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The West Philippine Basin: An Eocene to early Oligocene back arc basin opened between two opposed subduction zones

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[1] Based on geological and geophysical data collected from the West Philippine Basin and its boundaries, we propose a comprehensive Cenozoic history of the basin. Our model shows that it is a back arc basin that developed between two opposed subduction zones. Rifting started around 55 Ma and spreading ended at 33/30 Ma. The initial spreading axis was parallel to the paleo-Philippine Arc but became inactive when a new spreading ridge propagated from the eastern part of the basin, reaching the former one at an R-R-R triple junction. Spreading occurred mainly from this second axis, with a quasi-continuous counter-clockwise rotation of the spreading direction. The Gagua and Palau-Kyushu ridges acted as transform margins accommodating the opening. Arc volcanism occurred along the Palau-Kyushu Ridge (eastern margin) during the whole opening of the basin, whereas the paleo-Philippine Arc decreased its activity between 43 and 36 Ma. The western margin underwent a compressive event in late Eocene-early Oligocene time, leading to the rising of the Gagua Ridge and to a short subduction episode along Eastern Luzon. In the western part of the basin, the spreading system was highly disorganized due to the presence of a mantle plume. Overlapping spreading centers and ridge jumps occurred toward the hot region and a microplate developed. Shortly after the end of the spreading, a late stage of amagmatic extension occurred between 30 and 26 Ma in the central part of the basin, being responsible for the deep rift valley that cut across the older spreading fabric. *INDEX TERMS:* 3040 Marine Geology and Geophysics: Plate tectonics (8150, 8155, 8157, 8158); 3035 Marine Geology and Geophysics: Midocean ridge processes; 8157 Tectonophysics: Evolution of the Earth: Plate motions—past (3040); 9320 Information Related to Geographic Region: Asia; *KEYWORDS:* Philippine, back arc, Southeast, Asia, geodynamic, model

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1. Introduction

[2] The West Philippine Basin (WPB) is a wide oceanic basin covering most of the western part of the Philippine Sea Plate (PSP). Despite its unusually great size, it has not been intensively studied, and its Cenozoic history is still controversial. Several models have been proposed for the kinematic evolution of Southeast Asia during the Tertiary, each of them integrating the formation of the WPB in various ways. We classify the published models into two groups, one considering the WPB as a trapped piece of a larger oceanic plate, and the other regarding it as a back arc basin.

[3] The first "entrapment model" was proposed by *Uyeda and Ben Avraham* [1972], and was modified by *Uyeda and McCabe* [1983]. According to them, the WPB resulted from the entrapment of a segment of the Kula-Pacific Ridge in the Middle Eocene time behind the newly formed Palau-Kyushu Ridge, during a plate reorganization. This model was adopted by *Hilde and Lee* [1984]. Later, *Jolivet et al.* [1989] proposed a variant of this model, in which the WPB was formed by trapping of a piece of the North New Guinea/Pacific Ridge, during the Middle Eocene. The main argument supporting this entrapment origin is the high angle between the fossil spreading axis and the paleo-volcanic arc (the Palau-Kyushu Ridge) [*Mrozowski et al.*, 1982; *Hilde and Lee*, 1984].

[4] On the other hand, *Lewis et al.* [1982] first proposed a back arc origin for the formation of the WPB. These authors suggested that the basin opened behind a subduction zone located along the East Mindanao-Samar Arc. *Seno and Maruyama* [1984], *Rangin et al.* [1990], and *Lee and Lawver* [1995] also suggested that the WPB is a back arc basin. However, in Seno's model, the basin would have opened behind a subduction zone located along the Palau-

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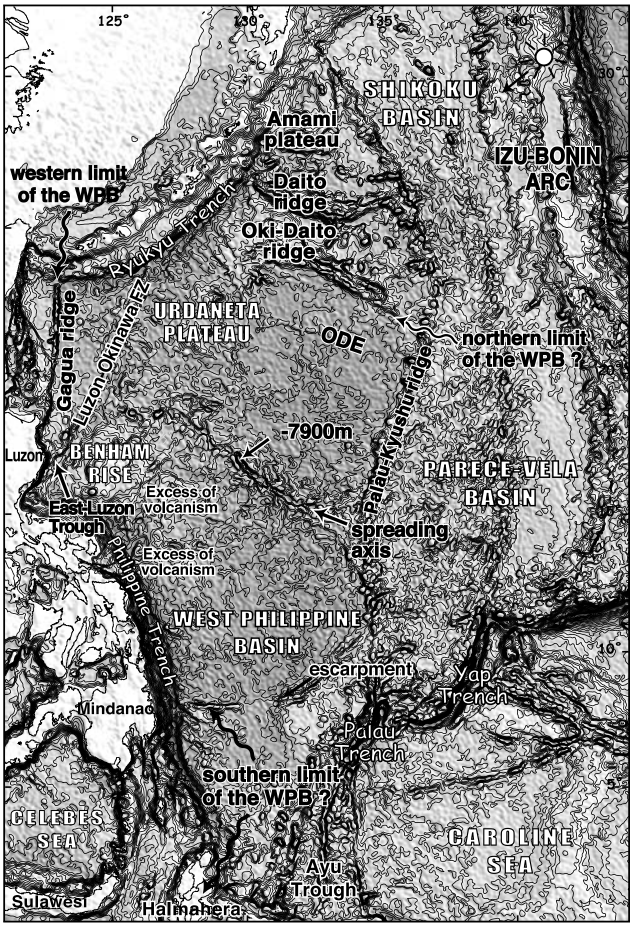

Figure 1. Contoured and shaded view of the satellite-derived bathymetry [*Smith and Sandwell*, 1997] of the Philippine Sea Plate and major seafloor features of the West Philippine Basin. ODE: Oki-Daito Escarpment.

Kyushu Ridge beginning at 48 Ma. Finally, *Hall et al.* [1995a, 1995b] and *Hall* [1997, 2001] suggested that the WPB is a back arc basin that opened between two active subduction zones, and that the plate has undergone a strong clockwise rotation during its development. Concerning the formation of the WPB, these models are based on the spreading history proposed by *Hilde and Lee* [1984] from their interpretation of magnetic anomalies within the basin.

[5] Our data support Hall's model while providing much more details of the spreading processes. In this paper, we attempt to show how recent data that have been collected onshore and offshore in the region during the last decade, help to better understand the Cenozoic history of the WPB. We propose a model of formation that integrates former and new data that have been collected within the basin. It takes into account the magmatic and tectonic events that occurred along its margins since the Early Eocene, and paleomagnetic data that give information about the drift of the basin and its margins. We are therefore able to determine how the basin was formed and what the driving forces for the opening were. Our study also provides arguments that demonstrate that the WPB is a back arc basin opened between two opposed subduction zones.

2. Tectonic Setting and Main Morphological Features of the WPB

[6] The West Philippine Basin (WPB) subducts at the Ryukyu Trench to the north, and at the Philippine Trench to the west (Figure 1). Between the two subduction zones, the western boundary of the basin is located along the Gagua Ridge, a linear and prominent oceanic ridge which separates the small oceanic Huatung Basin from the WPB [*Deschamps et al.*, 1998, 2000; *Sibuet et al.*, 2002]. To the east, the WPB is bounded by the Palau-Kyushu Ridge, an inactive volcanic arc [*Karig et al.*, 1975]. The basin is limited to the north by the Cretaceous to Early Eocene Amami-Oki-Daito region [*Matsuda et al.*, 1975; *Ozima et al.*, 1983; *Hickey-Vargas*, 1998]. The southern boundary of the WPB is not well defined because of the lack of detailed data in the southernmost part of the PSP. It could be located around 8–10°N, along a curved escarpment which separates two domains with different depths [*Mrozowski et al.*, 1982], or further south at the latitude of Halmahera (Figure 1).

[7] The depth of the WPB ranges between 5000 and 6000 m. The fossil spreading axis is an axial valley whose depth locally reaches 7900 m [*Fujioka et al.*, 1999] (Figure 1). In the western part of the basin, it is less obvious in the bathymetry, especially west of a major NNE-SSW fracture zone named the Luzon-Okinawa Fracture Zone. In this region, the sea bottom shallows at the vicinity of the Benham and the Urdaneta plateaus. The Benham Rise culminates at 38 m below the sea level [*Karig et al.*, 1975]. According to *Hilde and Lee* [1984], it represents the counterpart of the Urdaneta Plateau, and both plateaus were formed by an excess of volcanism at the WPB spreading axis.

3. Spreading in the West Philippine Basin Based on Bathymetric and Magnetic Data

[8] Bathymetric and magnetic data recently collected in the WPB during Japanese and French cruises provide information about spreading in the basin (Figure 2) [*Oshima et al.*, 1988; *Matsumoto et al.*, 1993; *Ohara et al.*, 1997; *Lallemand et al.*, 1997; *Deschamps et al.*, 1999; *Fujioka et al.*, 1999; *Okino et al.*, 1999; *Fujioka et al.*, 2000; *Okino and Fujioka*, 2002].

