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ORIGINAL RESEARCH PAPER

Age and tectonic evolution of the northwest corner of the West Philippine Basin

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Abstract To understand the tectonic characteristics and age of the northwestern part of the West Philippine Basin (WPB), multi-beam bathymetry and geomagnetic data have been collected and analyzed. The seafloor morphology obviously shows NW–SE trending seafloor fabrics and NE–SW trending fracture zones, indicating a NE–SW seafloor spreading direction. An overlapping spreading center near 22°20′N and 125°E is identified. Besides, numerous seamounts indicate an excess supply of magma during or after the oceanic crust formation. A V-shaped seamount chain near 21°52′N and 124°26′E indicates a southeastward magma propagation and also indicates the location of the seafloor spreading ridge. On the basis of the newly collected geomagnetic data, the magnetic anomaly shows NW–SE trending magnetic lineations. Both bathymetry and geomagnetic data reveal NE–SW seafloor spreading features between the Gagua Ridge and the Luzon Okinawa fracture zone (LOFZ). Our magnetic age modeling indicates that the age of the northwestern corner of the WPB west of the LOFZ is between 47.5 to 54 Ma (without including overlapping spreading center), which is linked to the first spreading phase of the WPB to the east of the LOFZ. In addition, the age of the Huatung Basin is identified to be between 33 to 42 Ma, which is similar to the second spreading phase of the WPB.

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Introduction

The evolution of the Philippine Sea Plate (PSP) is not easy to be understood because it is surrounded by subduction zones (Fig. 1). In the east, there are the Izu-Bonin and Mariana island arc systems where the Pacific Plate is subducting beneath the PSP. In the north of the PSP, the subduction toward the southwest Japan has been active since at least early Cretaceous. Continued subduction subsequently included subduction of the Kula—Pacific Ridge (Uyeda and Miyashiro 1974; Michel et al. 2001). To the south, the PSP is bounded by the Yap Trench. The Ryukyu Trench and Philippine Arc mark the western boundaries of the PSP where the plate is subducting beneath the Eurasian Plate at a rate of 68 mm/year in a direction of 309°N near Taiwan (Seno et al. 1993). The Philippine Sea is divided into two parts by the roughly N–S trending Kyushu-Palau Ridge (KPR). The western part consists of the WPB and the Daito Ridge province. East of KPR, there are the Shikoku Basin and the Parece-Vela Basin.

The WPB is a wide oceanic basin covering most of the western part of the PSP. Most previous studies concluded that the WPB was spread symmetrically from the Central Basin Spreading Center (CBSC). However, the kinematic evolution of the WPB is still controversial. The published models can roughly classify into two groups. One suggested that the WPB was probably formed by back-arc opening from the CBSC during Paleocene-Eocene (Lewis and Hayes 1980; Mrozowski et al. 1982; Seno and

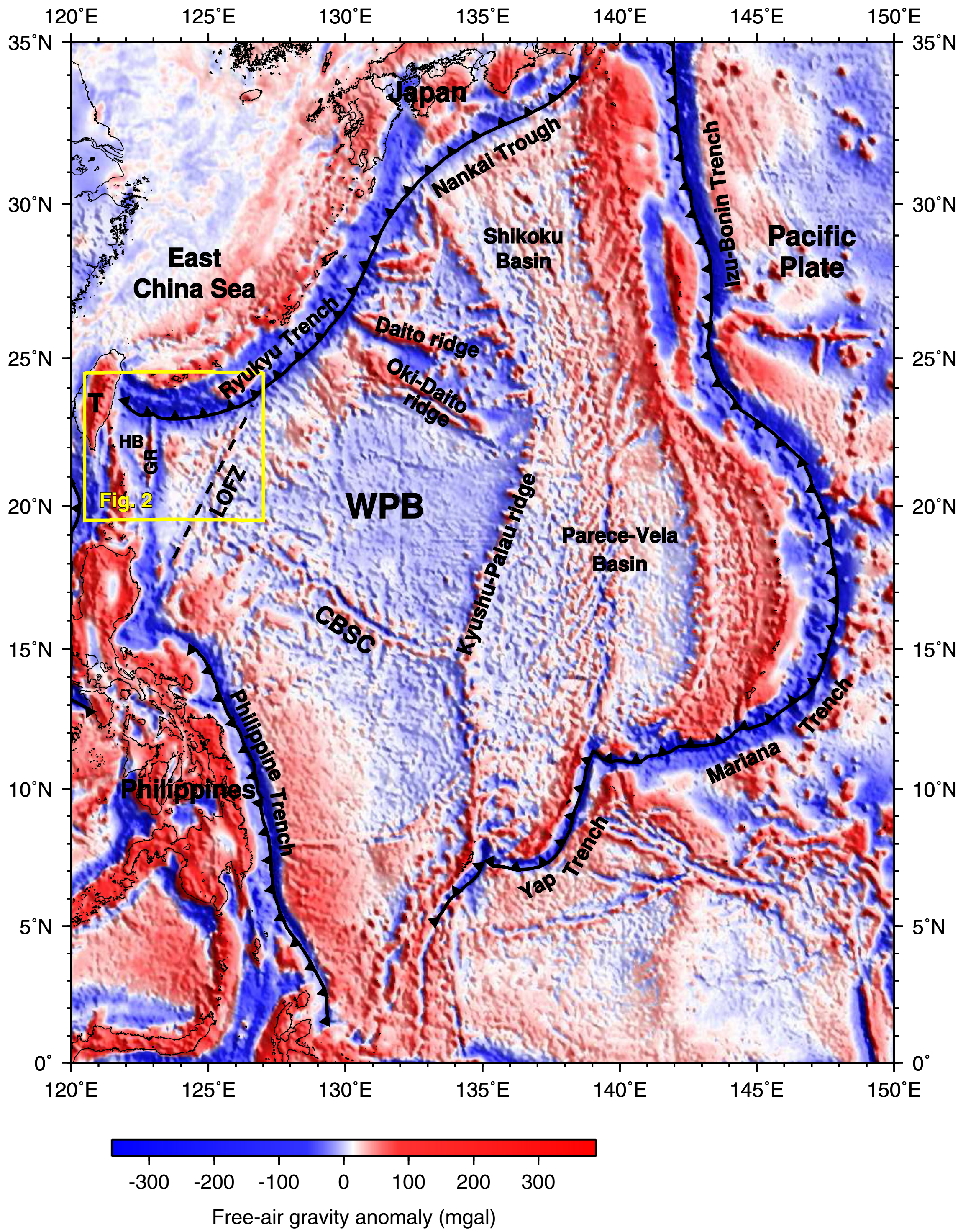


Fig. 1 Free-air gravity anomalies draped onto the bathymetry of the Philippine Sea Plate. The *yellow box* indicates the study area. *CBSC* central basin spreading center, *GR* gagua ridge, *HB* huatung basin, *LOFZ* Luzon-Okinawa fracture zone, *WPB* West Philippine Basin

Maruyama 1984; Rangin et al. 1990; Lee and Lawver 1995; Hall et al. 1995, Hall 1997, 2001; Deschamps and Lallemand 2002; Honza and Fujioka 2004). The other group suggested that the WPB was a trapped piece of normal oceanic plate after the Pacific Plate changed its motion direction in the early Tertiary (Uyeda and Ben-Avraham 1972; Uyeda and McCabe 1983; Hilde and Lee 1984; Handayani 2004).

