

New bathymetry and magnetic lineations identifications in the northernmost South China Sea and their tectonic implications

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Abstract

The seafloor spreading of the South China Sea (SCS) was previously believed to take place between ca. 32 and 15 Ma (magnetic anomaly C11 to C5c). New magnetic data acquired in the northernmost SCS however suggests the existence of E–W trending magnetic polarity reversal patterns. Magnetic modeling demonstrates that the oldest SCS oceanic crust could be Late Eocene (as old as 37 Ma, magnetic anomaly C17), with a half-spreading rate of 44 mm/yr. The new identified continent–ocean boundary (COB) in the northern SCS generally follows the base of the continental slope. The COB is also marked by the presence of a relatively low magnetization zone, corresponding to the thinned portion of the continental crust. We suggest that the northern extension of the SCS oceanic crust is terminated by an inactive NW–SE trending trench–trench transform fault, called the Luzon–Ryukyu Transform Plate Boundary (LRTPB). The LRTPB is suggested to be a left-lateral transform fault connecting the former southeast-dipping Manila Trench in the south and the northwest-dipping Ryukyu Trench in the north. The existence of the LRTPB is demonstrated by the different patterns of the magnetic anomalies as well as the different seafloor morphology and basement relief on both sides of the LRTPB. Particularly, the northwestern portion of the LRTPB is marked by a steep northeast-dipping escarpment, along which the Formosa Canyon has developed. The LRTPB probably became inactive at ca. 20 Ma while the former Manila Trench prolonged northeastwards and connected to the former Ryukyu Trench by another transform fault. This reorganization of the plate boundaries might cause the southwestern portion of the former Ryukyu Trench to become extinct and a piece of the Philippine Sea Plate was therefore trapped amongst the LRTPB, the Manila Trench and the continental margin.

Introduction

The South China Sea (SCS) is a wedge-shaped marginal sea, whose oceanic crust is largely distributed in the eastern half of the basin and diminishes toward the southwest (Figures 1 and 2). The formation of the SCS oceanic crust was suggested to be linked to pull-apart basins by left-lateral strike-slip faulting associated with the India-Asia collision (Tapponnier et al., 1982, 1986), a proto-SCS subduction beneath Palawan and northern Borneo (Taylor and Hayes, 1980, 1983; Lee and Lawver, 1995; Hall, 1996; Rangin et al., 1999) or a combination of above two mechanisms (Morley, 2002). Whatever model is preferred, the understanding of the formation age and the distribution of the SCS oceanic crust can provide crucial information on the tectonic evolution of the SCS.

The magnetic lineations in the SCS basin were first recognized by Ben-Avraham and Uyeda (1973). The ages of the SCS oceanic crust have later been identified between 32 and 15 Ma (i.e. magnetic anomaly C11–C5c) by using marine magnetic reversal timescales (Taylor and Hayes, 1980; Hayes and Taylor, 1983; Briais et al., 1993). As shown in Figure 2, the SCS oceanic crust is generally outlined by relatively low gravity anomalies. The mid-ocean ridge of the southwestern basin is also revealed by a relatively low gravity anomaly zone (Figure 2). Relative to the continent–ocean boundary (COB) defined by Briais et al. (1993), the SCS oceanic crust probably extends southwestwards to about 109° E and 8° N, where a N–S trending shear zone probably exists (Figure 2) (Nissen et al., 1995). The COB defined by Briais et al. (1993) is generally between the bathymetric depths of 2500 and 3000 m,

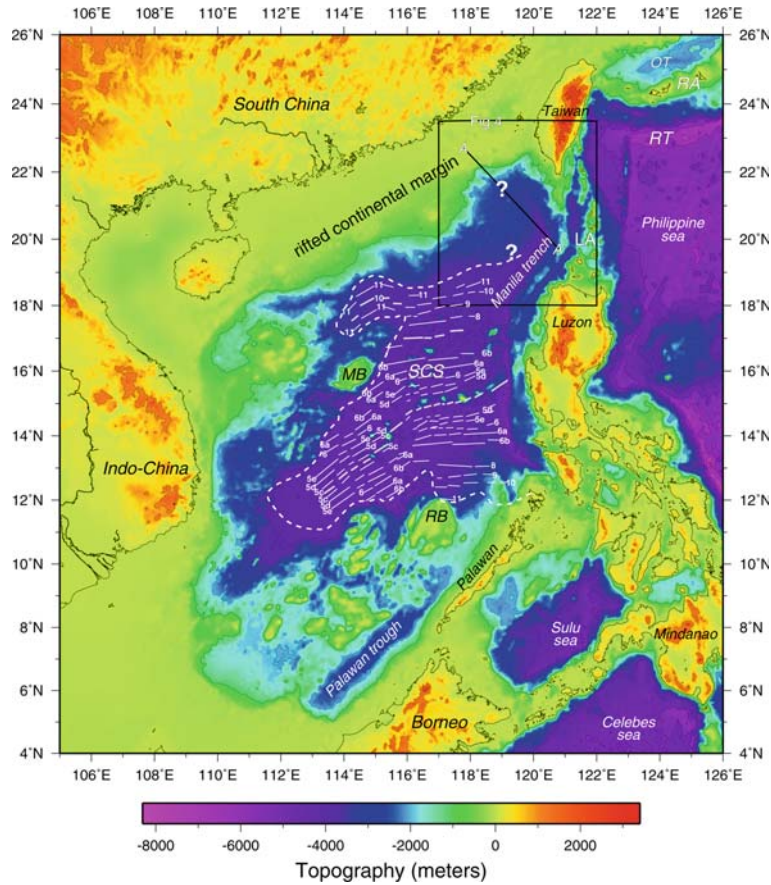


Figure 1. General topography of the South China Sea (SCS) and the contiguous marginal seas. The magnetic lineations identified by Briais et al (1993) are superposed on the bathymetry. Line AA' indicates a possible transform fault in the northernmost SCS. LA: Luzon Arc; MB: Macclesfield Bank; OT: Okinawa Trough; RA: Ryukyu Arc; RB: Reed Bank; RT: Ryukyu Trench.

except that the northern segment is much deeper and terminates at the Manila Trench (Figure 1). Recently, we have acquired new magnetic data in the northernmost SCS, beyond the oldest oceanic crust identified by Briais et al. (1993), that shows clearly the existence of E–W trending magnetic lineations (Figures 3 and 4). Our observation indicates that the real oldest SCS oceanic crust could exist further north than that suggested by Briais et al. (1993).

Based on the gravity signature and the characteristics of rifted basins in the East Asian margin, Hsu and Sibuet (1995) and Sibuet and Hsu (1997) have proposed that prior to the Taiwan mountain building, the Ryukyu subduction system could have extended southwestwards of the present-day Taiwan location (Figure 2). In that

hypothesis, the southwestern end of the former Ryukyu Trench had to be terminated by a transform fault plate boundary in the northernmost SCS or off southwest Taiwan, if the plates involved are rigid. A plausible location of the old transform fault is suggested by the line AA' in Figures 1 and 2. Accordingly, the tectonics of the northernmost SCS involves not only the early formation of the SCS oceanic crust but also the configuration of the former Ryukyu subduction system. The latter is de facto linked to the possible mechanisms of the Taiwan orogeny. In this study, we will identify the age of the oldest oceanic crust of the SCS basin by interpreting the magnetic anomalies lineations. We will also discuss the tectonic features of the northernmost corner of the SCS.