3.1. Seafloor Fabric

[9] In the northeastern part of the basin, bathymetric data reveal the presence of a southerly facing WNW-ESE escarpment, named the Lapu-Lapu anomaly by *Mrozowski et al.* [1982] and the Oki-Daito escarpment (ODE) by *Ohara et al.* [1997] (Figure 3). This feature roughly parallels the Oki-Daito Ridge, which is located more to the north (Figure 1). The seafloor fabric abruptly changes across the ODE. North of the escarpment, abyssal hills trend N170, whereas south of it, they are NW-SE oriented (Figures 3, 4, and 5). We note that the basin floor is shallower north of the ODE compared to the south, but the spacing of hills north and south of the escarpment is about the same, suggesting a formation with a roughly similar spreading rate [*Okino et al.*, 1999, Figure 2]. In the far northwestern part of the basin, bathymetric data again show that the basin floor is relatively shallow, and that abyssal hills roughly trend N-S [*Oshima et al.*, 1988] (Figure 5). In its southwestern part,

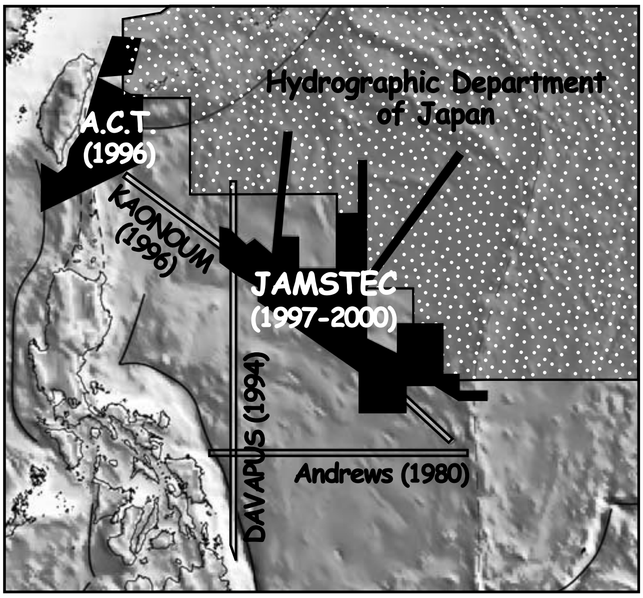

Figure 2. Area where geophysical data used in this study have been acquired during oceanographic cruises. It includes the A.C.T. cruise, KAONOUM transect [*Lallemand et al.*, 1997], DAVAPUS transect [*Lallemand et al.*, 1998], JAMSTEC STEPS cruises [*Fujioka et al.*, 1999], the Hydrographic Department of Japan cruises [*Ohara et al.*, 1997] and an E-W transect along which only side-scan sonar imagery data have been collected [*Andrew*, 1980].

close to the Philippine Trench, the spreading fabric clearly trends N170 (Figures 5 and 6), showing that the spreading fabric is close to N-S in the oldest parts of the WPB.

[10] North of the spreading center, the trend of abyssal hills as well as magnetic anomalies is broadly NW-SE, perpendicular to the Palau-Kyushu Ridge and to the Luzon-Okinawa Fracture Zone [*Okino et al.*, 1999; *Fujioka et al.*, 1999; *Deschamps*, 2001] (Figures 4 and 5). In general, hills and magnetic anomalies are well organized, except in the vicinity of the Urdaneta Plateau. Magnetic anomalies are erratic in this region [*Okino et al.*, 1999] and overlapping spreading centers have been evidenced, as shown by the presence of 30 km-wide corridors displaying discordant spreading fabric (Figure 5) [*Yoshida et al.*, 2000]. Only scarce data are available close to the Benham Plateau. They reveal discordant but well-marked NNE-SSW bathymetric features that interrupt N170-trending abyssal hills (Figure 7 and see at 16°50′N on Figures 4 and 5). These features are typical of a triple junction trace [*Pockalny et al.*, 2001; *Viso et al.*, 2001]. Another trace of a triple junction is evidenced more to the north, between latitudes 19°00′N and 19°30′N. In between these two traces of triple junction, the rift valley is no longer present, the spreading fabric is highly disturbed and displays various trends, and the seafloor is shallower (Figures 1, 4, and 5).

[11] In the central part of the basin, when approaching the spreading axis, abyssal hills are more E-W-oriented, and close to the axis, they trend N70/80E. The spreading fabric rotates progressively from a NW-SE to N70/80E orientation. In the eastern part of the basin, abyssal hills that are located within a distance of 100 km from the rift valley are interrupted by several nontransform discontinuities (NTDs) trending N10/20W [*Deschamps et al.*, 1999; *Deschamps*, 2001] (Figures 4 and 5). These discontinuities are expressed as diffuse and gently sinuous valleys that run perpendicular to the spreading fabric. In the central part of the basin, the rift valley is dextrally offset by two transform faults (TFs) which also trend N10W [*Fujioka et al.*, 1999] (Figures 4 and 5). Surprisingly, in most places, the rift valley trends N140E to N110E [*Fujioka et al.*, 1999], neither parallel nor perpendicular to the spreading fabric or the TFs and NTDs. Abyssal hills that parallel the axial valley are found only within a very narrow strip of seafloor on both sides of the valley (Figures 4 and 5).

3.2. Interpretation: Spreading Directions in the WPB

[12] The trend of the magnetic anomalies and of the seafloor structures helps us to determine the history of spreading in the WPB. In order to interpret the trend of the fabric in term of direction of spreading, we make the assumption that the spreading direction was perpendicular to the fabric. Abyssal hills are indeed always perpendicular (within 5°) to the spreading direction, even in the case of oblique rifting as observed along the Reykjanes and Mohns ridges (Norwegian Sea) [*Dauteuil and Brun*, 1993, 1996] and also in the Gulf of Aden rift [*Dauteuil et al.*, 2001]. Based on this assumption, spreading occurred in an E–W to ENE–WSW direction perpendicular to the N–S spreading fabric during the first phase of spreading in the WPB (Figure 8). The shallow depth of the seafloor in the domains formed during this oldest spreading episode may indicate excess of volcanism at the spreading axis. After this first spreading phase, the direction of spreading evolved rapidly toward a NE-SW direction [*Okino et al.*, 1999; *Fujioka et al.*, 1999; *Deschamps*, 2001] (Figures 4, 5, and 8). The direction of opening then became parallel to the Palau-Kyushu Ridge and to the Luzon-Okinawa Fracture Zone. Excess of volcanism at the spreading axis would have been responsible for the formation of the Urdaneta and Benham plateaus, and also for the disorganization of the spreading system (ridge jumps and overlapping spreading centers) in the western part of the basin.

[13] After the NE–SW spreading phase, the direction of spreading continuously rotated counter-clockwise [*Deschamps*, 2001] (Figure 8). Northwest of the Benham

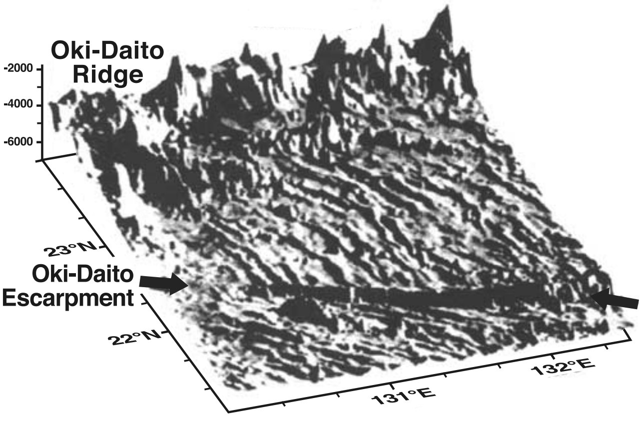

Figure 3. Three-dimensional bathymetric image of the Oki-Daito Escarpment, showing the abrupt change of the seafloor fabric direction across the escarpment. Modified from *Ohara et al.* [1997].

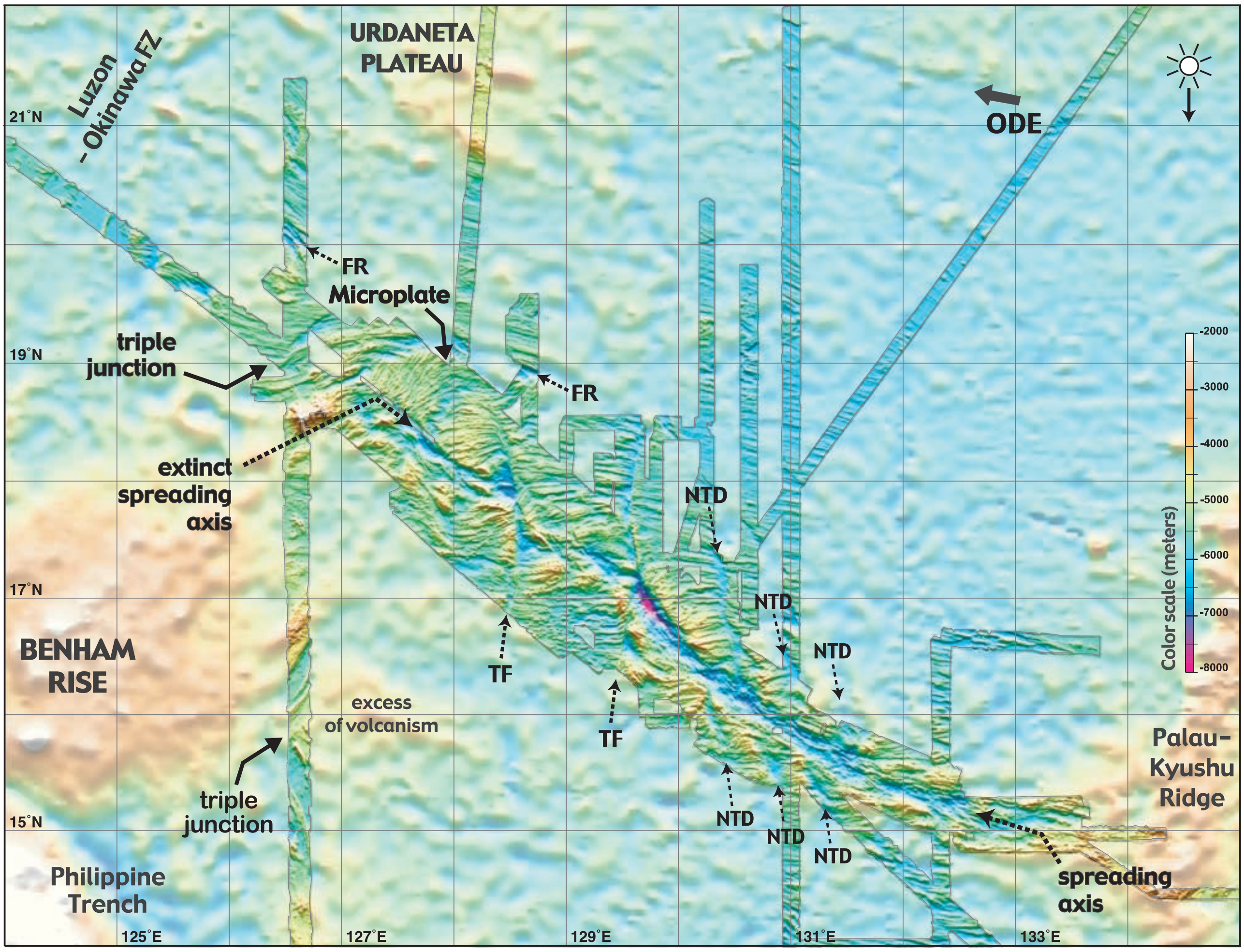

Figure 4. Bathymetric map from the central part of the West Philippine Basin obtained by swath mapping during several Japanese and French cruises. See Figure 2 for references. *Smith and Sandwell*'s [1997] satellite-derived bathymetric data are used when detailed data are not available in digital format. ODE: Oki-Daito Escarpment, TF: Transform Fault, NTD: Non-Transform Discontinuity, FR: Failed Rift.