Several interpretations and identifications of magnetic anomalies within the WPB have been proposed. Hilde and Lee (1984) first identified two main opening phases along the CBSC between 58 and 35 Ma. From 58 to 45 Ma, seafloor spreading would have occurred in a NE–SW direction at a half-spreading rate of 44 mm/year; the second phase between 45 and 35 Ma, seafloor spreading rate slowed down to 18 mm/year and changed direction from NE–SW to N–S. The WPB was gradually rotated clockwise during the spreading history (Honza and Fujioka 2004; Hall 1997, 2001). Deschamps et al. (2002) and Deschamps and Lallemand (2002) further analyzed swath-bathymetry and magnetic anomaly data of the relict spreading center region. They suggested that the spreading began at 55 Ma and ended at 30 Ma. After the end of the seafloor spreading, a short episode of amagmatic extension would have occurred at 30–26 Ma along the CBSC.

Okino and Fujioka (2003) have done a detailed analysis (including bathymetric, magnetic and gravity data) of the CBSC between 126°E and 133°30′E. They suggested that along the CBSC, the morphology of ridge segments exhibit typical slow spreading features in the eastern segments but fast spreading features in the westernmost segments. Deschamps and Lallemand (2002) and Deschamps et al. (2008) have identified several OSCs in the vicinity of the Urdaneta Plateau, east of the LOFZ. The large supply of basaltic magma in the early stage generated the Benham Rise and the Urdaneta Plateau. These two topographic highs are revealed by the high free-air gravity anomaly (Fig. 1). Deschamps et al. (2008) collected multi-beam bathymetric data in the northwestern part of the WPB and proposed that the spreading pattern is more complicated in the western part of the WPB than in its eastern part, due to the presence of the mantle plume during spreading. However, in their data set, it only covers a small area to the west side of the LOFZ. Therefore, the seafloor structures and its evolution to the west of the LOFZ are still not clear.

Recently, detailed marine geophysical data have been collected in the adjacent areas of the WPB, including multi-beam bathymetric and geomagnetic data (Fig. 2). We have used the new data to better understand the structure and the evolution of the northwestern part of the WPB.

Major features from bathymetric and magnetic data

Bathymetric features

Multi-beam bathymetry data in the study area were compiled by Yeh et al. (2014). As shown in Fig. 3, due to the great amount of sediments supplying from Taiwan (Lundberg et al. 1997; Malavieille et al. 2002), there are no visible seafloor spreading fabrics in the HB. The GR indeed behaves as a sediment barrier. In consequence, east of the GR the sediment cover is much thinner and the NW–SE trending spreading fabrics and several NE–SW trending fracture zones can be identified. Abyssal hill typically parallel to the spreading center segments, and fracture zones are generally orthogonal to them. Accordingly, the seafloor morphology indicates a NE–SW spreading direction between the GR and the LOFZ.

Near 22°25′N and 124°40′E, a N115° structural trend terminates N150° trending structures (Fig. 3b). The change in strike of the tectonic lineaments indicates the location of a inner pseudo-fault (Fig. 3b). It delineates an OSC located near 22°20′N and 125°E. South of the inner pseudo-fault, five separate jumped spreading groups were developed together with five overlapping basins (Fig. 4). The outer pseudo-fault is not observed probably due to a swath bathymetric data gap or subducted beneath the Ryukyu trench. An OSC is usually associated with an intermediate or fast-spreading ridge (MacDonald et al. 1988, 1991; Grindlay et al. 1991) and is attributed to a high magma supply. Many seamounts distributed in this area correspond to an extra magma supply in the northwestern part of the WPB. Upwelling mantle plume material tends to propagate away from the seafloor spreading axis and causes the V-shaped seamounts train (Hey et al. 1988). Hence, the V-shaped seamount trains (Fig. 4) indicate a southeastward propagating direction of the upwelling mantle magma during the oceanic formation to west of the LOFZ. Furthermore, the axis of the V-shaped seamounts can point out the trace of an extinct spreading center.

Magnetic features

We use the magnetic anomaly data compiled by Doo et al. (2014). Basically, the newly collected data (from 2004 to 2010), data from Hsu et al. (2004), CCOP (1996), global ocean magnetic dataset of Quesnel et al. (2009) and the aeromagnetic survey in the Philippines (Bureau of Energy Development 1985) were used in their dataset. The magnetic anomaly map shows different magnetic patterns to the east and to the west of the GR (Fig. 5). To the west side, the magnetic anomaly map reveals E–W trending magnetic lineations or the N–S spreading direction in the HB, same as indicated by Hilde and Lee (1984), Hsu et al. (1998) and Deschamps et al. (2000). However, to the east of the GR, the NW–SE direction of the magnetic lineations is observed. This NW–SE trending magnetic lineations feature exist eastward till a NE–SW trending fracture LOFZ (Fig. 5). That indicates a NE–SW seafloor spreading direction for the area. The different seafloor spreading directions in both sides of the GR could indicate different periods of formation. The GR can be can be regarded as a fracture zone (Deschamps et al. 1998) or a transverse ridge associate with a