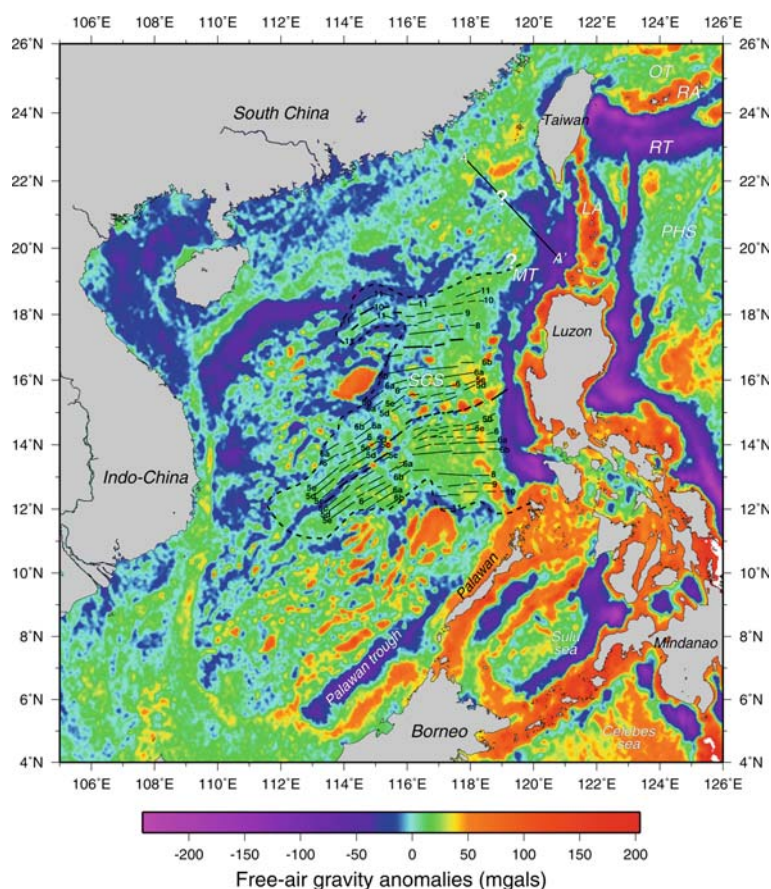


Figure 2. Satellite-derived marine free-air gravity anomalies of the South China Sea (SCS) and adjacent areas (Sandwell and Smith, 1997). The location of a possible transform fault is indicated by line AA'. LA: Luzon Arc; MT: Manila Trench; OT: Okinawa Trough; PHS: Philippine Sea; RA: Ryukyu Arc; RT: Ryukyu Trench.

Morphology of the northernmost SCS

The northernmost SCS abuts the southeastern Asian continental margin and is contiguous to the Taiwan orogen in the northeast (Figure 1). The morphology of the northernmost SCS is mainly characterized by the presence of the Formosa Canyon and the northern end of the Manila Trench (Figure 5) (Liu et al., 1998; Yu and Chang, 2002), along which the lithosphere of the SCS subducts eastwards beneath the Luzon island arc (Figure 1). The northern tip of the present-day Manila Trench extends northwards until north latitude $21^{\circ} 15'$. Further north, its trace becomes unclear and gradually connects with the deformation front in the west of the Taiwan mountain belt. Because of the northwestward convergence of the Luzon Arc,

the accretionary prism in terms of the thrust-and-fold structures is prominent off southern Taiwan (Liu et al., 1997). The thrust-and-fold structures are generally trending NWN and are bounded in the west by the deformation front, marked by the presence of the Penghu Canyon (Figure 5).

New bathymetric map

To better understand the morphotectonics of the junction area among the northernmost SCS, the rifted Southeast Asian continental margin and the Taiwan collision zone, we have collected new multi-beam bathymetric data in the northernmost SCS. Together with the multi-beam bathymetric data collected near Taiwan during the ACT cruise (Lallemant et al., 1997), we have compiled

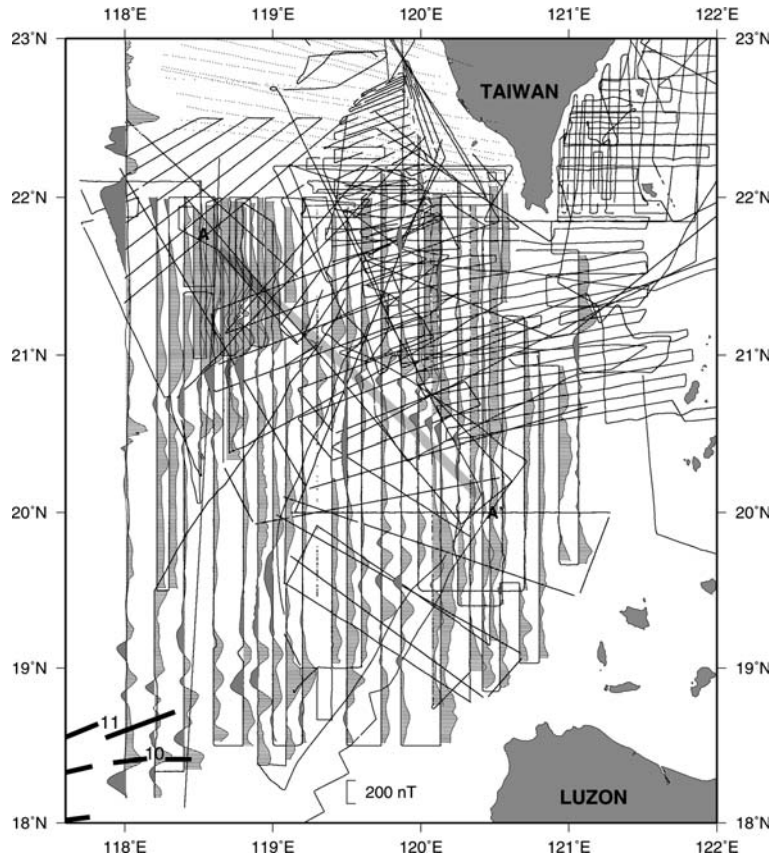


Figure 3. The track lines of magnetic data used for the compilation in the study area. Most of the N–S trending data are newly collected in northern SCS and are projected to $N270^\circ$. The shaded areas indicate positive magnetic anomalies, while the slash areas indicate negative magnetic anomalies. The magnetic lineations C11–C9 identified by Briais et al. (1993) are plotted for comparison. AA' indicates the location of a possible old transform fault.

a new bathymetric map of the northernmost SCS and off southwest Taiwan (Figure 5). The new bathymetric map particularly shows a clear image of the whole Formosa Canyon (Figure 5).

The Formosa Canyon is developed across the continental slope (Figure 5). The head of the Formosa Canyon is composed of a main channel trending NWW–SEE oblique to the gravity-slide direction of the continental slope and several gravity-slide-controlled gullies (Figures 5 and 6a). These multi-bifurcations merge into one single channel at the base of the continental slope, and then the channel flows southeastward along a linear escarpment (Figures 5 and 6b). The Formosa Canyon changes its course near $119^\circ 10' E$ and $21^\circ 20' N$ from NW–SE to E–W direction and finally joins the Manila Trench. Formed at a magnetic reversal epoch, a seamount raising over one thousand meters above the seafloor stands

just to the south where the Formosa Canyon changes its course (cf. Figures 4, 5 and 6c). Taking bathymetric cross-sections across the Formosa Canyon (Figures 5 and 7), we can observe that the E–W trending segment of the Formosa Canyon displays a V-shaped canyon (Figure 7d). The E–W trending segment of the Formosa Canyon may distinguish the continental slope from the deep ocean basin (Figure 5). An obvious phenomenon is that the physiographic features near the base of the continental slope generally trending NE–SW direction, reflecting the sedimentary processes due to gravity sliding (Figure 5). Whereas, to the south of the E–W trending segment of the Formosa Canyon the seafloor morphology are generally oriented N–S. In contrast, the western part of the Formosa Canyon trending NW–SE follows the northern flank of a linear escarpment, whose vertical offset

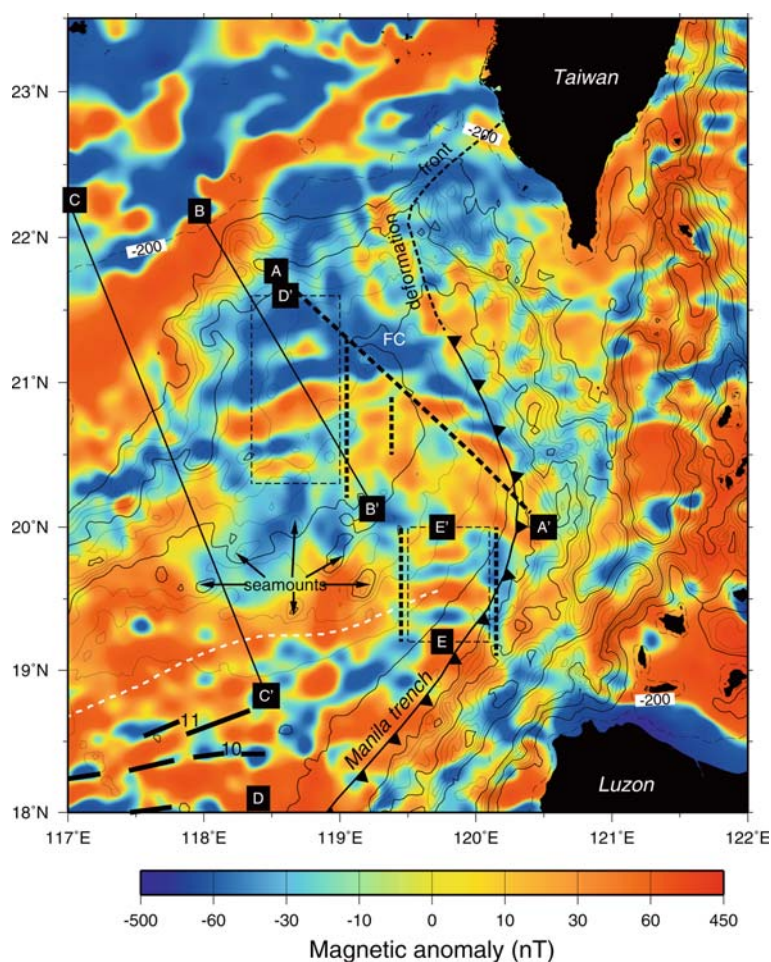


Figure 4. New compiled magnetic map in the northernmost SCS and the area between Taiwan and Luzon islands. The location of a possible old transform fault is indicated by line AA'. The dashed boxes indicate the presence of magnetic polarity reversals in the study area. Heavy dashed lines indicate the locations of fracture zones. The magnetic lineations C11–C9 identified by Briais et al. (1993) are plotted for comparison. White dashed line indicates the COB suggested by Briais et al. (1993).

can attain 400 m (profiles AA' and BB' in Figures 5, 7 and 6b). However, no recent plate tectonic events occur along the Formosa Canyon. The linear escarpment has been formed by strong erosion along the channel and the sedimentary deposits on either side of the channel have displayed differential subsidence (Yeh and Hsu, 2004, this volume).