Rise, fan-shaped abyssal hills are found within a 1000-km^2 area that is bordered by elongated valleys. They reveal the presence of a microplate which developed between two active spreading centers (Figures 4 and 5) [*Deschamps et al.*, 1999]. Toward the end of the opening, spreading occurred in a N10/20W direction, parallel to the TFs and NTDs, and the spreading rate progressively slowed down, as shown by the increasing height and spacing of abyssal hills. Finally, in the central and eastern parts of the basin, a late stage of amagmatic extension was probably responsible for the NW–SE orientation of the rift valley and its associated steep escarpments, which are related to large normal faults (Figures 4, 5, and 8). This episode was probably brief since abyssal hills that parallel the axial valley are found only within a very narrow strip of seafloor on both sides of the valley (Figures 4 and 5). A low supply in magma during this latest episode could explain the great depth of the spreading axis as proposed by *Deschamps et al.* [1999]. Dextral shear along the rift valley identified by *Deschamps et al.* [1999] would be responsible for its great depth. In the western part of the basin, close to the Benham Rise, the NE–SW to NNE–SSW abyssal hills observed between two triple junction traces (Figures 4, 5, and 7) attest for a NW–SE to WNW–ESE spreading episode in this area.

4. Duration of the Spreading

4.1. Age Determinations Over the WPB

[14] Several age determinations have been performed on igneous and sedimentary rocks from the WPB. These rocks have been either cored [*Karig*, 1975], dredged [*Shecheka et al.*, 1995], or sampled during dives [*Fujioka et al.*, 1999; R. Shinjo, University of Ryukyus, personal communication, 2001]. Results of dating are summarized in Table 1a, and plotted in Figure 9. Available ages range from 50 to 15 Ma. This indicates that volcanism occurred within the WPB between the Early Eocene and the Middle Miocene. However, the ages determined on igneous rocks within the basin cannot simply be interpreted as recording the spreading in the basin, because most of the youngest ages were measured on OIB-like basalts [*Shecheka et al.*, 1995; *Hickey-Vargas*, 1998]. Volcanic activity related to the presence of a hot spot in the region may have occurred during the spreading and even later [*Hickey-Vargas*, 1998].

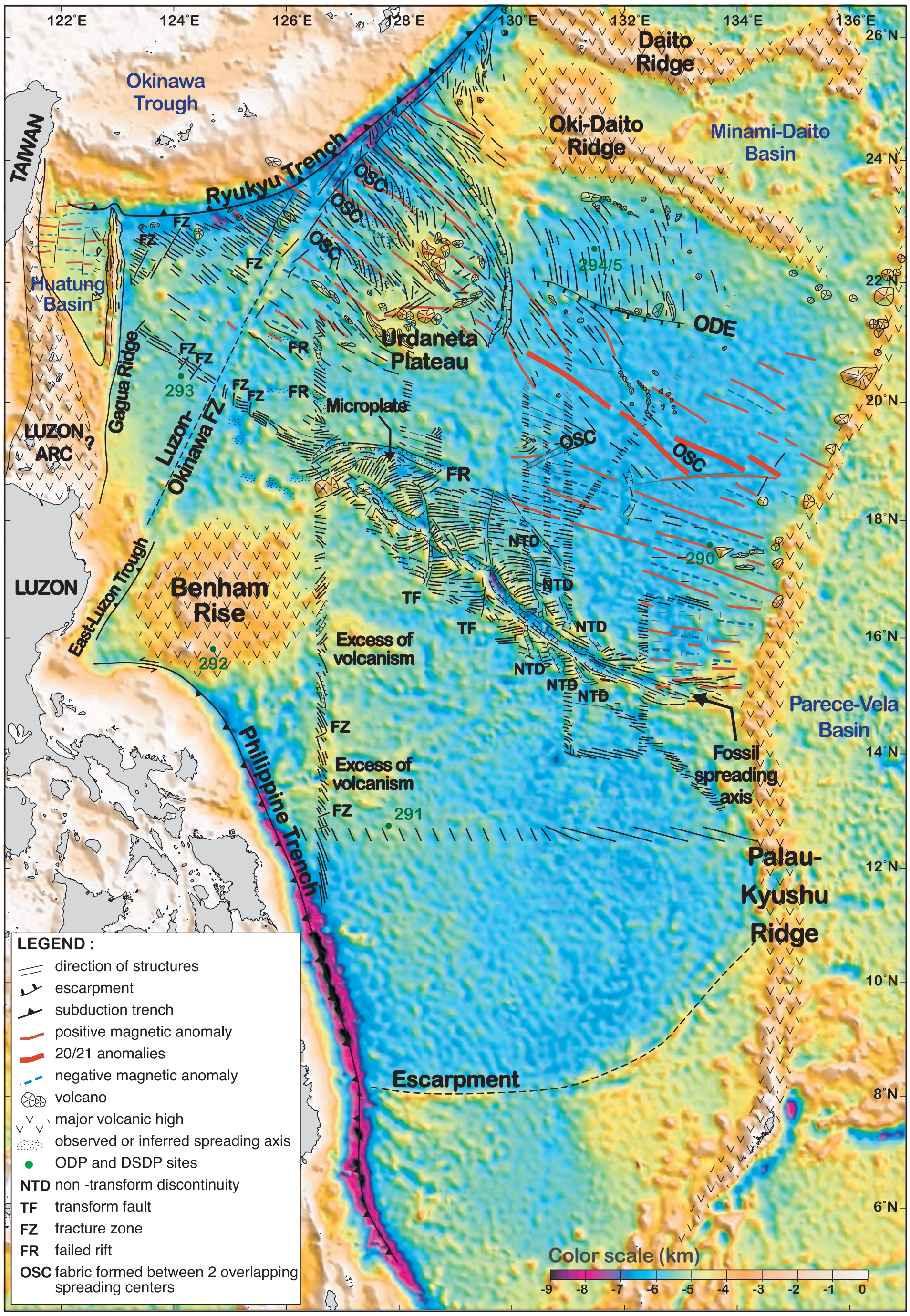

Figure 5. Structural map of seafloor structures, including orientation of main magnetic anomalies, when available. Bathymetric map is made with *Smith and Sandwell*'s [1997] data.

[15] Ages that have been measured on igneous rocks from the WPB do not automatically reflect the activity of the spreading axis but the identification of magnetic anomalies, combined with these data, helps us to better determine the timing of the opening.

4.2. Magnetic Anomalies Identifications

[16] Several identifications of the magnetic anomalies within the WPB have been proposed, giving rise to a variety of spreading models. *Shih* [1980] proposed that the basin formed between 56 Ma and 25.5 Ma, with a constant NE-SW opening direction. *Mrozowski et al.* [1982] suggested formation with the same spreading direction between 43 Ma and 37 Ma. *Hilde and Lee* [1984] proposed that the basin formed between 58 and 33 Ma by two phases of spreading: the first between 58 and 45 Ma in a NE-SW direction, and the second between 45 and 33 Ma in a N-S direction. The recent discovery of several ages of 28, 26 and 14.9 Ma in the vicinity of the spreading axis (see previous paragraph), as well as greater details in the seafloor fabric and in the trend of magnetic anomalies [*Okino et al.*, 1999] (Figures 5 and 10), justify the reexamination of this last model.

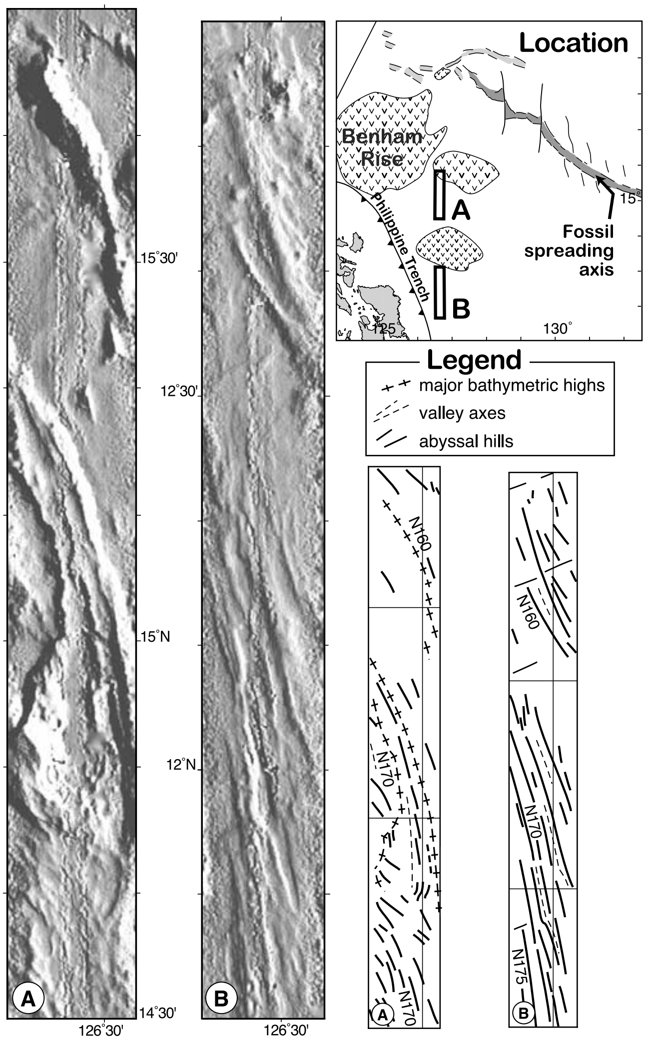

Figure 6. 2D shaded view (from NE) and structural interpretation of the seafloor fabric at two locations in the southern part of the West Philippine Basin (DAVAPUS data after *Lallemand et al.* [1998] and with permission of C. Rangin). Abyssal hills display a general N170E trend.

