospheric structure, buoyancy and coupling across the southernmost Ryukyu subduction zone: an example of decreasing plate coupling. Earth Planet. Sci. Lett. 186 (3–4), 471–478.

Hsu, S.-K., 2017. Geological Investigation of Mineral Resource Potential in the Offshore Northeastern Taiwan: High Resolution Sonar and Magneic Surveys (2/4). Report of Central Geological Survey, 106–13. (in Chi- nese with English abstract).

Hsu, S.-K., Sibuet, J.C., Monti, S., Shyu, C.-T., Liu, C.-S., 1996. Transition between the Okinawa trough backarc extension and the Taiwan collision: New insights on the southernmost Ryukyu subduction zone. Mar. Geophys. Res. 18, 163–187.

Hsu, S.-K., Yeh, Y.-C., Sibuet, J.-C., Doo, W.-B., Tsai, C.-H., 2013. A mega-splay fault system and tsunami hazard in the southern Ryukyu subduction zone. Earth Planet. Sci. Lett. 362, 99–107.

Hsu, H.-H., Lin, L.-F., Liu, C.-S., Chang, J.-H., Liao, W.-Z., Chen, T.-T., Chao, K.-H., Lin, S.-L., Hsieh, H.-S., Chen, S.-C., 2019. Pseudo-3D seismic imaging of Geolin mounds hydrothermal field in the Southern Okinawa Trough offshore NE Taiwan. Terr. Atmos. Ocean. Sci. 30, 705–716.

Kao, H., Shen, S.S.J., Ma, K.F., 1998. Transition from oblique subduction to collision: Earthquakes in the southernmost Ryukyu arc-Taiwan region. J. Geophys. Res. Solid Earth 103 (B4), 7211–7229.

Kimura, M., 1985. Back-arc rifting in the Okinawa Trough. Mar. Pet. Geol. 2 (3), 222–240.

Kodaira, S., Iwasaki, T., Urabe, T., Kanazawa, T., Egloff, F., Makris, J., Shimamura, H., 1996. Crustal structure across the middle Ryukyu trench obtained from ocean bottom seismographic data. Tectonophysics 263 (1-4), 39–60.

Lallemand, S., Font, Y., Bijwaard, H., Kao, H., 2001. New insights on 3-D plates interaction near Taiwan from tomography and tectonic implications. Tectonophysics 335 (3–4), 229–253.

Lee, C.-S., Chung, S.-L., 1998. Southernmost part of the Okinawa Trough (SPOT): An active extension/ collision/ subduction area. EOS Trans. Am. Geophys. Union 79 (W109).

Lee, C.-S., Shor, G.-G., Bibee, L.-D., Lu, R.-S., Hilde, T., 1980. Okinawa Trough: Origin of a back-arc basin. Mar. Geol. 35, 219–241.

Lee, Y., Tsai, C., Lee, C., 2004. The study of active submarine volcanoes and hydrothermal vents in the southernmost part of Okinawa Trough. In: American Geophysical Union, Fall Meeting 2004, abstract id. S41A-0939.

Letouzey, J., Kimura, M., 1986. The Okinawa Trough: genesis of a back-arc basin developing along a continental margin. Tectonophysics 125 (1–3), 209–230.

Lin, J.-Y., Hsu, S.-K., Sibuet, J.-C., 2004a. Melting features along the Ryukyu slab tear, beneath the southwestern Okinawa Trough. Geophys. Res. Lett. 31, L19607 https://doi.org/10.1029/2004GL020862.

Lin, J.-Y., Hsu, S.-K., Sibuet, J.-C., 2004b. Melting features along the western Ryukyu slab edge (Northeast Taiwan): Tomographic evidence. J. Geophys. Res. 109, B12402 https://doi.org/10.1029/2004JB003260.

Lin, C.-H., Hsu, L.-W., Ho, M.-Y., Shin, T.-C., Chen, K.-J., Yeh, Y.-H., 2007a. Low-frequency submarine volcanic swarms at the southwestern end of the Okinawa Trough. Geophys. Res. Lett. 34 (6).

Lin, J.-Y., Sibuet, J.-C., Lee, C.-S., Hsu, S.-K., Klingelhoefer, F., 2007b. Origin of the southern Okinawa Trough volcanism from detailed seismic tomography. J. Geophys. Res. 112 (B8).

Lin, J.Y., Sibuet, J.C., Lee, C.S., Hsu, S.K., Klingelhoefer, F., Auffret, Y., Lin, C.H., 2009. Microseismicity and faulting in the southwestern Okinawa Trough. Tectonophysics 466 (3–4), 268–280.

Lin, J.-Y., Wu, W.-N., Su, C.-C., Tsai, C.-H., Sun, H.-H., Chen, Y.-F., Chin, S.-J., Lin, Y.-C., 2019. Spatial and temporal distribution of low frequency volcanic earthquakes in the southern Okinawa Trough backarc basin. Terr. Atmos. Ocean. Sci. 30, 621–631.