In Figure 5, we have identified a new submarine canyon named Dongsha Canyon. The Dongsha Canyon, like the Formosa Canyon, is developed across the continental slope and flows eastwards. At its eastern end, it curves around the previously mentioned seamount, then joins the Formosa Canyon (Figures 5 and 6c). In summary, the canyon system in the northernmost

SCS and off southwest Taiwan is mainly composed of the Kaoping Canyon, the Penghu Canyon, the Formosa Canyon and the Dongsha Canyon (Figure 5). These canyons finally converge into the Manila Trench.

Magnetic anomalies

New magnetic map

Off southwest Taiwan, the magnetic map of Hsu et al. (1998) has shown the ENE-WSW trending lineations. The existence of these magnetic lineations could be the results of magnetic polarity reversals, revealing the nature of the

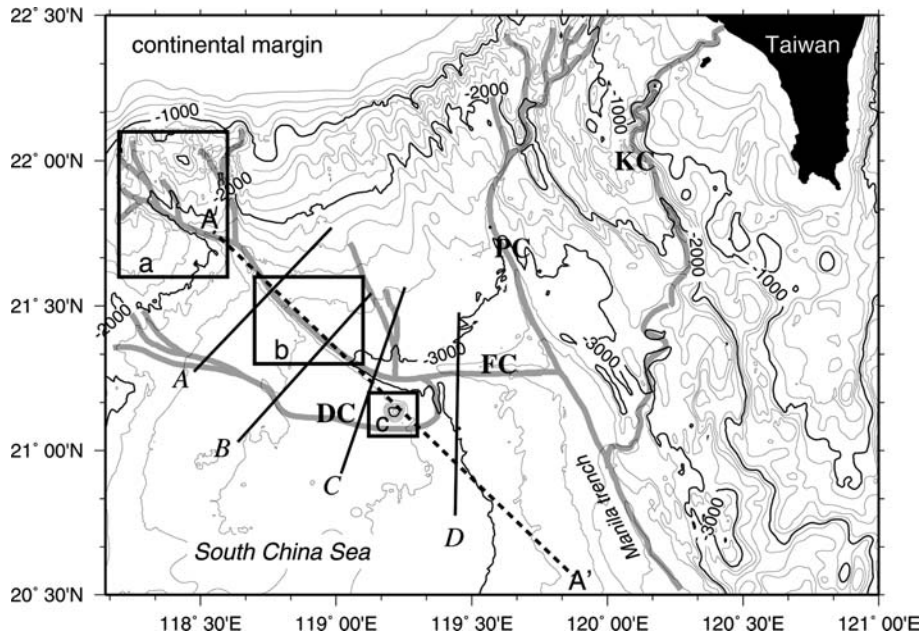


Figure 5. New bathymetric map in the northernmost SCS and off southwest Taiwan. Three 3D views are shown in Figure 6. Bathymetric profiles A, B, C and D are shown in Figure 7. FC: Formosa Canyon; KC: Kaoping Canyon; PC: Penghu Canyon; DC: Dongs Canyon.

oceanic crust, or could be simply caused by problems of the compiled magnetic data rather than real lineations. To replenish the magnetic data in the northernmost SCS and off southwest Taiwan, we have conducted several N–S trending magnetic surveys (Figure 3). By adjusting the ship track crossover errors (Hsu, 1995), we have compiled the newly acquired and the old magnetic data based on the datum level of the ACT cruise data (Hsu et al., 1998). Basically, the northernmost SCS contains several E–W trending magnetic lineations (Figure 3), while the area off southwest Taiwan displays weak variation of the magnetic anomaly amplitude. No clear correlation of E–W trending magnetic reversal pattern can be recognized off southwest Taiwan (Figure 4). The blurred signature is limited to the north of the Formosa Canyon and east of the Manila Trench (Figure 4). It might imply that the basement of the oceanic crust off southwest Taiwan, if exists, is rather deep, and is covered by thick sediments from the pileup of the accretionary prism due to the northwestward convergence of the Luzon arc (Suppe, 1981; Teng, 1990) and/or the foreland basin deposition (Lin and Watts, 2002; Yu and Chou, 2002).

Because the patterns of the magnetic anomalies change from one side to the other side of the LRTPB (line AA' in Figure 4), the magnetic anomalies suggest the existence of a transform fault plate boundary along the LRTPB. As shown in the dashed boxes of Figure 4, to the south of the LRTPB, the lineations of E–W trending magnetic polarity reversals can be obviously observed. Several associated fracture zones (heavy dashed lines in Figure 4) are inferred by the sudden terminations of the magnetic lineations. However, Late Miocene volcanism in this region (Gong et al., 1997) has probably disturbed some magnetic lineation patterns (Figure 4). It is noted that the identified magnetic lineations are located to the north of the oldest oceanic crust of the SCS as suggested by Briais et al. (1993) (Figures 1 and 4). The existence of additional oceanic crust in the northernmost SCS suggests that the oldest oceanic crust of the SCS is probably older than 32 Ma.

Equivalent magnetization map and continent-ocean boundary (COB)

In order to understand the basement characters of the study area, we have performed a magneti-

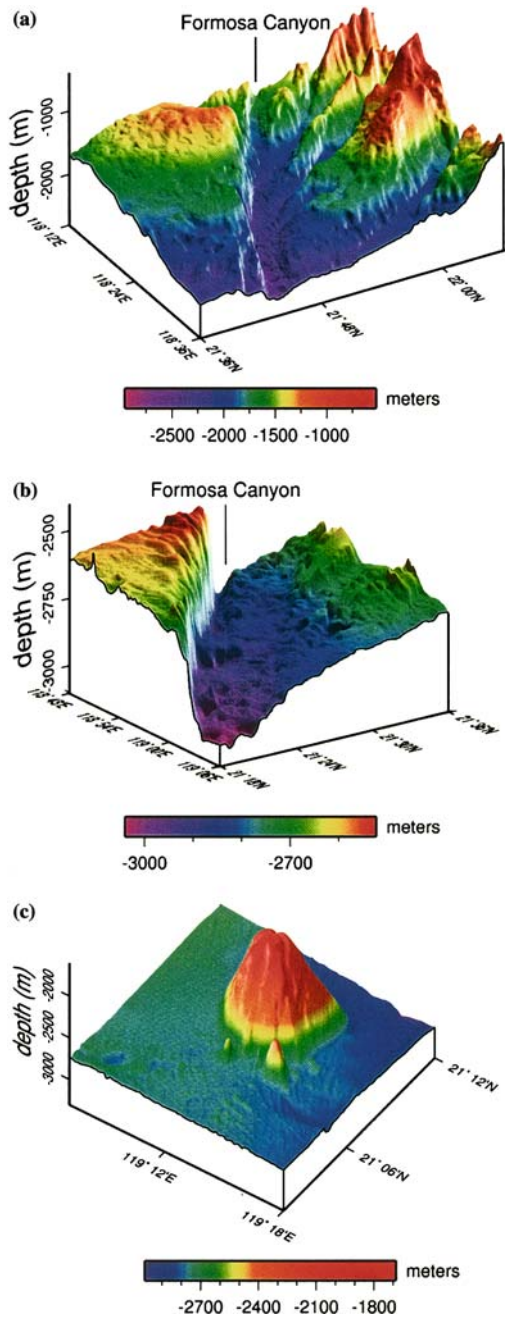


Figure 6. Three 3D topographic views of the boxes in Figure 5. (a) The multi-bifurcations head of the Formosa Canyon at the continental slope area. (b) A linear escarpment. (c) A seamount distinguishes the eastern and western portions of the Formosa Canyon.