[17] On the magnetic map, we note the presence of a large positive anomaly (Figure 10), characteristic of anomalies 20 and 21 that are observed in several places in the Pacific Ocean. The identification of these anomalies is common with those obtained by Hilde and Lee, and the spreading rates they have used are entirely consistent with the roughness of the sea bottom observed by *Fujioka et al.* [1999], *Deschamps et al.* [1999], and *Deschamps* [2001]. Hilde and Lee's model proposes an intermediate spreading rate during the first phase of spreading, and then a slow spreading rate during the second phase. This slowing down of the spreading rate is consistent with the increasing amplitude and height of abyssal hills when approaching the spreading axis [*Deschamps*, 2001]. However, concerning the region that is situated north of the ODE, we differ from Hilde and Lee's model. New bathymetric data from this part of the basin [*Okino et al.*, 1999] show that the spreading fabric trends N-S, obliquely to the tracks along which magnetic anomalies were identified (Figures 3, 5, and 10). We therefore revise their model concerning this oldest part of the basin, and in order to infer an age for the beginning of the spreading, we extrapolate the spreading rates that are suggested by their model perpendicular to the trend of abyssal hills. However, the limited amplitude and height of the abyssal hills north of the ODE suggest that the spreading rate could have been a little bit higher north of this escarpment. We therefore infer an age of about 54 Ma for the beginning of the spreading in the WPB. Using a 50 km/Ma spreading rate, 4 Ma is the period of time needed to form the 200 km of seafloor between the ODE and the northeastern boundary of the basin, if measured perpendicular to the spreading fabric. The youngest anomaly which has been identified near the spreading axis is anomaly 13 (33 Ma) but it is possible that the activity of the ridge lasted a few m.y. beyond this, at an extremely slow rate with a tiny magnetic signature.

4.3. Conclusion: Age of Spreading in the WPB

[18] From the identification of the magnetic anomalies and extrapolation of the spreading rate to the oldest parts of the basin, we suggest that spreading may have occurred in the WPB from approximately 54 Ma to 33/30 Ma. Age determinations show possible magmatic activity at the ridge axis between 28 and 15 Ma (Figure 9 and Table 1a). We suggest that the late and short NE–SW stage of opening that occurred in the central part of the basin (see section 3.2) may have occurred after the end of spreading, near 28–26 Ma. It is possible that there is no clear magnetic anomaly associated with this event since only few tens of kilometers of seafloor were produced at that time. We ignore the 15 Ma age that has

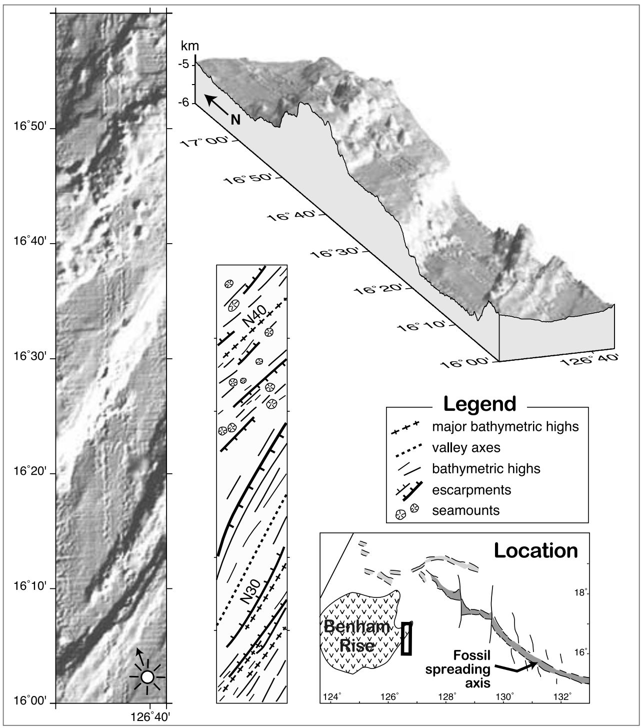

Figure 7. 2D and 3D-shaded views from the northeastern corner of the Benham Rise, with structural interpretation. Abyssal hills and faults are N30 to N40E-oriented. The presence of many small-size seamounts indicates excess of volcanism from a NE-SW to NNE-SSW active spreading axis (DAVAPUS data after *Lallemand et al.* [1998] and with permission of C. Rangin).

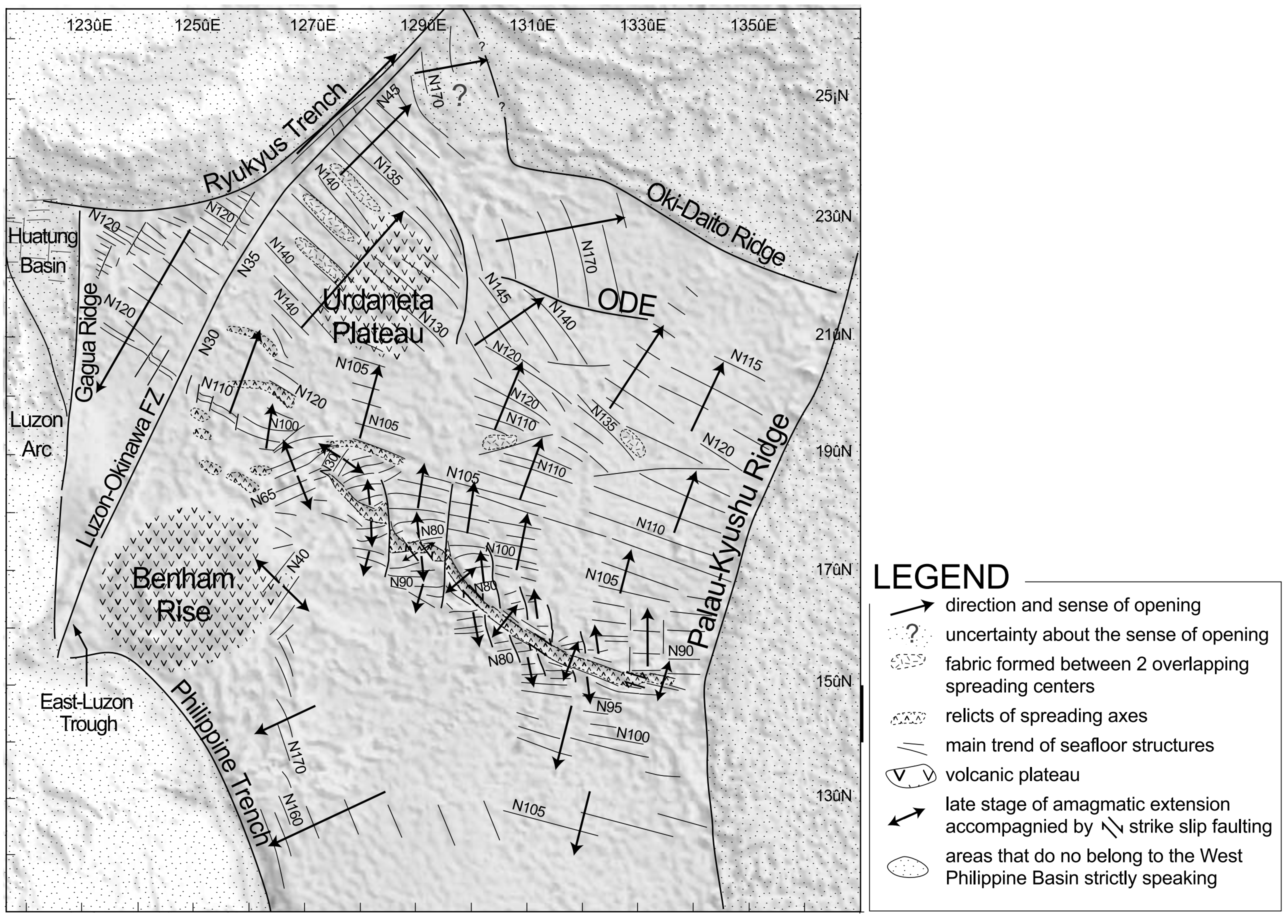

Figure 8. Direction of opening within the West Philippine Basin, deduced from seafloor structures and magnetic anomalies study.

been determined on only one sample collected very close to the 28 and 26 Ma samples [*Fujioka et al.*, 1999].

5. Cenozoic Volcanic Arc Activity at the WPB Borders

[19] Our model of reconstruction of the WPB includes new constraints on the spreading history of the basin and takes into account the tectonic and volcanic events that occurred along its margins. We first attempted to define precisely the boundaries of the basin, and then tried to clarify its geodynamic context.