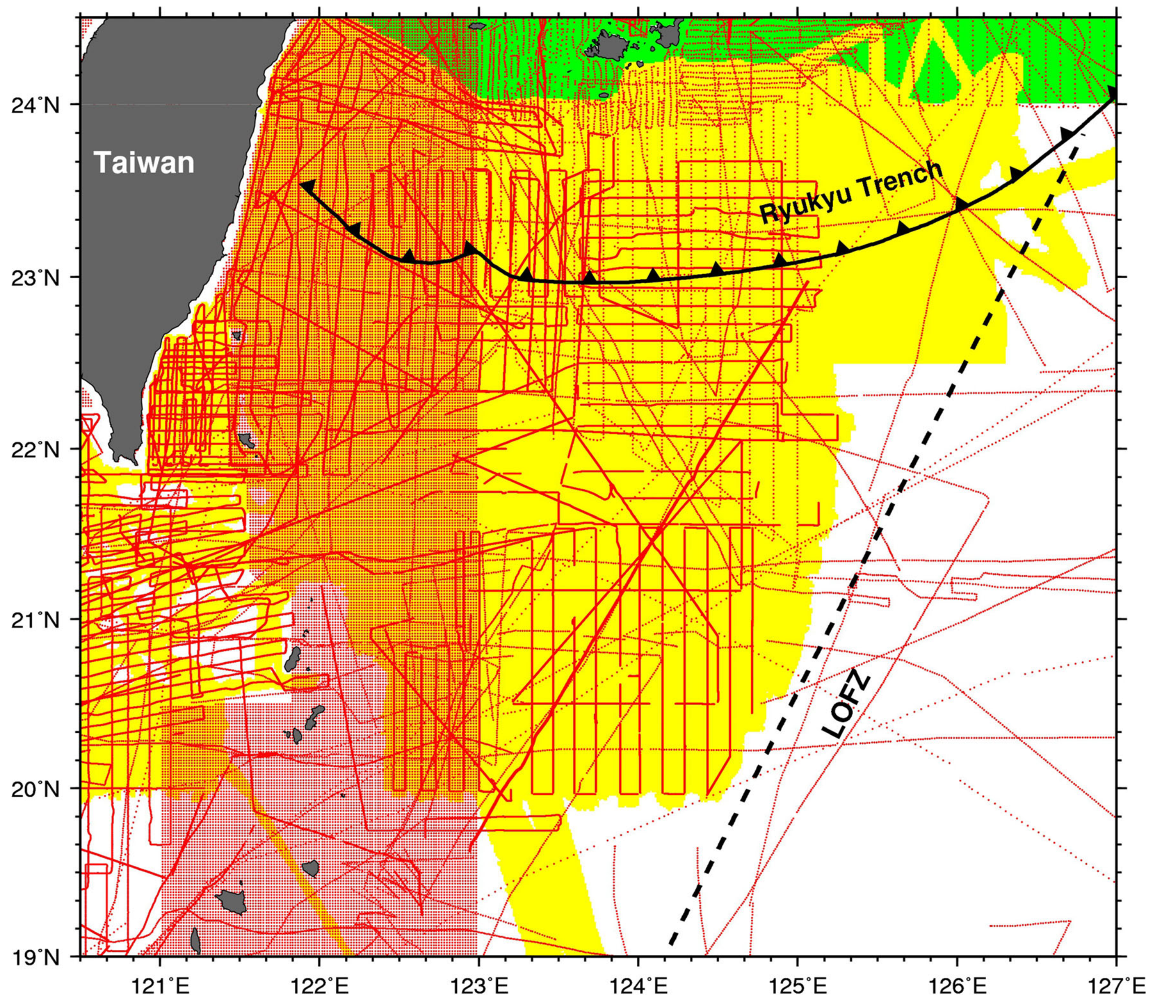
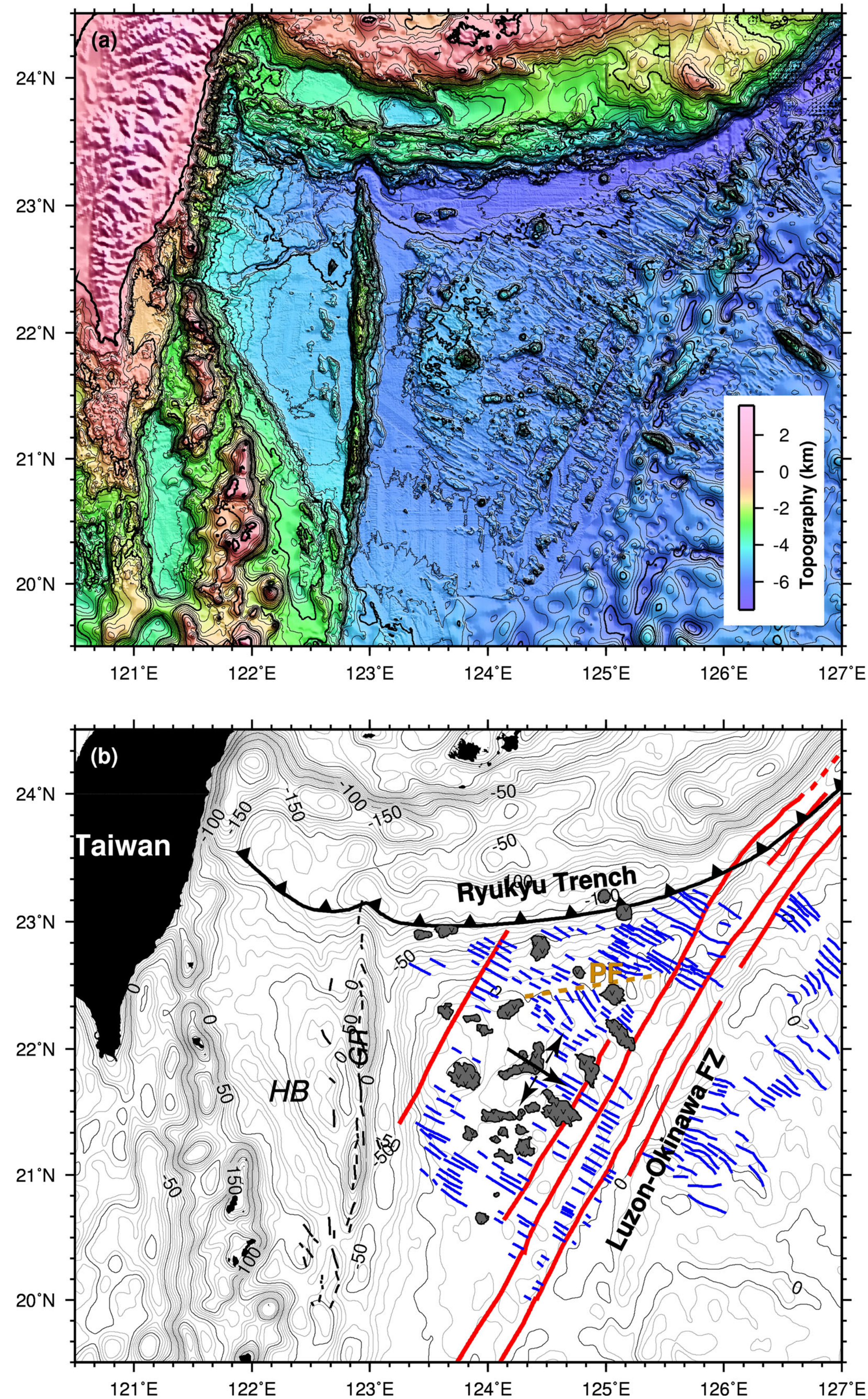