zation inversion by assuming that the magnetization inclination and declination of the crust are similar to the present-day geomagnetic paramete-

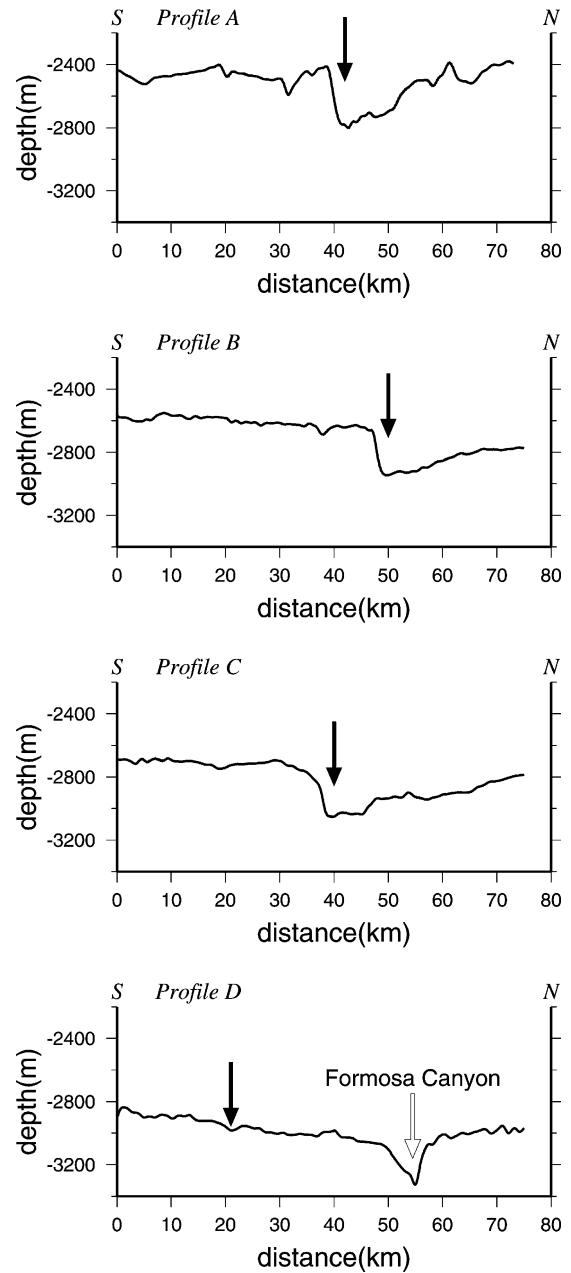


Figure 7. Four bathymetric profiles across the Formosa Canyon (see locations in Figure 5). Black arrows indicate the locations of a possible transform fault. In profile A, B, and C the Formosa canyon coincides with the occurrence of an old transform fault.

ters and an equivalent magnetized layer of 4 km thick whose top surface coincides with the seafloor. A horizontal grid spacing of 4 km \times 4 km is adopted for the inversion area. The magnetization of each block is derived by fit-

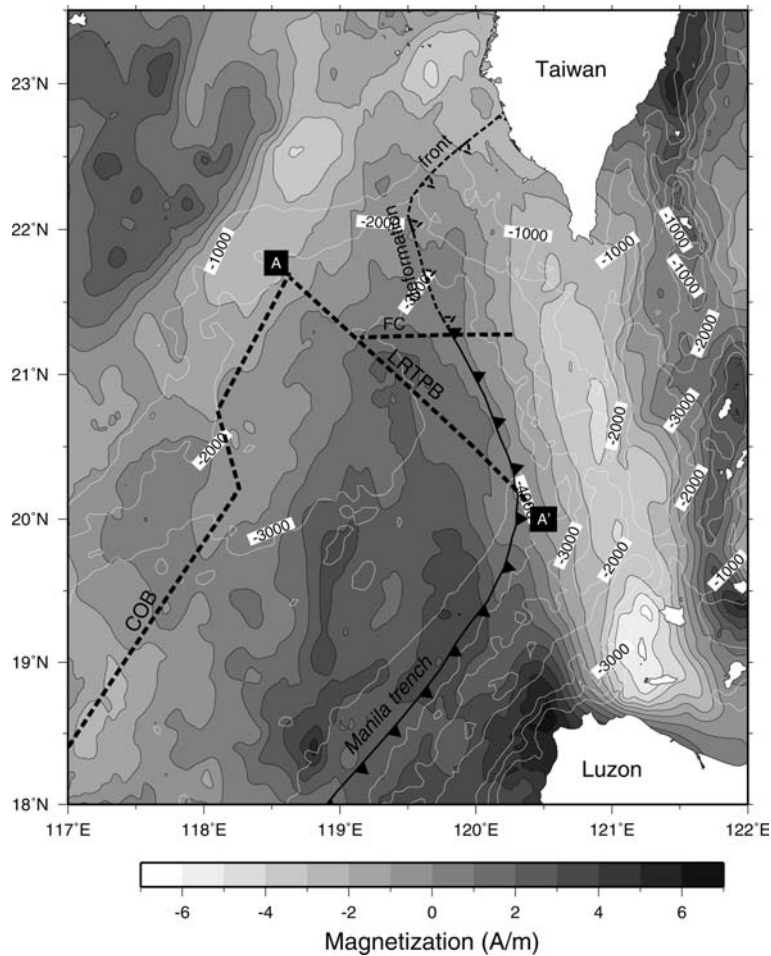


Figure 8. The equivalent magnetization distribution for the magnetic data shown in Figure 4. The magnetic inversion is done by assuming a constant thickness of magnetized layer whose top coincides with the sea floor. FC: Formosa Canyon. L RTPB: Luzon-Ryukyu transform plate boundary. COB: continent-ocean boundary.

ting the calculated and observed magnetic data in the sense of least-square-error. The result is shown in Figure 8. We have also performed an inversion by assuming a constant thickness of 4 km for a horizontal magnetized layer. The magnetization pattern is similar.

As shown in Figure 8, the Luzon Arc generally reflects a high magnetization zone except for the area around $121^{\circ} 20' E$ and $19^{\circ} N$ where a strongly low magnetization exists. The low magnetization zone extends northwards along the forearc area of the Luzon Arc. Another relatively low magnetization zone marks the western ends of the previously mentioned E–W trending magnetic lineations (cf. Figures 4 and 8). It is noted that the northernmost SCS shows good integrity

of magnetization distribution (Figure 8). No clear magnetization characteristics reflect the northernmost COB location as suggested by Briaies et al. (1993). By contrast, the new defined COB is bordered in the west by the low magnetization zone (the dashed line in Figure 8). The defined COB in the northernmost SCS is located between bathymetric contour line of 2200–3000 m. Some inferred fracture zones also reveal relatively low magnetization values (e.g. the relatively low magnetization zone alone $E 119^{\circ} 25'$).

The Formosa Canyon generally separates two different magnetization areas in the north and in the south (Figure 8). The area surrounded by the Fomosa Canyon, the Manila Trench and the L RTPB displays two clear magnetic lineations

(Figure 4) and relatively high magnetizations, close to the nature of the SCS oceanic crusts (Figure 8). The area between south Taiwan and the Formosa Canyon displays gentle magnetization (Figure 8) but no clear magnetic reversal patterns (Figure 4). However, this area was modeled to have thin crust (Yeh and Hsu, this volume; Tsai et al., this volume). The crust nature off southwest Taiwan is still questionable. If we consider the NE–SW trending zone of extremely low magnetization off southwest Taiwan to be the same as the Manila forearc region (Figure 8), the area north of the Formosa Canyon and south of the Taiwan could be originally a forearc region. This interpretation is compatible to the hypothesis that the former Ryukyu subduction system had been extended to the southwest of Taiwan and terminated at the northern tip of the LRTPB (Hsu and Sibuet, 1995; Sibuet and Hsu, 1997, 2004). Accordingly, we trace the location of the COB along the low magnetization zone near the base of the continental slope and then along with the Formosa Canyon.

Age identification of the northernmost SCS oceanic crust

Before identifying the age of the oceanic crust in the northernmost SCS, we examine if the magnetic reversal patterns are related to oceanic crusts imprinted by geomagnetic field reversals and not just reflect rifted continental crust? To answer this question, we first notice that the magnetic reversal patterns in the northernmost SCS are generally E–W trends, suggesting a N–S seafloor spreading direction. By contrast, the Asian continental margin has generally experienced NW–SE rifting (Sibuet and Hsu 1997). In fact, the suggested COB is marked by a abrupt change of gravity anomalies on both sides of the NE–SW trending COB, especially near 118° 20' E and 21° 20' N (Figure 2); The sharp change of the gravity signature implies a shear boundary in the west of the northernmost SCS oceanic crust.