5.1. Boundaries of the WPB

[20] The WPB is limited to the west by the Gagua Ridge and the Huatung Basin (Figures 1 and 11). According to *Hilde and Lee* [1984], this basin is Eocene in age and belongs to the WPB. However, morphological and geophysical studies of the Gagua Ridge performed by *Deschamps et al.* [2000] show that the ridge is a plate boundary of the WPB rather than an intraoceanic fracture zone of the WPB. Partly based on the results of paleontological and ^{40}Ar/^{39}Ar radiometric laser-dating of rocks from the Huatung Basin and the basement of the Luzon Arc, and on magnetic anomalies identification performed on eight profiles strictly perpendicular to them, *Deschamps et al.* [2000] demonstrated that the basement of the Huatung Basin is Early Cretaceous, and that the Gagua Ridge acted as a plate boundary between this basin and the WPB. Their identification of anomalies is fully consistent with a deep-tow magnetic profile acquired in 1999 [*Lee et al.*, 1999]. On the other hand, *Sibuet et al.* [2002] argue for an Eocene age for the Huatung basin, based only on the identification of magnetic anomalies along three of the eight profiles across the basin, and ignoring the datings of basement rocks. In any case, *Sibuet et al.* [2002] and *Deschamps et al.* [2000] agree in that the Gagua Ridge is a former strike-slip plate boundary and represents the western limit of the WPB.

[21] Concerning the northward extension of this limit, *Lallemand et al.* [2001] have evidenced with the help of tomographic sections in the area of the Ryukyu Trench, a slab detachment which occurred 3–5 years ago along a weak zone. Such a weak zone parallels the Okinawa-Luzon FZ and appears to be a good candidate for the northwestern boundary of the WPB, which is the limit between the WPB and the Early Cretaceous oceanic domain that should extend north of the Gagua Ridge (Figure 11).

[22] The Gagua Ridge connects southward with the eastern coast of Luzon. We infer that Luzon and the eastern belt of the Philippine archipelago represent the southwestern boundary of the WPB. Numerous ophiolitic rocks have been described in the Philippine Mobile Belt, from East Halmahera up to northern Luzon (Figure 11) [e.g., *Bureau of Mines and Geosciences* (*BMG*), 1982; *Karig*, 1982, 1983;

Table 1a. Nature and Age of Rocks Recovered From the West Philippine Basin (Strictly Speaking)[a]

Site	Location	Nature of Dated Rocks	Age	Source
290/290A, Leg 31	17°44.85′N/133°28.08′E	- sediments	- Late Eocene/Oligocene or older	*Karig et al.* [1975]
	17°45.05′N/133°28.44′E	- reworked fossils	- Upper Cretaceous	
291/291A, Leg 31	12°48.43′N/127°49.85′E	- nannofossils and radiolarians	- Late Eocene	- *Karig et al.* [1975]
	12°48.45′N/127°49.98′E, (Southwest BWP)		- 48 Ma (basement)	- *Louden* [1976]
		- basalt (plagioclases)	- 42.6 Ma, 43.9 Ma (Ar/Ar isochron)	- *Hickey-Vargas* [1998]
292, Leg 31	15°49.11′N/124°39.05′E (Benham Rise)	- nannofossils	- Late Eocene or older	- *Karig et al.* [1975]
		- basalt	- 38.2 Ma, 37.1 Ma (K/Ar - w. rock)	- *McKee* [1974]
		- basalt	- 49.4 ± 2 Ma (Ar/Ar - w. rock)[1]	- *Ozima et al.* [1983]
		- basalt (plagioclases)	- 35.5 Ma, 36.2 Ma (Ar/Ar isochron)	- *Hickey-Vargas* [1998]
293, Leg 31	20°21.25′N/124°05.65′E (West BWP)	- sediments	- Late Eocene or older	- *Karig et al.* [1975]
		- reworked fossils	- Upper Cretaceous & late Eocene	
		- gabbros (in breccia)	- 42 Ma (Ar/Ar - w. rock)[2]	- *Ozima et al.* [1983]
294/295, Leg 31	22°34.74′N/131°23.13′E	- alkaline basalt	- 48.8 ± 2 Ma (Ar/Ar - w. rock)[1]	- *Ozima et al.* [1983]
	22°34.76′N/131°22.04′E (Northern BWP)	- basalt	- 19.7 Ma, 18.7 Ma (Ar/Ar isochron)	- *Hickey-Vargas* [1998]
		- reworked fossils	- Paleocene-Early Eocene	- *Karig et al.* [1975]
296, Leg 31	22°34.74′N/131°23.13′E	- sediments	- early Oligocene?	- *Karig et al.* [1975]
	29°20.41′N/133°31.52′E	- lapilli tuffs	- 48 Ma (Ar/Ar - w. rock)[2]	- *Ozima et al.* [1983]
447, DSDP 58	18°00.88′N/133°17.37′E (East BWP)	sediments	Middle Oligocene or older	*Karig et al.* [1975]
Vinogradov seamount	18°33.9′E/126°41.9′N	- alkaline basalt (3V-51-2)	- 22 ± 2 Ma (K/Ar)	*Shecheka et al.* [1995]
		- trachyte (3V-24-2)	- 26 ± 3 Ma (K/Ar)	
Urdenata Plateau	- 21°25.0′N/128°30.5′E	- alkaline basalt (2834-1-2)	- 39.1 ± 3 Ma (K/Ar)	*Shecheka et al.* [1995]
	- 21°25.0′N/128°30.5′E	- trachyte (2834-1-10)	- 40 ± 5 Ma (K/Ar)	
	- 21°29.5′N/128°23.4′E	- phonolite (2837-1-1)	- 23.1 ± 3 Ma (K/Ar)	
CBF	~15°N/132°30′E (dive 336)	alkaline basalt	27.4 ± 1.6 Ma (K/Ar)	*Okino et al.* [1999]
CBF	16°28.5′N/130°10.8′E (334)	basalts and dolerites	28.1 ± 0.16, 26.1 ± 0.9, 14.88 ± 0.16 Ma (Ar/Ar & K/Ar)	*Fujioka et al.* [1999]
	16°18′N/130°09.5′E (335)			
NW BWP	24.2°N/127.6°E	basalt (E-MORB)	20–25 Ma (Ar/Ar)	R. Shinjo (personal communication, 2001)

[a] Method of dating is indicated. Concerning the datings which were made by *Ozima et al.* [1983], radiometric ages are ranked as 1, 2, 3, according to their quality. (1): (i) ^{40}Ar/^{39}Ar age which has both well defined isochron and plateau age, (ii) a concordant K/Ar age determined on several different minerals separated from the rock, (iii) a concordant age determined by K/Ar and Rb/Sr methods. (2): (i) ^{40}Ar/^{39}Ar age which is determined for an approximate isochron, but does not form an age plateau, (ii) a roughly concordant K/Ar age on several rocks or separated mineral samples. (3): (i) a single K/Ar age, (ii) an ^{40}Ar/^{39}Ar age obtained only from the total fusion age, but for which neither an isochron or age plateau is defined. See Figure 9 for location of samples.

Table 1b. Nature and Age of Rocks Recovered From Other Locations of the West Philippine Basin (In the Broad Sense of the Term)[a]

Site	Location	Dated Elements	Age	Source
Amami Plateau	?	- tonalite (GDP-11–17)	- 69.5 Ma (K/Ar)	*Matsuda et al.* [1975]
		- hornblende (GDP-11–17)	- 75.1 Ma (K/Ar)	
		- basalt, andesite, tonalite	- 75–85 Ma	
		- basalt	- 82–85 Ma (K/Ar)	
Daito Ridge	?	- basalt	- 56 Ma	- *Shiki* [1985]
		- basalt	- 59 Ma (Ar/Ar - whole rock)	- *Ozima et al.* [1977]
445, DSDP LEG 58 (Daito Ridge)	25°31.36′N/133°12.49′E	- sediments	- Middle Eocene (47–48 Ma)	- *Karig et al.* [1975]
		- andesite in conglomerate	- 59 ± 3 Ma (Ar/Ar - whole rock)[1]	- *Ozima et al.* [1983]
Minami-Daito B.	?	tholeiitic and alkaline basalt	57, 59 Ma (Ar/Ar - whole rock	*Ozima et al.* [1977]
446A, DSDP LEG 58 (Minami-Daito Basin)	24°42.04′N/132°46.49′E	- sediments	- Early Eocene (50–52 Ma)	- *Karig et al.* [1975]
		- doleritic sill	- 56.7 ± 1 Ma (Ar/Ar - whole rock)[1]	- *Ozima et al.* [1983]
		- gabbroic sill	- 56.4 ± 3 Ma (Ar/Ar - whole rock)[1]	- *Ozima et al.* [1983]
		- basaltic sill	- 54.1 ± 1 Ma (Ar/Ar - whole rock)[1]	- *Ozima et al.* [1983]
		- basaltic sill	- 36 Ma (Ar/Ar - whole rock)[3]	- *Ozima et al.* [1983]
		- basaltic sill	- 48.2 Ma (K/Ar - whole rock)	- McLee and Klock [1980]
		- basaltic sill (plagioclase)	- 50.1 Ma, 41.3 Ma (Ar/Ar isochron)	- *Hickey-Vargas* [1998]
Huatung Basin	- 20.40°N/122.47°E (gabbro)	- amphibole 1 (RD19D)	- 116.2 ± 4.2 Ma (Ar/Ar plateau age)	*Deschamps et al.* [2000]
			- 114.3 ± 2.3 Ma (Ar/Ar isochron age)	
		- amphibole 2 (RD19D)	- 124.1 ± 2.5 Ma (Ar/Ar complete fusion)	
		- amphibole 1 (RD19H)	- 121.2 ± 4.6 Ma (Ar/Ar plateau)	
			- 121.8 ± 2.7 Ma (Ar/Ar isochron)	
	- 21.49°N/122.69°E (gabbro)	- amphibole 2 (RD19H)	- 114.1 ± 4.0 Ma (Ar/Ar complete fusion)	
		- amphibole 1 (RD 20)	- 123.2 ± 7.8 Ma (Ar/Ar plateau)	
			- 123.3 ± 2.3 Ma (Ar/Ar isochron)	
		- amphibole 2 (RD 20)	- 105.2 ± 8.7 Ma (Ar/Ar plateau)	
			- 97.3 ± 2.3 Ma (Ar/Ar isochron)	
		- amphibole 3 (RD 20)	- 105.1 ± 13.6 Ma (Ar/Ar complete fusion)	
Lanyu Island	Yehyu Creek	Radiolarian chert	Barremian (115 Ma)	*Yeh and Cheng* [2001]

[a] Method of dating is indicated. Concerning the datings which were made by *Ozima et al.* [1983], radiometric ages are ranked as 1, 2, 3, according to their quality. (1): (i) ^{40}Ar/^{39}Ar age which has both well defined isochron and plateau age, (ii) a concordant K/Ar age determined on several different minerals separated from the rock, (iii) a concordant age determined by K/Ar and Rb/Sr methods. (2): (i) ^{40}Ar/^{39}Ar age which is determined for an approximate isochron, but does not form an age plateau, (ii) a roughly concordant K/Ar age on several rocks or separated mineral samples. (3): (i) a single K/Ar age, (ii) an ^{40}Ar/^{39}Ar age obtained only from the total fusion age, but for which neither an isochron or age plateau is defined. See Figure 9 for location of samples.