Fig. 2 Data used of the study area. *Yellow* part indicates multi-beam bathymetry covering area [including ACT cruise (Lallemand and Liu 1997; Liu et al. 1998)]; *green* part indicates 500 m grid bathymetry data from J-EGG500. *Red dots* indicate magnetic data complied by Doo et al. (2014). *LOFZ* Luzon-Okinawa fracture zone

fracture zone (Hsu et al. 1998). In the literature, there were several studies on the age of the oceanic crust in the HB but different results were suggested. For example, Hilde and Lee (1984) used marine magnetic data analysis and geomagnetic modeling and proposed that the HB was formed in the second spreading phase of the WPB (∼40 Ma). Using the same approach, Sibuet et al. (2002) suggested that the HB was formed between C20 and C23 (51–43 Ma). Kuo et al. (2009) measured phase velocities of Rayleigh-wave between OBS (broad-band ocean-bottom seismometer) and stations on the eastern coast of Taiwan and proposed that the characteristic of the phase velocities of the HB is comparable to the 15–30 Ma Parece-Vela basin. Hsu et al. (1998) also suggests the oceanic crust west of the GR is younger than in the east. However, based on the Ar–Ar dating for the gabbros dredged from the flank of the GR and geomagnetic modeling, Deschamps et al. (2000) suggested that the HB was generated in the early Cretaceous (∼125 Ma). To date, the age identification is still very controversial.

Fig. 3 **a** Swath bathymetry map of the northwestern part of the West Philippine Basin. **b** The identified structures of the study area. Gravity anomaly contours of 10 mgal interval are plotted. *Blue lines* indicate seafloor fabrics; *red lines* indicate fracture zones; *orange dashed line* indicates pseudofault; *black arrows* indicate magma propagating direction. *HB* huatung basin, *GR* gagua ridge, *PF* pseudofault

Hilde and Lee (1984) identified several E–W magnetic stripes between the GR and the LOFZ and proposed that the area was linked to the second phase of the CBSC spreading between 45 and 35 Ma. Because only NW–SE seafloor fabrics (Fig. 3) and magnetic stripes (Fig. 5) are observed in the area between the GR and the LOFZ, suggesting that there was no second N–S spreading phase. Between the LOFZ and the Urdaneta Plateau and the


(a)
24°N
23°N
22°N
21°N
20°N
121°E
122°E
123°E
124°E
125°E
126°E
127°E
Topography (km)
2
0
-2
-4
-6
(b)
Taiwan
Ryukyu Trench
PF
GR
HB
Luzon-Okinawa FZ

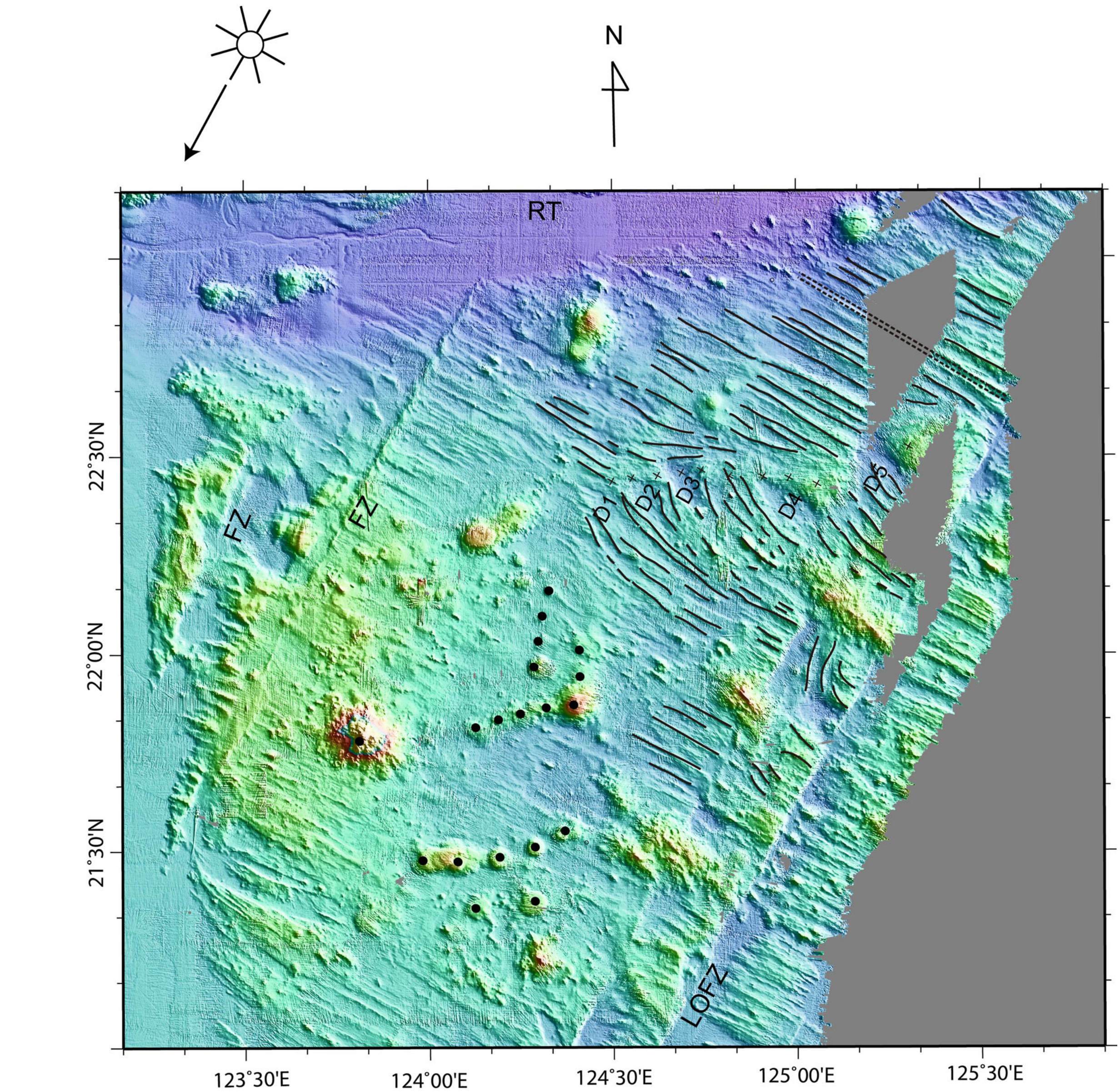


Fig. 4 Swath-bathymetric map for showing an overlapping spreading center and the V-shaped seamount chains spatial distribution. Every *black dot* represents the crest of seamount. Five fail rifted depressions (D1–D5) are identified. The V-shaped propagator was terminated by the LOFZ. *Double dashed line* indicates the possible relict spreading center

Benham Rise, magnetic stripes are also roughly in the NW–SW orientation. However, because several OSCs are distributed in this area, it is difficult to identify the oceanic crust age in this area.