To examine the crustal thickness, we have conducted a multi-channel seismic reflection profile across the suggested oceanic crust area (profile BB' in Figure 4). The characteristics of the seismic structures generally reveal the nature of oceanic crust relief (Tsai et al., this volume). By subtracting the effects of water layer and upper

crustal structures from the free-air gravity anomaly, we have obtained the Bouguer anomaly that is supposed to reflect the geometry of the crust/mantle boundary (Moho). The Bouguer anomaly along profile BB' generally increases oceanwards (Figure 9a). By assigning appropriate densities, the gravity modeling indicates a reasonable oceanic crustal thickness of 6–7 km in the E–W trending magnetic lineation area (Figure 9a). The modeled crustal thickness is compatible with the existence of oceanic crust in the northernmost SCS. To the south of profile BB', the Eastern Trench seismic reflection profile of Nissen et al. (1995) is used for comparison (profile CC' in Figures 4 and 9b). In Figure 9b, we have calculated the Bouguer anomalies on the basis of the free-air gravity anomalies and the crustal structures. However, here we did not model the Moho surface variation; we just used the results obtained by Nissen et al. (1995). The good fit of the synthetic and Bouguer gravity anomalies indicates that the Moho depths are appropriate (Figure 9b). In fact several seamounts are prominently observable in the southern portion of profile CC' (Figure 4). Thus, the crustal thickness of 11–12 km in the southern portion of profile CC' could be attributed to post-spreading volcanic intrusions in the existing oceanic crusts.

To model the age of the oceanic crust identified in the northernmost SCS, we have conducted a magnetic survey along profiles DD' and EE', respectively (Figures 4 and 10). The profile DD' has tied to the magnetic anomaly C10 and C11 identified by Briais et al. (1993). The geomagnetic polarity timescale of Cande and Kent (1995) is used for modelling. The synthetic magnetic anomaly is produced by assuming a horizontal constant layer of 1.5 A/m and 2 km thick at 4.5 km deep below sea surface. A skewness parameter of 120°, similar to the one used by Taylor and Hayes (1980), has been found. The synthetic and observed magnetic anomalies are normalized for comparison. As shown in the profile DD' of Figure 10a, we first adopt a constant half-spreading rate of 40 mm/yr and the northernmost SCS oceanic crust is well modeled as old as 37 Ma (Magnetic anomaly C17). To have a better modeling, we then use variant half-spreading rates and the oldest SCS oceanic crust is found to be formed at a half-spreading rate of 44 mm/yr (Figure 10b). However, the magnetic

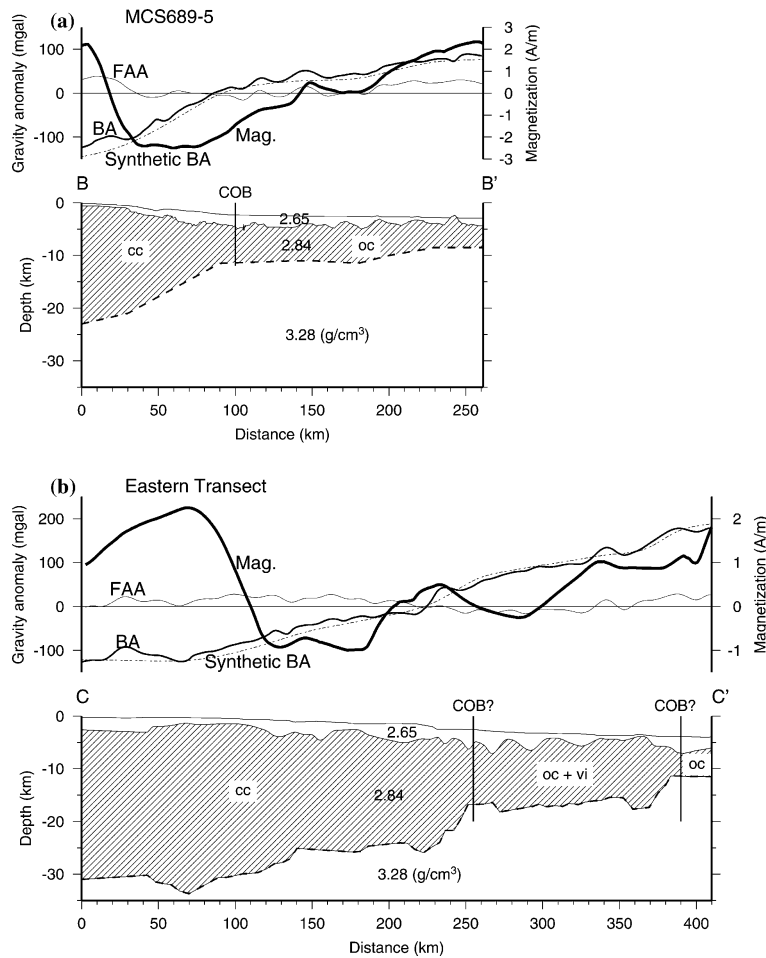


Figure 9. Gravity modeling of (a) profile MCS689-5 and (b) the Eastern Transect of Nissen et al. (1995). The Bouguer anomaly (BA) reflects the relief of the Moho surface. Note that to the left of the COB there is a low magnetization region corresponding to the thinned continent crustal zone. cc: continental crust. oc + vi: oceanic crust with volcanic intrusions. oc: oceanic crust. See the locations of the profiles in Figure 4.

anomalies of the oceanic crust between 31 and 34 Ma (C12–C13) along profile DD' seem to be obscured by the presence of volcanic intrusions (cf. Figures 4 and 10). It is noted that the southern segment of the profile DD' is slightly oblique to the magnetic lineations identified by Briaies et al. (1993) (Figure 4). Therefore, the half-spreading rate of 34 mm/yr is reduced to about 28 mm/yr. To the east of profile DD', the magnetic anomalies along the profile EE' are modeled to be formed during magnetic anomalies C10–C12 at a half-spreading rate of about 28 mm/yr (Figure 10). This spreading rate is similar to that one found by Briaies et al. (1993). Compared the locations of magnetic anomalies

C10 and C11 near 118° 20' E and 18° 30' N to our identified magnetic anomalies C10 and C11 near 119° 45' E and 19° 30' N, it suggests that a left-lateral transform fault lies in between.

On the basis of the geomagnetic reversal time-scale of Cande and Kent (1995), we have recalculated the half-spreading rates suggested by Briaies et al. (1993) for the eastern portion of the SCS. Together with our identified ages between C17 and C12, it is concluded that the SCS oceanic crust was initially formed at a half-spreading rates of about 44 mm/yr at ca. 37 Ma (Late Eocene) (Figure 11). This Late Eocene seafloor spreading rate is similar to the one of the West Philippine Basin identified by Hilde and Lee

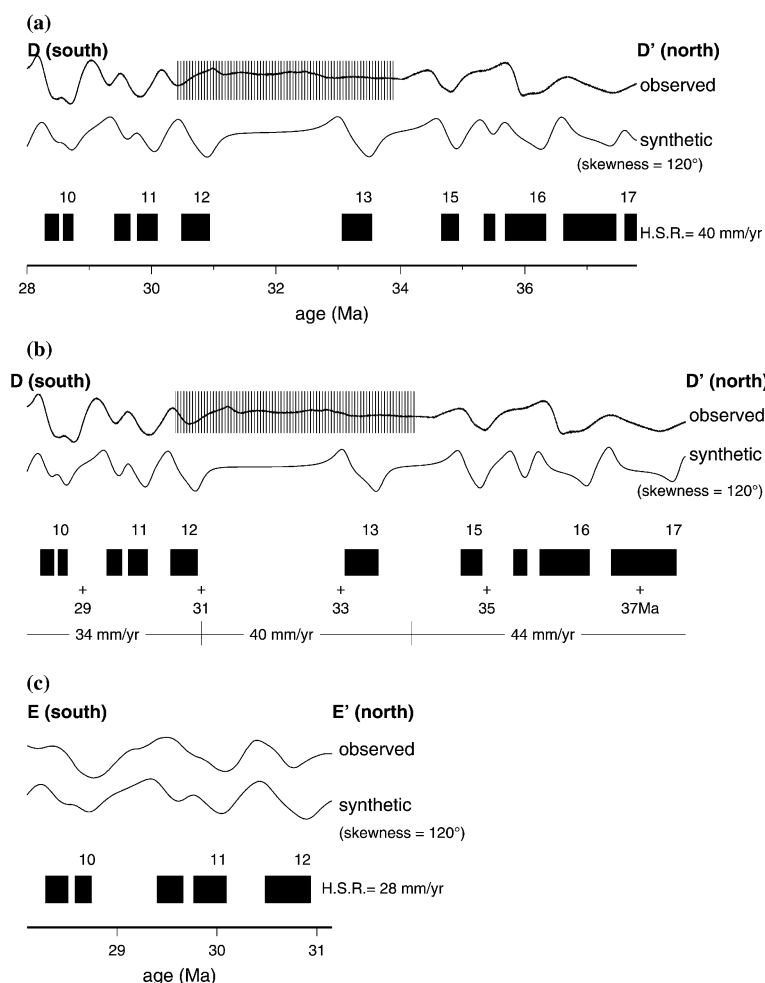


Figure 10. Observed magnetic anomalies along the profiles DD' and EE' in the northernmost SCS compared to synthetic profiles (see the locations of the profiles in Figure 4). The synthetic profiles are computed on the basis of the geomagnetic reversal timescale of Cande and Kent (1995). Black blocks represent periods of normal polarity. The skewness parameter is set at 120° . The shaded area indicates possible volcanic intrusions. H.S.R.: Half-spreading rate.