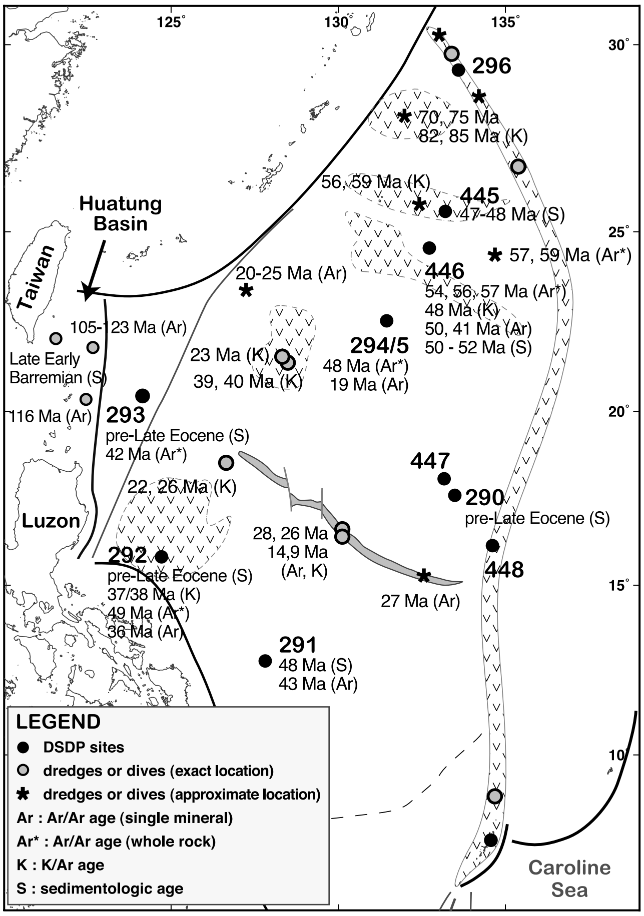

Figure 9. Ages determined on rocks that have been recovered from the West Philippine Basin (in the broad sense of the term). See Table 1 for exact location and description of samples.

Hawkins et al., 1985; *Hall et al.*, 1988; *Geary et al.*, 1988; *Arcilla*, 1991; *Rangin et al.*, 1991; *David*, 1994; *Malaihollo and Hall*, 1996]. Most of these rocks are older than Late Cretaceous and geochemical studies demonstrate that they probably come from a back arc basin [e.g., *Billedo*, 1994; *Yumul et al.*, 1997; *David*, 1994]. *Ballantyne* [1991], however, suggests that some of the Early Cretaceous boninitic rocks that constitute the East Halmahera ophiolite could have been formed in a fore arc environment, based on its similarities with ophiolite complexes in New Guinea that were commonly described in such a context. This last interpretation can easily be ruled out since modern examples of boninites emplacement are observed in back arc settings in the Lau and North Fiji Basin [*Kamenetsky et al.*, 1997].

[23] In general, it appears that the boundaries of the WPB are mainly constituted by pre-Upper Cretaceous oceanic rocks, except for the Amami-Oki-Daito triangle which is partly composed of Paleocene to Early Eocene rocks (Figure 9 and Table 1b) [*Matsuda et al.*, 1975; *Shiki et al.*, 1975; *Shiki*, 1985; *McKee and Klock*, 1980; *Hickey-Vargas*, 1998; *Ozima et al.*, 1983], and the central part of the Palau-Kyushu Ridge which probably developed during the opening of the basin.

[24] We suggest that the WPB opened within a Jurassic to Cretaceous domain, possibly a back arc basin. Figure 11 shows the initial area that may have been covered by the WPB. This area is restored by taking into account the parts of the basin that disappeared in the Ryukyu and Philippine trenches, from tomographic [*Lallemand et al.*, 1998, 2001] and seismological data [*Cardwell et al.*, 1980; *Hamburger et al.*, 1983; *Barrier et al.*, 1991. We also took into account the shortening episode that is suspected to have occurred along the Gagua Ridge and the eastern coast of Luzon in Eo-Oligocene time [*Lewis and Hayes*, 1983; *Deschamps et al.*, 1998; *Deschamps*, 2001].

5.2. Evidence for Active Subduction Along the Palau-Kyushu Ridge Since the Early Eocene

[25] Before the opening of the Parece-Vela and Shikoku basins since 30 Ma [*Okino et al.*, 1999] and of the Mariana Trough since 6 Ma [*Hussong and Uyeda*, 1981], the Izu-Bonin-Mariana Arc and the Palau-Kyushu Ridge (PKR) constituted a single volcanic arc. Table 2 synthesizes results of datings that were performed on volcanic rocks from these arcs. The accuracy of dating depends on the method used by authors, and has been partly discussed by *Cosca et al.*

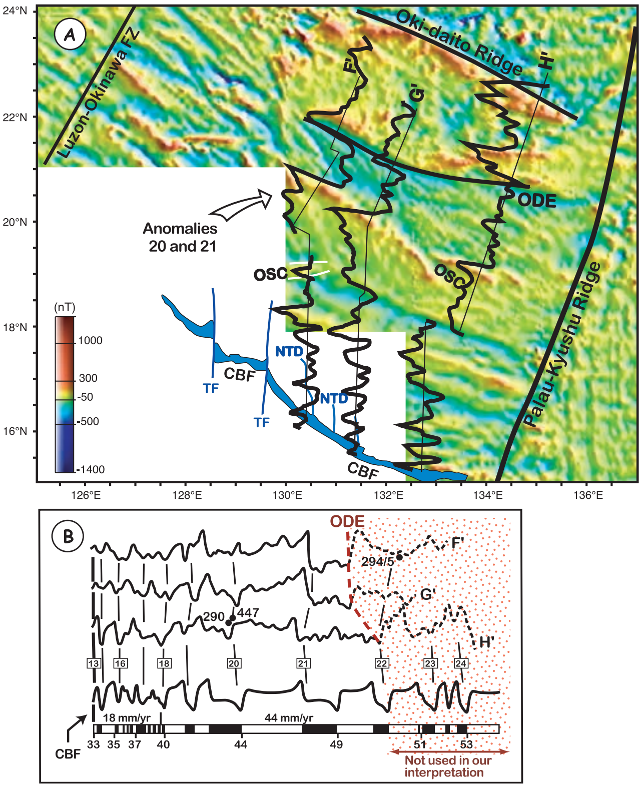

Figure 10. A. Magnetic data over the northeastern part of the West Philippine Basin, with location of 3 lines shown by *Hilde and Lee*'s [1984] magnetic identification. ODE: Oki-Daito escarpment, TF: Transform Fault, NTD: Non-Transform Discontinuity, OSC: fabric formed between two Overlapping Spreading Centers, CBF: Central Basin Fault, i.e., fossil spreading axis. Figure modified from *Okino et al.* [1999]. B. Identification performed by previous authors and confirmed in our study, after verification made with the help of more recent and detailed data (see A, above) [*Okino et al.*, 1999]. Magnetic data that are located north of the Oki-Daito Escarpment are ignored here since the spreading fabric trends N–S obliquely to the tracks along which magnetic anomalies were previously identified.