The spreading pattern is complex in the west part of the WPB due to the presence of hotspot activity during spreading. In the east, spreading pattern is single and stable (Deschamps and Lallemand 2002; Okino and Fujioka 2003; Deschamps et al. 2008). When the seafloor spreading changed orientation, long ridge segments did break into shorter segments. Therefore, the arrangement of magnetic lineations in the eastern part of the WPB roughly follows the trending of the CBSC (NW–SE direction) (Fig. 5).

Age identification of the northwestern WPB and the HB oceanic crust

Northwest West Philippine Basin

In previous studies, Deschamps and Lallemand (2002) and Taylor and Goodliffe (2004) draw several NW–SE trending magnetic lineations in the area between the GR and the LOFZ, but they did not address the age. To model the age of the WPB oceanic crust between the GR and the LOFZ, we used the magnetic anomaly along profile A_1A_2 (Fig. 5), which is perpendicular to the direction of the magnetic lineations. DSDP site 293 was drilled into a thick apron of

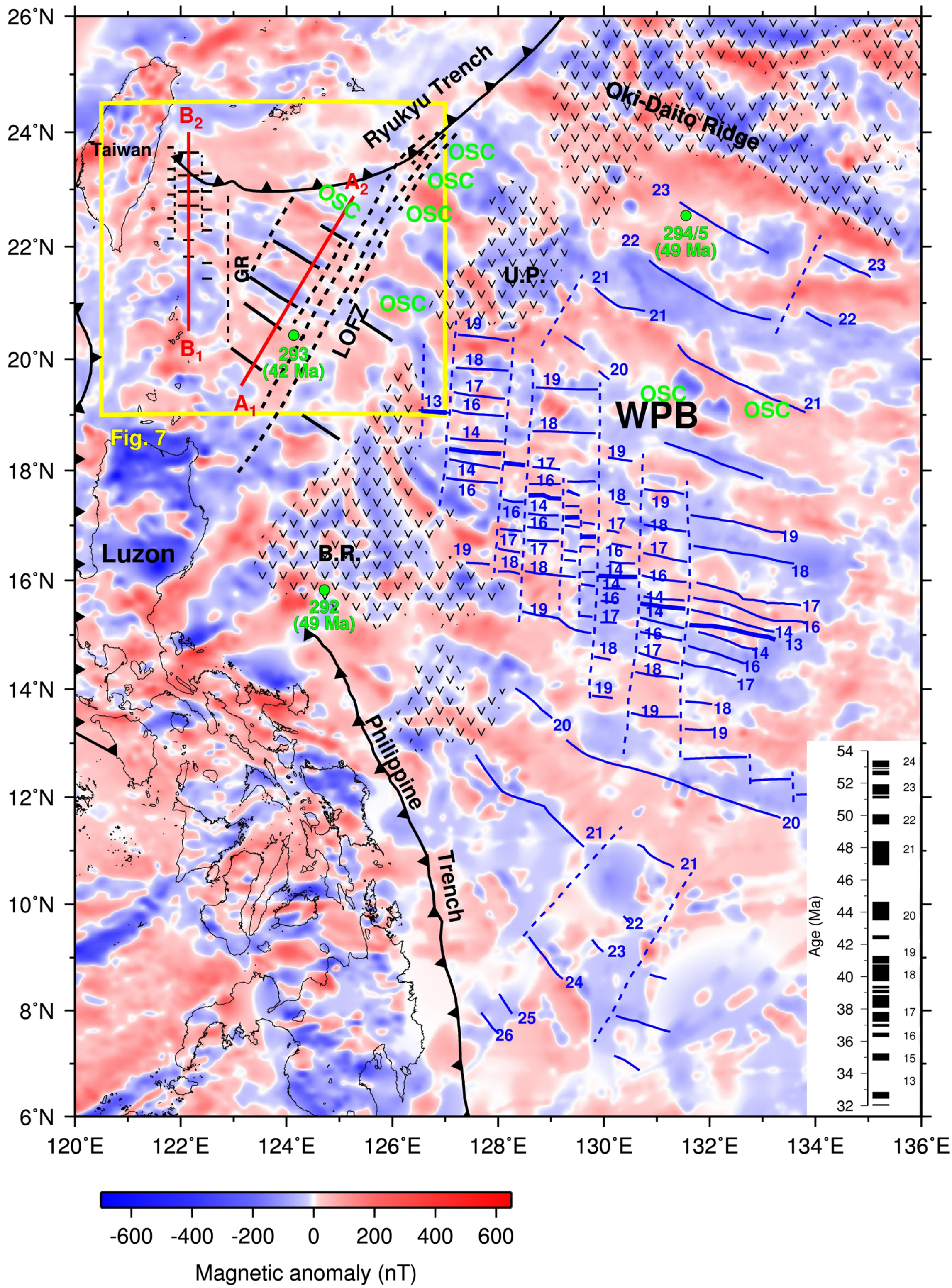


Fig. 5 New magnetic anomalies map. In east side of the LOFZ the magnetic lineations (*blue lines*) and fracture zones (*blue dashed lines*) were modified from Hilde and Lee (1984); in west side of the LOFZ the magnetic lineations (*black lines*) were identified by this study and fracture zones (*black dashed lines*) were identified from Fig. 3; in the HB the magnetic lineations were identified from Fig. 7. The *green dots* represent the DSDP sites 292, 293 and 294/5, that were dated as 42 Ma (site 293) and 49 Ma (sites 292 and 294/5) (Karig 1975; Ozima et al. 1983; Deschamps and Lallemand 2002). *OSC* overlapping spreading center