(1984). Between 31 and 20 Ma, the half-spreading was rather stable at a rate of 28 mm/yr (Figure 11). A 'sudden' decrease of half-spreading rate between 20 and 18 Ma occurred before the complete cessation of the SCS opening at about 15 Ma (Middle Miocene) (Figure 11).

Luzon-Ryukyu Transform Plate Boundary (LRTPB)

As mentioned previously, the NW–SE trending segment of the Formosa Canyon not only distinguishes magnetic anomaly features on both sides but also exhibits a topographic escarpment. These characteristics suggest that the upper

portion of the Formosa Canyon could be the location of an old transform fault (i.e. the LRTPB). One question is whether the presence of the old transform fault could be traced south-eastwards? Although the magnetic features are different on either side of the southeastern portion of the LRTPB (Figure 4), the bathymetry only experiences a slight vertical offset across the southeast portion of the LRTPB (Figure 7d). However, we can observe that the bathymetric contours south of the LRTPB generally trend $N30^\circ E$ while north of the LRTPB, they trend $N5^\circ W$. The change of directions in bathymetric contours across the LRTPB implies that the basement characters on either side of the LRTPB

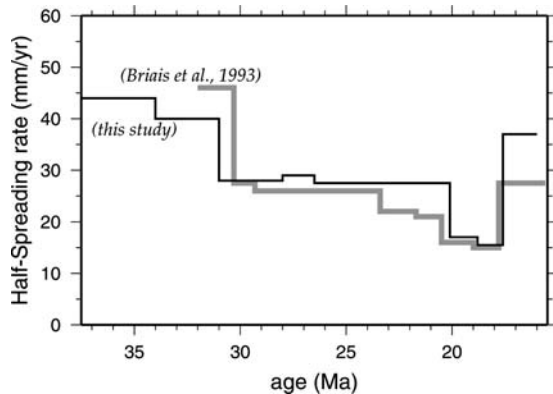


Figure 11. The distribution of the half-spreading rates in the eastern portion of the SCS. After 28 Ma, the rates are modified after Briais et al. (1993) on the basis of the geomagnetic reversal timescale of Cande and Kent (1995). Note that between 31 and 20 Ma the spreading rates (ca. 28 mm/yr) in fact are quite stable.

could be different. As a matter of fact, revealed by the 6-channel reflection seismic profiles collected during the ACT cruise (Sibuet et al., 2002), the sediment is thicker and the acoustic basement is deeper on the northern side of the LRTPB (Figure 12). Thus, the bathymetric and basement features are in agreement with the existence of the LRTPB.

Discussions

A trapped piece of the Philippine Sea Plate (TPS)?

The area surrounded by the LRTPB, the Formosa Canyon and the Manila Trench exhibits a high magnetization zone (Figure 8). Its magnetization characteristic is similar to the SCS and could be reasoned as an oceanic crust. We call this piece the TPS. The depths to the basement of the TPS are deeper than in the SCS area to the south of the LRTPB (Figure 12). This situation is also true if we take into account the isostatic response by correcting the sediment loading. The TPS has lower gravity anomaly than in the south (Figure 13). Two obviously E–W to SE–NW trending magnetic lineations can be found in the TPS (Figure 4). The TPS is currently subducting eastwards beneath the northern Manila subduction system.

The existence of the TPS points out a peculiarly tectonic issue of this region. Does the TPS belong to the SCS oceanic crust or not? Because the dredged sample from the seamount shown in Figure 6c is located on the LRTPB and is dated to be 22 Ma old (S.-L. Chung, personal communication), we may assume that the LRTPB was still active at that age. We suppose that the LRTPB was a left-lateral transform fault connecting two opposite subduction systems: the Manila trench system subducting southeastwards in the south and the Ryukyu trench system subducting northwestwards in the north. Because the TPS is located on the northern side of the LRTPB, it seems not related to the SCS crust in the south of the LRTPB. According to the plate-cooling model (Turcotte and Schubert, 2002) and due to the deeper basement, the TPS crust must be older than the contiguous SCS crust south of the LRTPB. Because the motion of the LRTPB is left-lateral and the northern SCS has generally the younger oceanic crust towards the south, the basement of the TPS would be shallower or younger if the TPS crust belonged to the SCS. Hence, we speculate that the TPS is a trapped piece of the Philippine Sea Plate, though the nature and age of the Philippine Sea Plate (i.e. the Huatung Basin) is still contentious (Deschamps et al., 2000; Sibuet et al., 2002). However, it is noted that the LRTPB is shown as a NW–SE trending shear zone, oblique to the E–W trending magnetic lineations in the northernmost SCS (Figure 4). Hence, it exists a possibility that the TPS belonged to an oldest SCS oceanic crust separated from its western oceanic crust by a N–S trending fracture zone. The motion of the LRTPB had pushed the oldest SCS oceanic crust northwestwards.

Possible kinematics for the occurrence of TPS

If we consider the distribution of the identified anomaly C15–C17, we can notice that the existence of the oldest SCS oceanic crust makes the COB of the northern SCS rather straight, mostly in the direction of N38° E (Figure 14). However, the counterpart of the oldest SCS oceanic crust in the southeast SCS basin is missing (cf. Figures 1 and 14). The subduction features are clearly found in seismic reflection profiles across the Palawan Trough but no subduction

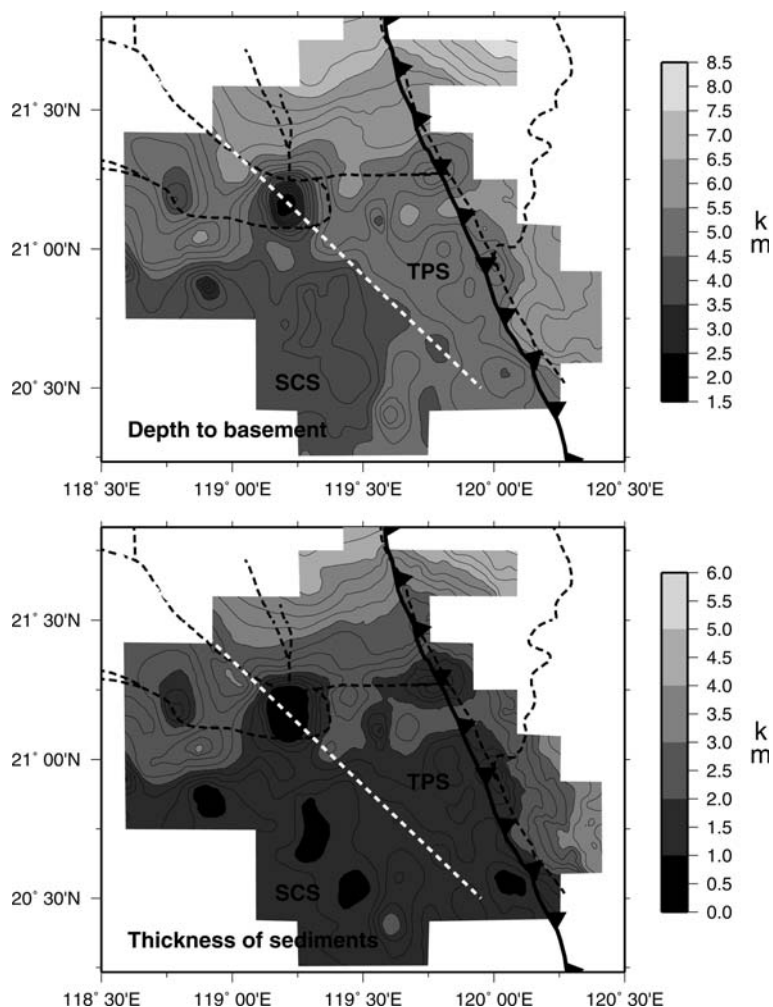


Figure 12. Depths to the top surfaces of the basement from seismic reflection data (Sibuet et al., 2002). The estimated thickness of sediments shown below. It is noted that the different depths to the basement and different sediment thickness on both sides of the L RTPB (the white dashed line). The black dashed lines show the canyon system of the study area. Trench symbol shows the location of the Manila Trench.