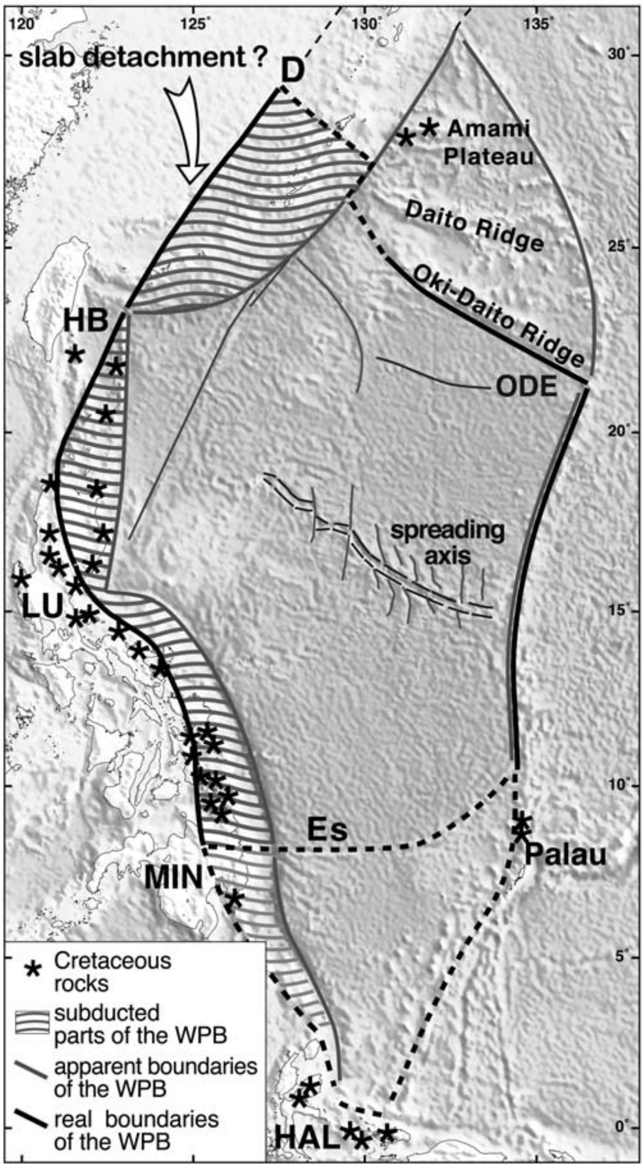

Figure 11. Initial size of the West Philippine Basin, when taking into account parts of the basin that disappeared by shortening and subduction. Gray heavy lines are apparent boundaries of the basin. Dark heavy lines indicate its real boundaries by projection onto the surface of the unfolded slabs. Dashed heavy dark lines represent uncertain boundaries. Stars correspond to locations of Early Cretaceous rocks outcrops. HB: Huatung Basin, LU: Luzon, MIN: Mindanao, HAL: Halmahera, Es: Steep escarpment that may represent the southern limit of the WPB [*Mrozowski et al.*, 1982], ODE: Oki-Daito Escarpment, D: discontinuity observed in the subducting slab using tomographic data [*Lallemand et al.*, 2001].

[1998]. We consider $^{40}Ar/^{39}Ar$ ages as the most reliable ones, and we trust in K/Ar ages only when they are consistent with other ages measured on similar terranes and/or paleontological ages determined on same outcrops.

[26] Datings show that arc volcanism occurred since at least 51 Ma (perhaps 55 Ma) in the northern part of the arc (Figure 12 and Table 2). The northern part of the proto-PKR was thus an active volcanic arc bordering a subduction zone since the Early Eocene time. There is an apparent lack of Early Eocene to Middle Eocene volcanic rocks along the southern portion of the proto-PKR. Only one such age has been determined in Palau island (51 Ma [*Cosca et al.*, 1998]) and it is strongly questioned by the author himself because of the alteration of the sample and the discrepancy between K/Ar, Ar/Ar isochron and Ar/Ar plateau ages. Thus, if we ignore this questionable dating, we conclude that arc volcanism may have begun along the southern part of the proto-PKR in the Middle Eocene. The occurrence in the PKR of a few volcanic rocks which are 29 to 26 Ma old, suggests that arc activity progressively ended since the beginning of the opening of the Parece-Vela and Shikoku basins. We conclude that a subduction zone bounded the northeastern part of the WPB during its whole opening. It may have propagated along the southern part of the eastern margin in the Middle Eocene.

5.3. Cretaceous to Miocene Arc Volcanism in the Philippine Mobile Belt

[27] Geological studies in the Philippine Mobile Belt show that the Jurassic to Early Cretaceous ophiolitic rocks forming the basement of these terranes, are covered by volcanic/volcaniclastic rocks and limestones deposited in an island arc setting [e.g., *BMG*, 1981; *Wright et al.*, 1981; *Moore and Silver*, 1983; *Hall et al.*, 1988; *David*, 1994]. Similar rocks have been reported in the Northern and Southern Sierra Madre in Luzon [*Ringenbach*, 1992; *Billedo*, 1994]. Numerous datings have been made on these rocks by using distinct methods. Table 3 synthesizes these results. Because some K/Ar datings are not entirely dependable due to a possible loss of atmospheric argon, we consider them as reliable only when they are consistent with results of several other datings performed on similar samples from the same or close areas. Datings attest for a volcanic arc activity starting since late Upper Cretaceous time, from Halmahera up to the northeastern coast of Luzon (Table 3) [*Hall*, 1997]. This activity lasted until the Early Miocene, when a major and ubiquitous unconformity has been observed from Luzon to Halmahera [*Karig*, 1983; *Hall et al.*, 1988, 1995a; *Rangin and Pubellier*, 1990; *Ringenbach*, 1992; *Malahiollo and Hall.*, 1996]. We note an apparent lack of Middle Eocene volcanic rocks in the Philippine islands (Figure 13). This gap could be due to a deficiency of rock sampling or to a lack of material because of erosional processes. Since it correlates with a regional unconformity related to a tectonic event [*Hall et al.*, 1988; *Ringenbach*, 1992], we suspect that this apparent lack of volcanic eruption is rather due to a cessation or to a significant slowing down of the subduction along the Philippine archipelago toward 45/43 Ma. This is consistent with paleomagnetic data that evidence a stability of these terranes at this time and thus a possible significant decrease of the slab pull force along the subduction zone. We infer a resumption of volcanic activity in the late Eocene at 36 ± 3 Ma. The accuracy of dating prevents us from asserting a more precise age.

[28] Ages of volcanic rocks that are found within the Philippine Mobile Belt indicate arc activity before and then coeval with the WPB opening. This suggests that a subduction zone was active along the southwestern boundary of the basin. The Middle to late Eocene gap (43–36 Ma) in the ages of volcanism may indicate a significant slowing down or a cessation of subduction in the Middle Eocene. The authors had no argument at their disposal to discriminate

Table 2. Nature and Age of Arc Volcanic Rocks Older Than Late Miocene in the Palau-Kyushu Ridge and Izu-Bonin-Mariana Arc and Forearc[a]

Site	Location	Dated Elements	Age	Source
Palau-Kyushu Ridge	- 8°56.2′N/134°46.1′E (southern part of PKR)	- diorites and gneissic plagiogranites (7585-2)	- 125, 118, 87, 86 Ma (K/Ar)	- *Malyarenko and Lelikov* [1995]
	~29°50.0′N/133°21.0′E	- plagiogranite (GDP-8-12)	- 37.4 Ma (K/Ar)	
	- 29°50.0′N/133°21.0′E	- plagiogranite (N4-90)	- 42.7 Ma (K/Ar)	
	- 29°50.0′N/133°22.0′E	- plagiogranite (N4-91)	- 31.2 Ma (K/Ar)	
	- 29°50.0′N/133°22.0′E	- plagiogranite (N4-91)	- 26.2 Ma (K/Ar)	
	~29°50.0′N/133°22.0′E	- plagiogranite (D-60)	- 37.5 Ma (K/Ar)	
	- Minami-Koho seamount	- tonalite (D-76)	- 48.5 Ma (K/Ar)	
	- ?	- volcanic rock	- 49 Ma (K/Ar)	- *Mizuno et al.* [1977]
	- 29°56′N/133°19′E	- granodiorite	- 38 Ma (K/Ar)	- *Shibata and Okuda* [1975]
	- same location	- same sample	- 51 Ma (fission tracks)	- Nishimura [1975]
448/448A, DSDP LEG 58	16°20.46′N/134°52.45′E (central part of the PKR)	sediments	Middle Oligocene or older	*Karig et al.* [1975]
site 458/459B DSDP LEG 58	Mariana fore-arc	boninite or tholeiitic basalt	- 36.9, 43.6, 41.9, 28.0, 39.9, 39 Ma (K/Ar) - 49.9, 44.9 Ma (Ar/Ar)	*Cosca et al.* [1998]
site 782B DSDP LEG 125/6	Bonin fore-arc		- 36.2, 41.0, 33.8, 41.3, 43.9 Ma (K/Ar) - 45.7 Ma (Ar/Ar)	*Cosca et al.* [1998]
site 786 DSDP LEG 125/6	Bonin fore-arc	- boninites	- 41,3 Ma (K/Ar)	- *Mitchell et al.* [1992]
		- boninitic sill	- 34,6 Ma (K/Ar)	
		- boninite or tholeiitic basalt	- 43.3, 45.4, 46.6, 55.4 Ma (Ar/Ar)	- *Cosca et al.* [1998]
Izu-Bonin Is.	Chichijima	- andesite	- 27 Ma (K/Ar) (minimum age)	- *Kaneoka et al.* [1970]
		- boninites	- 34.2, 31.2, 27.9, 41.3 Ma (K/Ar)	- *Tsunakawa* [1983]
		- dacites	- 38.6, 43.0, 27.1 Ma (K/Ar)	- *Tsunakawa* [1983]
		- boninite or tholeiitic basalt	- 41.9 Ma (K/Ar), 45.7 Ma (Ar/Ar)	- *Cosca et al.* [1998]
		- boninite glass	- 48.1 Ma (K/Ar)	- *Dobson* [1986]
		- andesite	- 29 Ma (K/Ar)	- *Umino* [1985]
		- boninites, dacites	- 43-39 Ma (K/Ar)	- *Umino* [1985]
		- clinoenstatite	- 47.8 Ma (Ar/Ar)	- *Umino and Kushiro* [1989]
		- clinoenstatite	- 39 Ma (Ar/Ar)	- *Pearce et al.* [1992]
Izu-Bonin Is.	Hahajima	- andesite	- 41 Ma (K/Ar) (minimum age)	- *Kaneoka et al.* [1970]
		- andesite	- 23.3 Ma (K/Ar)	- *Tsunakawa* [1983]
		- basalt	- 29.9, 29.4 Ma (K/Ar)	
		- dacite	- 32.6 Ma (K/Ar)	
Izu-Bonin Is.	Ototojima	andesite	- 22.4 Ma (K/Ar)	*Tsunakawa* [1983]
Izu-Bonin Is.	Nakodojima	dacite	- 42.3 Ma (K/Ar)	*Tsunakawa* [1983]
Izu-Bonin Is.	Mukojima	boninite	- 22.4 Ma (K/Ar)	*Tsunakawa* [1983]
Izu-Bonin Is.	?	boninites	- 48 ± 0.5 Ma (Ar/Ar)	*Umino* [1985]
Guam Is.		- boninite	- 44 ± 3 Ma (K/Ar)	- *Tsunakawa* [1983]
		- boninite or tholeiitic basalt	- 33, 27.3, 36.2, 34.9, 24.2, 21.4 Ma (K/Ar)	- *Cosca et al.* [1998]
Saipan Is.		boninite or tholeiitic basalt	- 44.6, 44.7, 45.3, 27.6, 26.2, 28.3 Ma (K/Ar) and 46.1 Ma (Ar/Ar)	*Cosca et al.* [1998]
Palau Is.		boninite or tholeiitic basalt	- 47.9, 25.7, 32.6, 32.1, 31.9, 32.2, 33.9, 34.3, 30.2 Ma (K/Ar) and 51 Ma (Ar/Ar)	*Cosca et al.* [1998]

[a] See Figure 12 for location of samples.