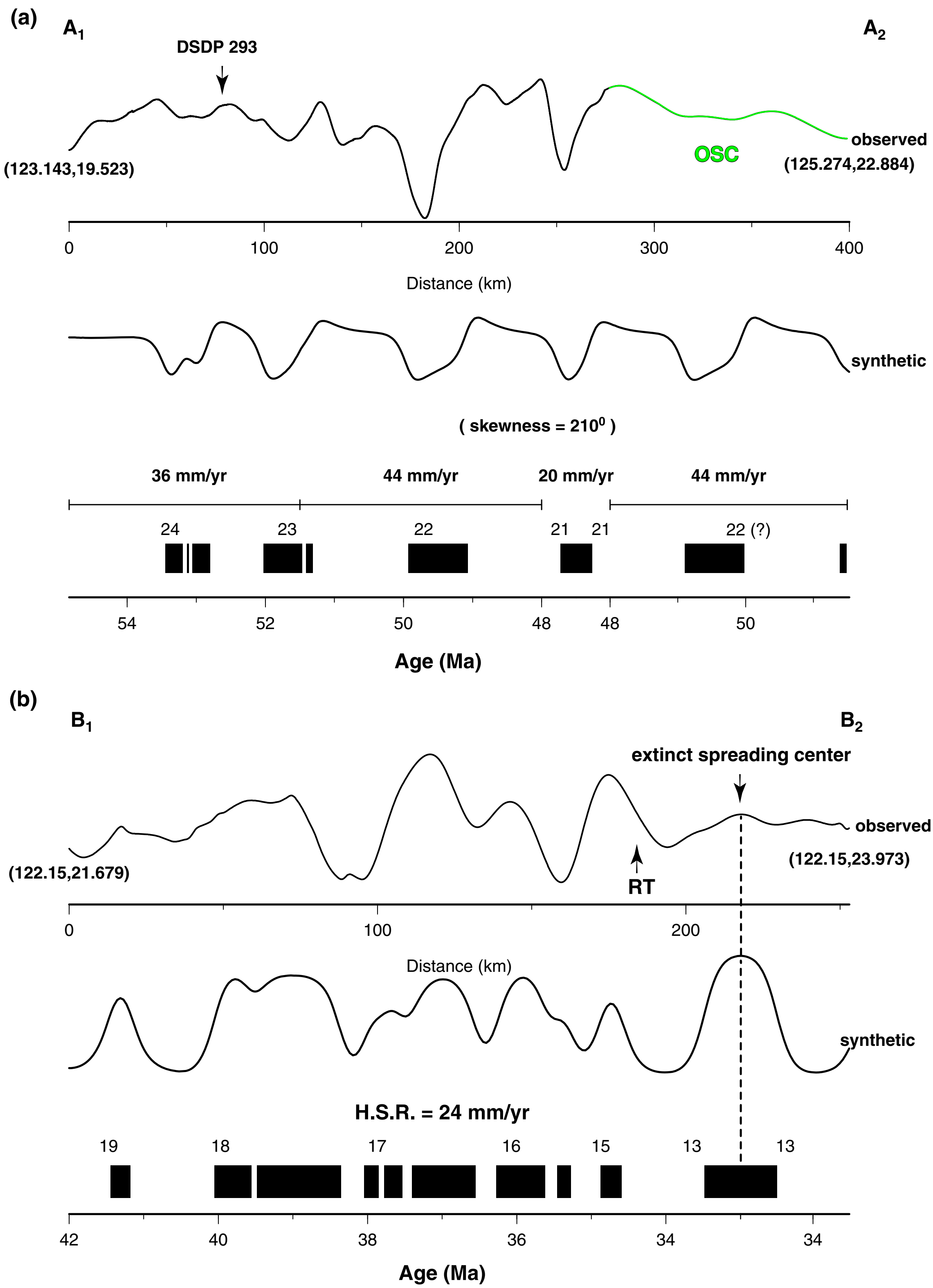


Fig. 6 **a** Observed magnetic anomalies along the profile A_1A_2 compared with synthetic profile (see the location of the profile in Fig. 5). *Black line* indicates real ship track line magnetic data. The synthetic profile is computed on the basis of the geomagnetic timescale of Cande and Kent (1995). *Black blocks* represent periods of normal polarity. The skewness parameter is set at 210°. *H.S.R.* half-spreading rate. **b** Observed magnetic anomalies along the profile B_1B_2 compared to synthetic profile (see the location of the profile in Fig. 3). Modeling adopts constant half-spreading rate. *RT* Ryukyu Trench, *MOR* mid-ocean ridge

sediments and is located in the south of our study area. The dating result indicates an age of Middle Eocene or older (42 Ma) (Karig 1975; Deschamps and Lallemand 2002). It indicates the minimum age of the oceanic crust is 42 Ma. Because the trend of the magnetic lineations between the GR and the LOFZ is similar to the trend in the east of the LOFZ (C20–C26), the age of the oceanic crust should be similar.

Due to the OSC located in the northern part of the profile A_1A_2, to avoid the ambiguity we do not take into account that part (north of 22°10′N). The geomagnetic polarity timescale of Cande and Kent (1995) is used in our modeling. We assume a 6 km thick constant layer whose top is at 6 km below sea level. Magnetization is set to be 3.0 A/m and a skewness parameter of 210°. The synthetic and observed magnetic anomalies are normalized for comparison. We have examined an extensive set of magnetic model generated with various spreading rates. We found the best fit (Fig. 6a) of a model, which suggests that the basin formed between 54 to 47.5 Ma at a half-spreading rate of 36 mm/year in the beginning 44 mm/year between 51.5 to 48 Ma, and finally down to 20 mm/year from 48 to 47.5 Ma.

Huatung basin

In order to identify magnetic anomalies in the HB, we used a N–S magnetic profile (profile B_1B_2), which cross the whole HB and is perpendicular to the direction of the magnetic lineations (Fig. 5). Suppose that the seafloor spreading pattern is similar to the WPB, the oceanic crust to the west of the GR could be younger than to the east. The parameters for modeling are the same as the WPB. We generated a magnetic anomaly model setting the constant half-spreading rate at 24 mm/year and the time of spreading onset after the northwestern WPB (between the GR and the LOFZ) spreading ceased. According to the parameters and assumptions, we calculate the synthetic magnetic anomaly. The synthetic and observed magnetic anomalies are normalized for comparison (Fig. 6b). The southward extension of E–W magnetic lineations is bordered by a linear feature oriented 331°N. South of this boundary, the pattern of magnetic anomalies is different, suggesting that the 331°N feature is a major boundary (Sibuet et al. 2002). Therefore, in our study we did not compare the part south of this boundary (dashed line shown in Fig. 7). As the synthetic result shows in Fig. 6b, only minor spreading rate variation occurred during the oceanic crust formation stage. Thus, we do not adjust the half-spreading rate and this model suggests that the HB formed between 42 to 33 Ma at a half-spreading rate of 24 mm/year. This result is similar to Hilde and Lee's (1984) result. Based on their result, C13 could be the extinct spreading center and this axis is located north of the Ryukyu Trench. This feature indicates that the extinct spreading center already subducted beneath the Ryukyu Trench.