Lo, C.-L., Wu, W.-N., Doo, W.-B., Huang, Y.-S., Hsu, S.-K., 2019. Crustal stress field in Ilan Plain, NE Taiwan and the westernmost Okinawa trough-deduced from seismic stress inversion. Terr. Atmos. Ocean. Sci. 30, 613–619.

Matsumoto, T., Kinoshita, M., Knakamura, M., Sibuet, J.-C., Lee, C.-S., Hsu, S.-K., Oomori, T., Shinjo, R., Hashimoto, Y., Hosoya, S., Imamura, M., Ito, M., Tukuda, K., Yagi, H., Tatekawa, K., Kagaya, I., Hokakubo, S., Okada, T., Kimura, M., 2001. Volcanic and hydrothermal activities and possible "segmentation" of the axial rifting in the westernmost part of the Okinawa Trough –preliminary results from the YOKOSUKA/SHINAK6500 Lequios cruise. JAMSTEC J. Deep Sea Res. 19, 96–107.

Miki, M., 1995. Two-phase opening model for the Okinawa Trough inferred from paleomagnetic study of the Ryukyu arc. J. Geophys. Res. 100, 8169–8184.

Miyazaki, J., Kawagucci, S., Makabe, A., Takahashi, A., Kitada, K., Torimoto, J., Chen, C., 2017. Deepest and hottest hydrothermal activity in the Okinawa Trough: the Yokosuka site at Yaeyama Knoll. R. Soc. Open Sci. 4 (12), 171570.

Okino, K., Tokuyama, H., Hotwater Scientific Party, 2002. Deep-tow sonar "WADATSUMI" survey in the Okinawa Trough. InterRidge News 11 (2), 36–39.

Park, J.O., Tokuyama, H., Shinohara, M., Suyehiro, K., Taira, A., 1998. Seismic record of tectonic evolution and backarc rifting in the southern Ryukyu island arc system. Tectonophysics 294, 21–42.

Shinjo, R., Kato, Y., 2000. Geochemical constraints on the origin of bimodal magmatism at the Okinawa Trough, an incipient back-arc basin. Lithos 54, 117–137.

Shinjo, R., Chung, S.-L., Kato, Y., Kimura, M., 1999. Geochemical and Sr-Nd isotopic characteristics of volcanic rocks from the Okinawa Trough and Ryukyu Arc: implications for the evolution of a young, intracontinental back arc basin. J. Geophys. Res. Sol. EA. 104, 10591–10608.

Sibuet, J.C., Hsu, S.-K., 2004. How was Taiwan created? Tectonophysics 379, 159–181.

Sibuet, J.C., Letouzey, J., Barrier, F., Charvet, J., Foucher, J.P., Hilde, T.W.C., Kimura, M., Chiao, L.-Y., Marsset, B., Muller, C., Stephan, J.F., 1987. Back arc extention in the Okinawa trough. J. Geophys. Res. 92, 14041–14063.

Sibuet, J.C., Hsu, S.-K., Shyu, C.-T., Liu, C.-S., 1995. Structural and kinematic evolutions of the Okinawa Trough backarc basin. In: Taylor, B. (Ed.), Backarc Basins: Tectonics and Magmatism. Plenum, New York, pp. 343–379.

Sibuet, J.C., Deffontaines, B., Hsu, S.-K., Thareau, N., LeFormal, J.P., Liu, C.-H., Party, A., 1998. Okinawa Trough backarc basin: early tectonic and magmatic evolution. J. Geophys. Res. Sol. EA. 103, 30245–30267.

Tsai, C.-H., 1999. Submarine Volcanoes and Hydrothermal Circulation in the Southernmost Part of Okinawa Trough: An Initial Study. Master Thesis. National Taiwan Ocean University, Keelung City, Taiwan, 92 pp. (in Chinese with English abstract).

Tsai, C.-H., Huang, C.-L., Hsu, S.-K., Doo, W.-B., Lin, S.-S., Wang, S.-Y., Lin, J.-Y., Liang, C.-W., 2018. Active normal faults and submarine landslides in the Keelung Shelf off NE Taiwan. Terr. Atmos. Ocean. Sci. 29, 31–38.

Tsai, C.-H., Hsu, S.-K., Chen, Y.-F., Lin, H.-S., Wang, S.-Y., Chen, S.-C., Liang, C.-W., Cho, Y.-Y., 2019. Gas plumes and near-seafloor bottom current speeds of the southernmost Okinawa Trough determined from echo sounders. Terr. Atmos. Ocean. Sci. 30, 649–674.

Wang, K.-L., Chung, S.-L., Chen, C.-H., Shinjo, R., Yang, T.-F., Chen, C.-H., 1999. Post-collisional magmatism around northern Taiwan and its relation with opening of the Okinawa Trough. Tectonophysics 308, 363–376.

Wu, Y.M., Shyu, J.B.H., Chang, C.H., Zhao, L., Nakamura, M., Hsu, S.-K., 2009. Improved seismic tomography offshore northeastern Taiwan: Implications for subduction and collision processes between Taiwan and the southernmost Ryukyu. Geophys. J. Int. 178, 1042–1054.