evidence has been found in the northern Palawan area (Taylor and Hayes, 1980). However, the tomographic image reveals the eastward-subducted Manila slab (Rangin et al., 1999). Thus, the missing oceanic crust (anomaly C12–C17) in the southeast SCS must have been subducted eastwards beneath the Palawan-Luzon region (or the Manila subduction system). On the other hand, the northward subduction of the Philippine Sea Plate along the former Ryukyu Trench could exist to the southwest of the present-day Taiwan location (Hsu and Sibuet, 1995; Sibuet and Hsu, 1997; Sibuet et al., 2002) and terminated at the northern end of the

L RTPB (Figure 15a). This subduction system has bordered the southeastward rifting East Asian continental margin. Taking into account the formation of the Luzon Arc (Yang et al., 1996) and the sudden decrease of the half-spreading rate of the eastern SCS between 20 and 18 Ma (Figure 8), we may suggest that the L RTPB became inactive at ca. 20 Ma (Early Miocene) (Figure 15b). Simultaneously, the northern tip of the Manila Trench prolonged northeastward and connected the northern portion of the former Ryukyu Trench by another left-lateral transform fault before the initiation of the Taiwan orogeny (Figure 15b). This plate

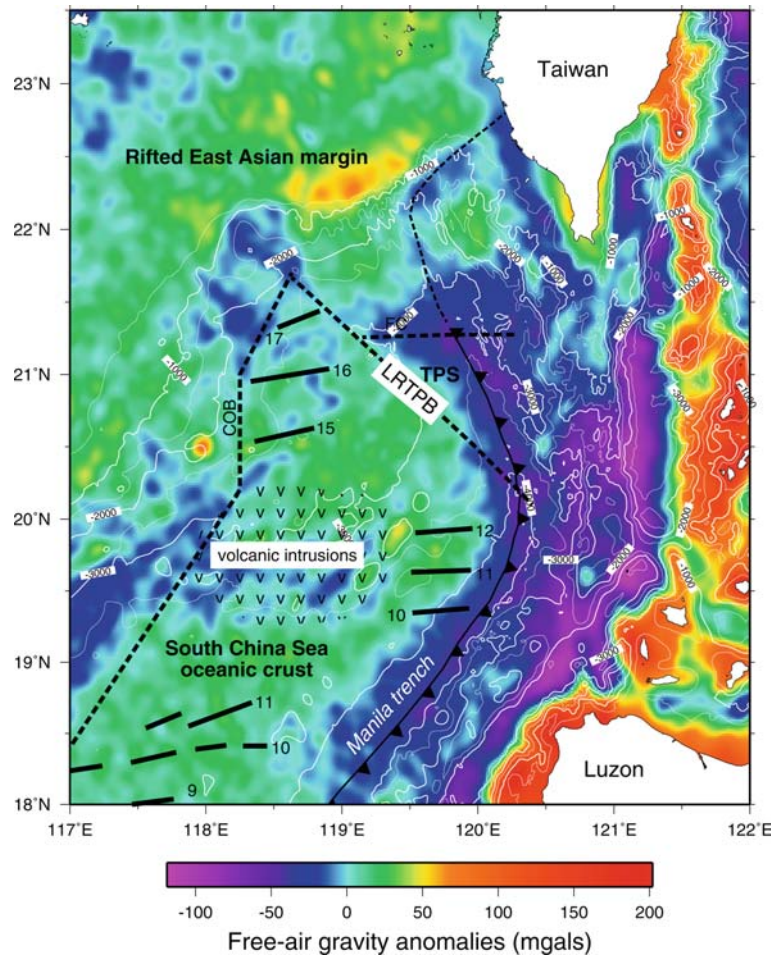


Figure 13. The newly identified magnetic lineations in the northernmost SCS, superposed on the free-air gravity anomalies. FC: Fomorsa Canyon; LRTPB: Luzon–Ryukyu transform plate boundary; TPS: trapped piece of Philippine Sea Plate. Note that the COB is delineated by a sharp change of gravity.

boundary reorganization made the southwestern portion of the Ryukyu Trench inactive (Figure 15b). Through the boundary reorganization, a piece of the Philippine Sea Plate (TPS) was trapped. The complete contact between the northern tip of the Manila Trench and the southern tip of the active Ryukyu Trench possibly occurred at ca. 15 Ma (Sibuet and Hsu, 2004). Because the spreading of the SCS also ceased at ca. 15 Ma, their relationship still needs to be clarified. However, a prompt question is: why there was no arc volcanism in the extinct portion of the Ryukyu subduction zone? This question is still open. A speculative explanation is that the subducted slab there did not penetrate deep enough to produce arc volcanism. In

other words, the action duration of the LRTPB might have not sustained too long.

Conclusions

We have presented new magnetic and bathymetric maps of the northernmost SCS and off southwest Taiwan. Compared to the locations of the magnetic lineations of ca. 32 Ma identified by Biais et al. (1993), we have found several E–W trending magnetic polarity reversals in the northernmost SCS. This finding demonstrates that the SCS oceanic crust may be extended northwards to 21.5° N. The oldest oceanic crust of the SCS is identified to be 37 Ma

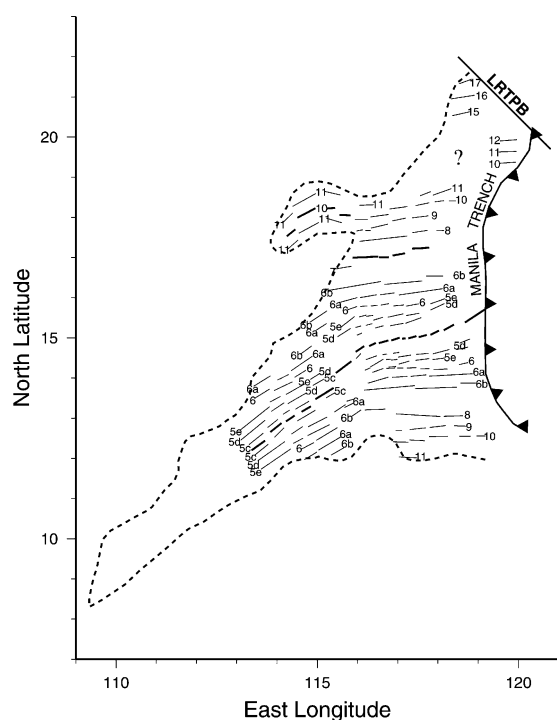


Figure 14. Distribution of the SCS oceanic crust. The location of the COB is drawn in dashed line. Note that the oceanic crust of age C12–C17 in the southern SCS had probably subducted southwards.

(magnetic anomaly C17, Late Eocene) with a half-spreading rate of 44 mm/yr. Because of the missing magnetic anomalies C12–C17 in the southern SCS, the oldest oceanic crust of the southern SCS must have been subducted beneath the Palawan–Luzon region.

The identified northern SCS oceanic crust is terminated by an old, NW–SE trending transform fault, L RTPB. The L RTPB is suggested to be a left-lateral transform fault connecting the former Manila Trench in the south and the former Ryukyu Trench in the north. At ca. 20 Ma, the seafloor-spreading rate of the SCS has dropped dramatically and the L RTPB possibly became inactive. The former Manila Trench has prolonged northeastwards, creating the Luzon Arc, and finally connected to the former Ryukyu Trench. The plate boundary reorganization has caused the southwest portion of the former Ryukyu subduction zone to become extinct, and a westernmost piece of the Philippine Sea Plate was trapped amongst the L RTPB, the Manila Trench and the continental margin.