In order to identify the age of the magnetic lineations in the HB, we select three magnetic profiles which are perpendicular to the direction of the magnetic lineation (P_1, P_2 and P_3 in Fig. 7). Profile P_2 is the same as profile B_1B_2 (Fig. 5). Based on the Profile P_2, we identified magnetic anomalies C13–C19 in profiles P_1 and P_3 (Fig. 8), and applied this result to the Fig. 7. According to our analysis result in the HB, the formation age is similar to the second spreading stage of the WPB but the spreading rate is slightly higher. Moreover, according to our study, the segments of the extinct spreading center in the HB is subducting beneath the Ryukyu Trench.

Discussion

Evolution of the West Philippine Basin

This paper mainly addresses the age and tectonic features of the northwest corner of the WPB, instead of the evolution history of the whole basin. However, due to the supplement of the geophysical data in the northwestern corner of the WPB we can have a more general idea for the evolution of the WPB. Based on the satellite-derived bathymetry data (Smith and Sandwell 1997) the CBSC morphology is clear between 133°E–127°E, but it becomes unclear west of 127°E (Fig. 1). Lewis and Hayes (1980) point out that at this longitude, the CBSC is offset to the north by a large right-lateral fracture zone, and it has probably already subducted beneath the Ryukyu Trench. Based on magnetic lineations identification, Hilde and Lee (1984) also supported the idea. Detailed bathymetric data indicate that the western termination of the CBSC is clear near 127°30′E and 18°30′N, marked by a NW–SE rift valley (Fujioka et al. 1999; Deschamps et al. 2002). Furthermore, Deschamps et al. (2008) proposed that a large graben located at ~126°E and 18°30′N probably representing the westward continuation of the CBSC. In their study, the seafloor fabrics in the area between the northwestern part of the WPB and the east of the LOFZ generally trend NW–SE, perpendicular to the LOFZ. Their orientation progressively changes from ~N133E in the northern part till ~N105E toward the south, close to the most recent locus of spreading. South of 21°N, it lacks detail bathymetry data.

Deschamps et al. (2008) point out that the northwestern part of the WPB formed through a series of northwestward propagating rifts and the LOFZ acted like a barrier to magma coming from the hotspot. Yeh et al. (2014) propose that the OSCs to the west side of the LOFZ and to the east

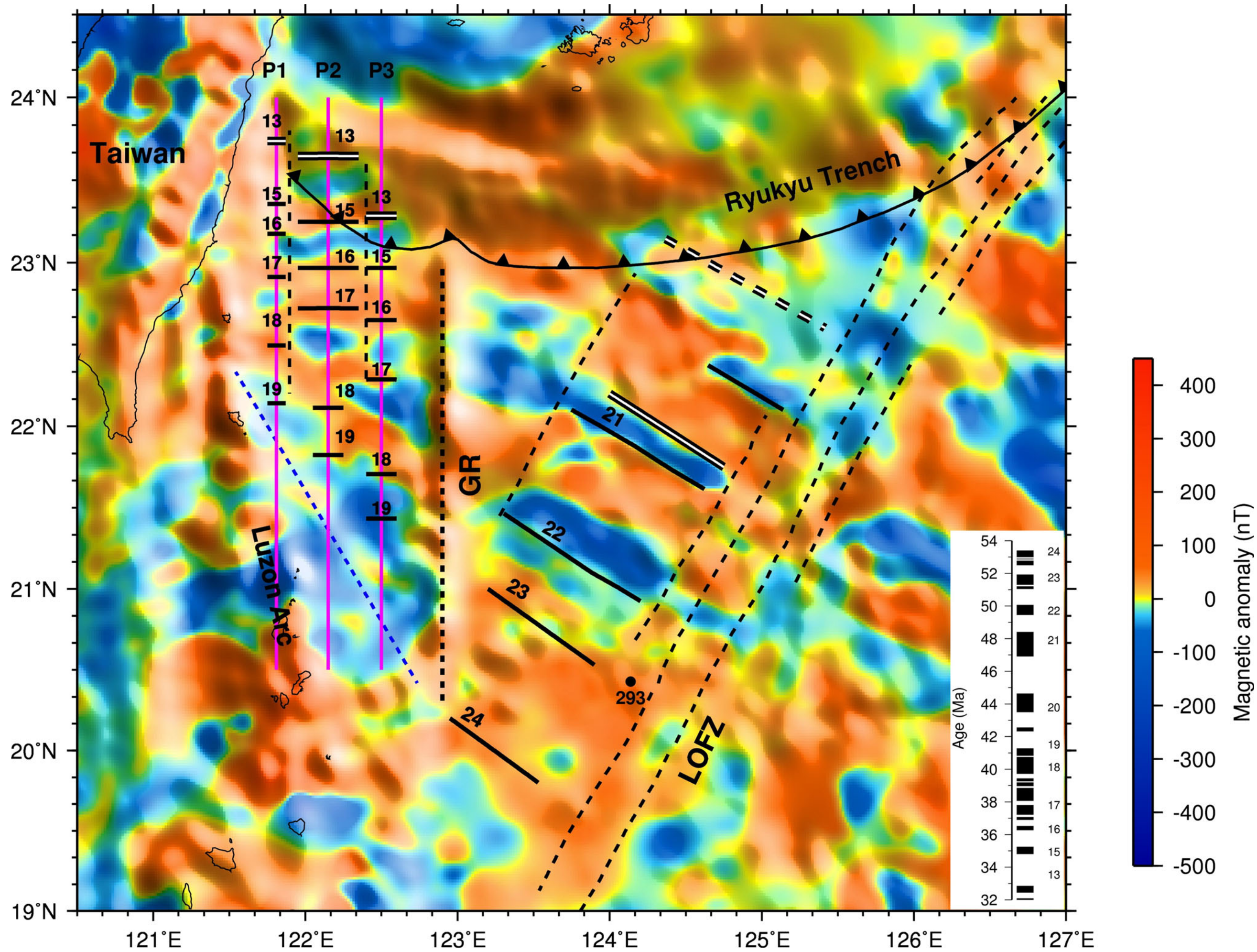


Fig. 7 Magnetic map in the northwestern West Philippine Basin. The magnetic lineations are identified by this study. *Black lines* indicate magnetic lineations; *black dashed lines* indicate fracture zones; *blue dashed line* indicates 331°N linear boundary identified by Sibuet et al. (2002)

side of the LOFZ have different magma sources based on the mantle Bouguer gravity anomaly result. According to their study, the volume of the magma source to the east of the LOFZ is larger than to the west. Thus, the spreading processes have been probably more stable in the area west of the LOFZ as shown by the presence of only one OSC and a relatively well-organized spreading fabrics. The LOFZ plays an important role in the WPB formation process. In Figs. 5 and 7, the NW–SE trending magnetic lineations are observed between the GR and the LOFZ even though the vicinity of the east of the LOFZ, which are consistent with bathymetry features.

As shown in Fig. 3, an OSC and two V-shape seamounts trains (south of the OSC) were observed between the Gagua ridge and the LOFZ. The axis of the V-shaped seamounts can point out an extinct spreading center and the OSC also indicates a spreading center. Taking into account the distance between the V-shaped seamount chain and the OSC (about 126 km), a ridge jump was inferred. If the ridge jump from north to south, we can observe the final spreading phase's feature in this area. In that case, according to bathymetry and magnetic anomaly results (Figs. 3, 7), no N–S spreading phase has occurred between the GR and the LOFZ. If the ridge jump from south to north, as Hilde and Lee's (1984) suggested, the area between the GR and the LOFZ belongs to the southern part of the WPB. The N–S spreading phase has apparently been subducted beneath the Ryukyu Trench. At about 45 Ma, perhaps due to a plate reorganization in the Pacific and a major rotation of $\sim 50°$ of the PSP which occurred between 50 and 40 Ma (Hall et al. 1995). To the east of the LOFZ, seafloor spreading continued along the CBSC, long ridge segment (NW–SE direction) did break into shorter lengths and spreading direction changes to N–S (Hilde and Lee 1984). The GR is thus the result of a transpression due to a change of motion of the PSP, which occurred at 43/45 Ma

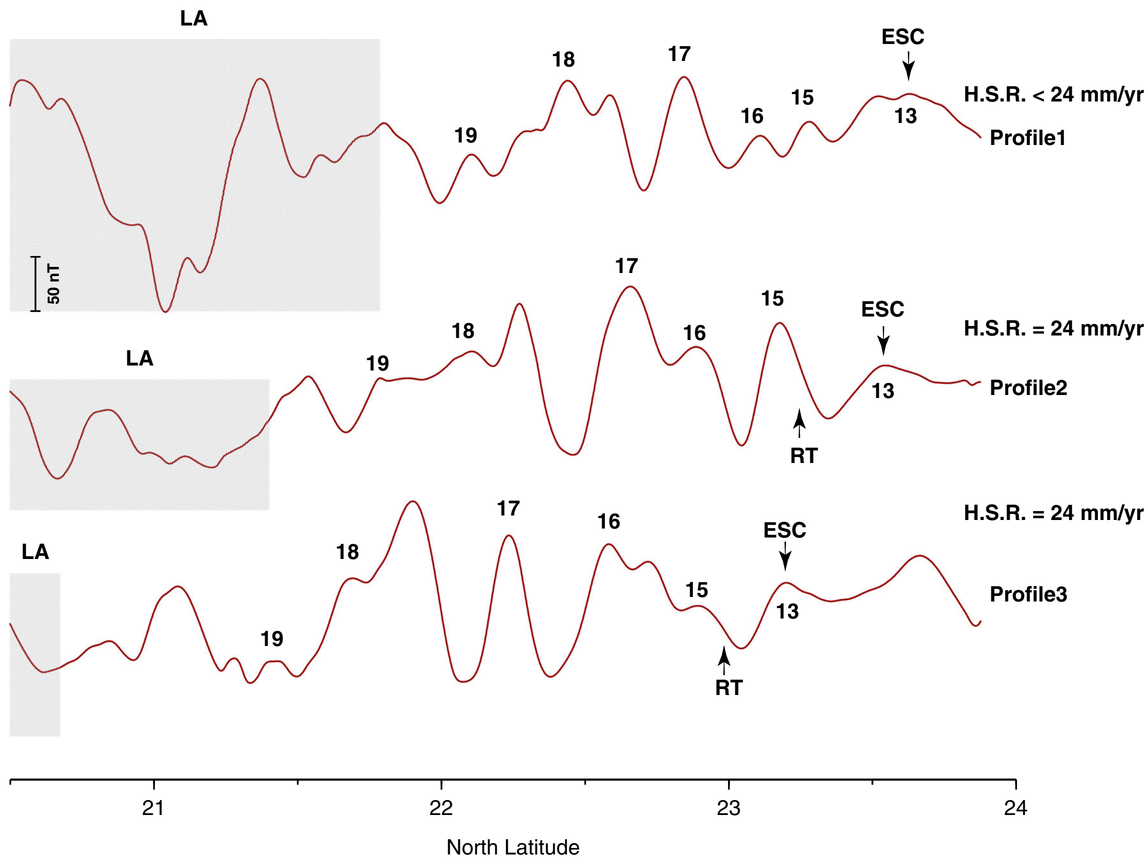


Fig. 8 Magnetic profiles (see Fig. 7 for locations). *LA* Luzon Arc, *RT* Ryukyu Trench, *ESC* extinct spreading center

(Deschamps et al. 1998). Meanwhile, the HB was formed in the N–S spreading direction, the same as the second spreading phase of the WPB. Spreading of the HB ceased (~33 Ma) roughly at the same time as the CBSC and the spreading rate is slightly higher (~24 mm/year) than CBSC (18 mm/year).

Conclusion

We have studied the geophysical characteristics of the northwestern West Philippine Basin and obtain the following conclusions:

1. The seafloor fabrics and the magnetic lineations in the northwest corner of the WPB between the GR and the LOFZ are oriented NW–SE, which suggests that the seafloor spreading was in NE–SW direction. This implies that the oceanic crust formation is related to the oceanic crust formed during the first phase of the WPB between the LOFZ and the GR. Moreover, the V-shape seamounts train indicates a southeastward propagating direction of the magma during the oceanic formation to west of the LOFZ.
2. According to our magnetic lineation identification, the oceanic crust between the GR and the LOFZ was formed between 54 to 47.5 Ma. The oceanic crust was formed at a half spreading rate of 36 mm/year in the beginning, 44 mm/year between 51.5 and 48 Ma and down to 20 mm/year at 47.5 Ma. Hilde and Lee (1984) suggest that the seafloor formed during such a N–S phase has already subducted beneath the Ryukyu subduction zone. Another possibility is that the second spreading phase has not occurred in this area.
3. According to our magnetic lineation identification, the oceanic crust in the Huatung Basin was formed between 42 to 33 Ma at a constant half spreading rate of 24 mm/year, similar to the second spreading phase of the WPB.
4. The extinct spreading center of the Huatung Basin is located near the southernmost Ryukyu subduction zone. Furthermore, it shows a strong plate coupling between the overriding and subducting plates (Hsu 2001) in the same area. Seismic hazard analysis and

evaluation is needed for the southernmost Ryukyu subduction zone area.

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