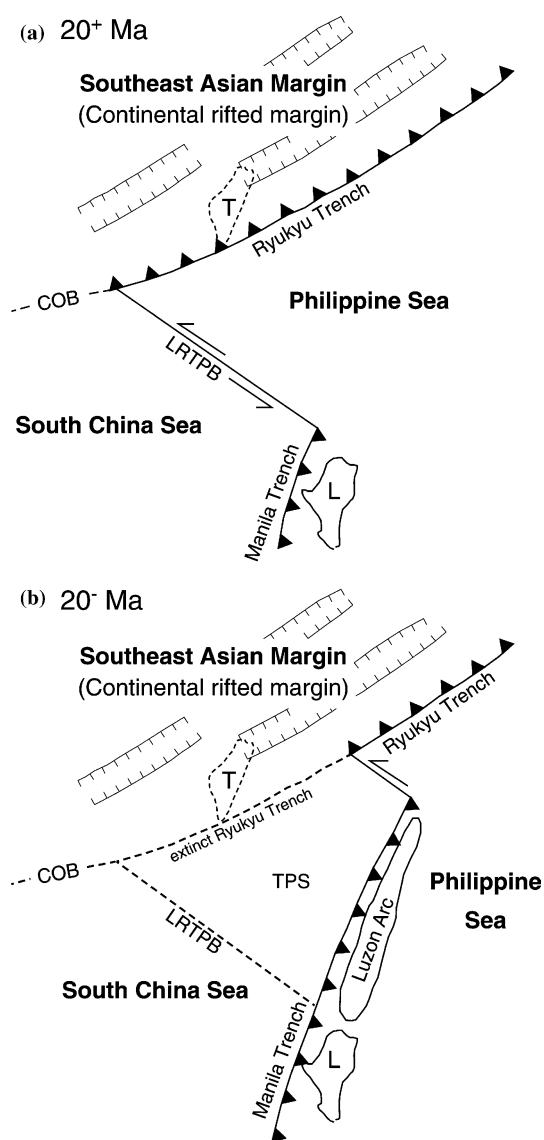


Figure 15. Schematic scenario of the tectonic evolution of the L RTPB at ca. 20Ma. T: present-day location of Taiwan; TPS: trapped piece of Philippine Sea Plate; L RTPB: Luzon–Ryukyu transform plate boundary.

In the northernmost SCS, the Formosa Canyon has developed at the continental slope of the East Asian margin. Its multi-bifurcations head merges into one single channel at the base of the continental slope. Marked by a linear escarpment, the NW–SE trending segment of the upper reaches of the Formosa Canyon have developed along the northwest portion of the L RTPB. The E–W trending lower reach of the

Formosa Canyon distinguishes the Asian continental margin from the deep ocean basin.

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References

- Ben-Avraham, Z. and Uyeda, S., 1973, The evolution of the China Basin and the Mesozoic paleogeography of Borneo, *Earth Planet. Sci. Lett.* **18**, 365–376.
- Briais, A., Patriat, P. and Tapponnier, P., 1993, Updated interpretation of magnetic anomalies and seafloor spreading stages in South China Sea: implications for the Tertiary tectonics of Southeast Asia, *J. Geophys. Res.* **98**, 6299–6328.
- Cande, S.C. and Kent, D.V. 1995, Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, *J. Geophys. Res.* **98**, 6299–6328.
- Deschamps, A., Monié, P., Lallemand, S.E., Hsu, S.-K. and Yeh, K.-Y., 2000, Evidence of early Cretaceous oceanic crust trapped in the Philippine Sea plate, *Earth Planet. Sci. Lett.* **179**, 503–516.
- Gong, Z. et al., 1997, Continental margin basin analysis and hydrocarbon accumulation of the northern South China Sea, Science Press, Beijing, China, 510pp.
- Hall, R., 1996, Reconstructing Cenozoic SE Asia, in Hall, R. and Blundell, D. J. (eds.), *Tectonic Evolution of Southeast Asia*, Geol. Soc. London, Spec. Publ. **106**, 203–224.
- Hilde, T.W.C. and Lee, C.-S., 1984, Origin and evolution of the west Philippine basin: a new interpretation, *Tectonophysics* **102**, 85–104.
- Hsu, S.-K., 1995, A cross-over technique to adjust track data, *Computers and Geosciences* **21**, 259–271.
- Hsu, S.-K., Liu, C.-S., Shyu, C.-T., Liu, S.-Y., Sibuet, J.-C., Lallemand, S., Wang, C. and Reed, D., 1998, New gravity and magnetic anomaly maps in the Taiwan-Luzon region and their preliminary interpretation, *TAO* **9**, 509–532.
- Hsu, S.-K. and Sibuet, J.-C., 1995, Is Taiwan the result of arc-continent or arc-arc collision?, *Earth Planet. Sci. Lett.* **136**, 315–324.
- Lallemand, S. et al., 1997, Swath bathymetry reveals active arc-continent collision near Taiwan, *EOS, Transactions AGU* **78**, 173–175.
- Lee, T.-Y., and Lawver, L.A., 1995, Cenozoic plate reconstruction of Southeast Asia, *Tectonophysics* **251**, 85–138.
- Lin, A.T. and Watts, A.B., 2002, Origin of the west Taiwan basin by orogenic loading and flexure of a rifted continental margin, *J. Geophys. Res.* **107**, doi:10.1029/2001JB000669.
- Liu, C.-S., Huang, I.L. and Teng, L.S., 1997, Structures features off southwestern Taiwan, *Mar. Geol.* **137**, 705–738.
- Liu, C.-S., Liu, S.-Y., Lallemand, S. and Lundberg, N., 1998, D.L. Reed, Digital elevation model offshore Taiwan and its tectonic implications, *TAO* **9**, 705–738.
- Morley, C.K., 2002, A tectonic model for the Tertiary evolution of strike-slip faults and rift basins in SE Asia, *Tectonophysics* **347**, 189–215.
- Nissen, S.S., Hayes, D.E., Bochu, Y., Weijun, Z., Yongqin, C. and Xiaopin, N., 1995, Gravity, heat flow, and seismic constraints on the processes of crustal extension: northern margin of the South China Sea, *J. Geophys. Res.* **100**, 22447–22483.
- Rangin, C., Sparkman, W., Pubellier, M. and Bijwaard, H., 1999, Tomographic and geological constraints on subduction along the eastern Sundaland continental margin (South-East Asia), *Bulletin de la Société Géologique de France* **170**, 755–788.
- Sandwell, D.T. and Smith, W.H.F., 1997, Marine gravity anomaly from Geosat and ERS1 satellite altimetry, *J. Geophys. Res.* **102**, 10039–10054.
- Sibuet, J.-C. and Hsu, S.-K., 1997, Geodynamics of the Taiwan arc-arc collision, *Tectonophysics* **274**, 221–251.
- Sibuet, J.-C. and Hsu, S.-K., 2004, How was Taiwan created?, *Tectonophysics* **379**, 159–186.
- Sibuet, J.-C., Hsu, S.-K., Le Pichon, X., Le Formal, J.-P., Reed, D., Moore, G. and Liu, C.-S., 2002, East Asia plate tectonics since 15 Ma: constraints from the Taiwan region, *Tectonophysics* **344**, 103–134.
- Suppe, J., 1981, Mechanics of mountain building and metamorphism in Taiwan, *J. Geol. Soc. China* **4**, 67–89.
- Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R. and Cobbold, P., 1982, Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine, *Geology* **10**, 611–616.
- Tapponnier, P., Peltzer, G. and Armijo, R., 1986, On the mechanics of the collision between India and Asia, in Coward M.P. and Ries, A.C. (eds.), *Collision Tectonics*, Geol. Soc. Spec. Publ. **19**, 115–157.
- Taylor, B. and Hayes, D.E., 1983, Origin and history of South China Sea Basin, in Hayes D.E. (Ed.), *The tectonic and geologic evolution of Southeast Asian seas and islands*, 2, Am. Geophys. Union., Washington, DC, 23–56.
- Taylor, B. and Hayes, D.E. 1980, The tectonic evolution of the South China Basin, in Hayes, D.E. (Ed.), *The tectonic and geologic evolution of Southeast Asian seas and islands*, 1, Am. Geophys. Union., Washington, DC, 89–104.
- Teng, L.S., 1990, Late Cenozoic arc-continent collision in Taiwan, *Tectonophysics* **183**, 57–76.
- Turcotte, D.L. and Schubert, G. 2002, *Geodynamics*, 2nd edn. Cambridge University Press, 456pp.
- Wessel, P. and Smith, W.H.F. 1998, New improved version of generic mapping tools released, *EOS Trans. AGU* **79**, 579.
- Yang, T.F. et al., 1996, A double island arc between Taiwan and Luzon: consequence of ridge subduction, *Tectonophysics* **258**, 85–101.
- Yu, H.-S. and Chang, J.-F., 2002, The Penghu submarine canyon off southwest Taiwan: morphology and origin, *TAO* **13**, 547–562.
- Yu, H.-S. and Chou, Y.-W., 2001, Characteristics and development of the flexural forebulge and basal unconformity of western Taiwan foreland basin, *Tectonophysics* **333**, 277–291.