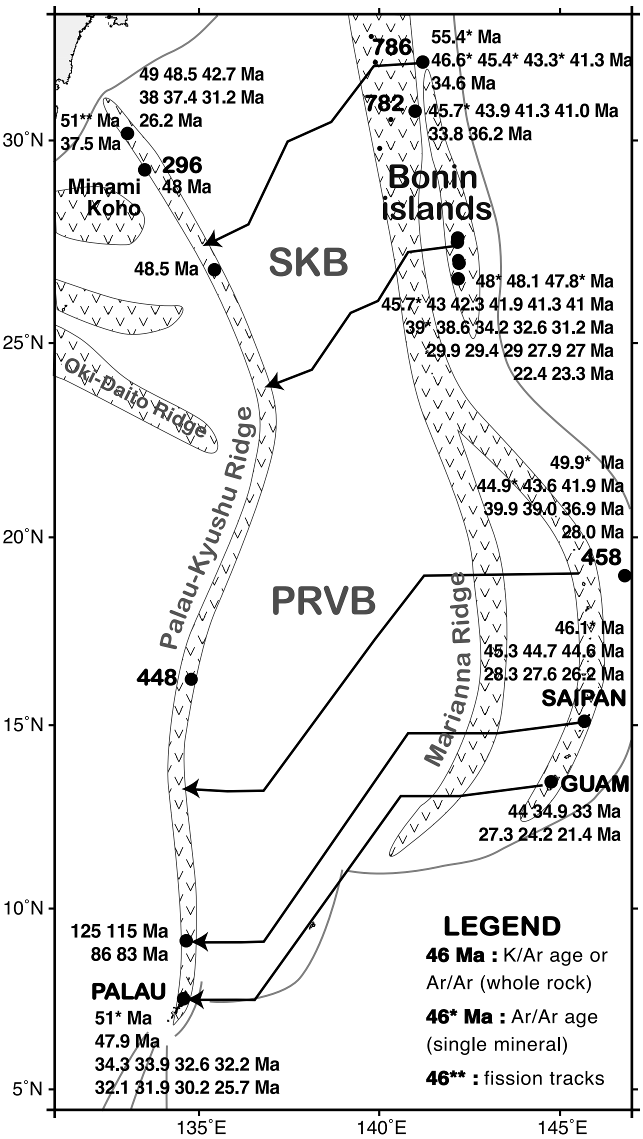

Figure 12. Location and age of arc volcanic rocks that are older than Late Miocene, along the eastern boundary of the Philippine Sea Plate. As Shikoku (SKB) and Parece-Vela (PRVB) started to open at 30 Ma, all the ages that are measured along the Izu-Bonin-Mariana (IBM) Arc and that are older than 30 Ma, indicate arc volcanism which occurred along the "Palau-Kyushu Ridge/IBM single Arc". Arrows indicate the kinematic of the basin's opening. They therefore show approximate locations, on the Palau-Kyushu Ridge, of dated rocks found along the eastern limit of the Philippine Sea Plate. Information about these samples is given in Tables 1 and 2.

between east or west vergence of the subduction zone. Paleomagnetic data from the Philippines and from the WPB itself indicate that there was no significant relative motion between these regions before the late Miocene [*Haston et al.*, 1988; *McCabe and Cole*, 1989; *Lee and Lawver*, 1995; *Hall et al.*, 1995a]. We thus consider that the Cretaceous to Eocene arc volcanism in the Philippines resulted from the subduction along its southwestern side, as already inferred by *Jolivet et al.* [1989], *Hall et al.* [1995a], *Lee and Lawver* [1995], and *Hall* [1997, 2002].

5.4. Conclusion: Nature of the WPB

[29] Ages of arc volcanic rocks recovered from the borders of the WPB show that during its opening, the basin was fringed by two active subduction zones. Subduction along the northern proto-PKR was continuous during the entire formation of the basin. Subduction along the southern proto-PKR probably started in the Middle Eocene. Subduction along the Philippine Mobile Belt occurred since at least the Late Cretaceous, but probably stopped or slowed down in the Middle Eocene. These subduction zones existed since the Early Eocene and Late Cretaceous respectively, suggesting that the WPB was isolated from surrounding domains since at least the Early Eocene. This is consistent with the paleomagnetic data within the basin and its margins which show that it has undergone a strong clockwise rotation since at least the Early Eocene [*Keating and Helsley*, 1985; *Haston et al.*, 1988; *Haston and Fuller*, 1991; *Koyama et al.*, 1992; *Hall et al.*, 1995a, 1995b, 1995c; *Hall*, 2001]. We conclude that the WPB is a back arc basin. This back arc origin is consistent with the petrology of basalts from the extinct spreading center [*Fujioka et al.*, 1999].

6. Discussion: Model for the Opening of the WPB

[30] Our study of the history of the spreading in the WPB enabled us to reconstruct the opening of the basin with 1 Ma steps. We then restored the basin to the geodynamic context of the epoch with the help of paleomagnetic data which were acquired in the basin and on its margins [e.g., *Louden*, 1976, 1977; *McCabe and Uyeda*, 1983; *McCabe*, 1984; *Keating and Helsley*, 1985; *Haston et al.*, 1988; *Haston and Fuller*, 1991; *Haston et al.*, 1992; *Koyama et al.*, 1992; *Hall et al.*, 1995a, 1995b]. *Hall et al.* [1995a, 2002] have synthesized these data and proposed for the southern part of the PSP 50° of clockwise rotation with southward translation between 50 and 40 Ma, no significant movement between 40 and 25 Ma, and 40° of clockwise rotation with northward translation between 25 and 0 Ma. For the northeastern part of the plate, declination and latitude curves indicate a clockwise rotation and a northward movement between 50 and 0 Ma. We have slightly modified these parameters within the error bars of paleomagnetic data, in order to fit the variations of the spreading directions within the WPB. To that end, we have restored the PSP every 5 Ma by successive rotations on a sphere that is tangent to the WGS84 ellipsoid. Our model indicates a strong rotation of the southern part of the plate between 53 and 45 Ma with the rotation pole which was determined by *Hall et al.* [1995a], i.e., 10°N/150°E, and no significant rotation between 44 and 25 Ma. The northeastern part of the plate underwent an almost continuous clockwise rotation and northward movement.

6.1. 54 Ma Stage

[31] Rifting began in the WPB around 55 Ma, in the back of the Philippine Arc. The first structures created in the basin were parallel to this arc. The seafloor formed during the first phase of spreading in the basin is relatively shallow, due to an excess of volcanism at the spreading axis related to the presence of an hot spot [*Macpherson and Hall*, 2001]. The Philippine and Palau-Kyushu arcs were E-W-trending. Northward subduction was active along the Philippine Arc. Before 45 Ma, the northward movement of Australia was slow (about 1cm/yr) [*Veevers*,

Table 3. Nature and Age of Arc Volcanic/Volcaniclastic Rocks Older Than Late Miocene in the Philippine Archipelago (Including Luzon) and Halmahera[a]

Location	Nature of the Rock	Age	Reference
- Caramoan province	- interstratified limestones with volcaniclactics	- Early to Upper Cretaceous (Globotruncana sp., Orbitolines sp.)	*David* [1994]
- Catanduanes Is.	- basalt (amphibole)	- 91,1 ± 0,5 Ma (Ar/Ar)	
	- andesite	- 121,09 ± 2,61 Ma (K/Ar)	
	- andesite	- 67,6 ± 1,5 Ma (K/Ar)	
Cagraray Island	similar to the Caramoan volcanic formation	Upper Cretaceous ?	*BMG* [1981] and *David* [1994]
Rapu-Rapu Island	intrusive diorite in ophiolitic subst.	77,1 ± 4,6 Ma (K/Ar)	*David* [1994]
Batan Island	similar to the Rapu-Rapu arc volcanic formation	Upper Cretaceous ?	*David* [1994]
Northern Sierra Madre	- arc tholeiites	- 87,15 ± 5,82 Ma (K/Ar)	*Billedo* [1994]
	- radiolarians	- Upper Cretaceous	
Southern Sierra Madre (Angat)	pelagic foraminifera in volcaniclastic sediments	Upper Cretaceous (Campanien-Maastrichtien)	*Ringenbach* [1992]
East Mindanao and Visayas	volcanodetritic serie	Upper Cretaceous to Eocene	*Hawkins et al.* [1985], *Wright et al.* [1981], and *Moore and Silver* [1983]
Cebu Island	porphyric diorites	108 ± 1 Ma	*Walther et al.* [1981]
Halmahera	- volcanic rocks	- 94–80 Ma	- *Ballantyne* [1991]
	- volcaniclastic sequence	- Upper Cretaceous to middle Eocene	- *Hall et al.* [1988]
Bacan Is.	volcanic rocks	97–94 Ma	*Malaihollo* [1993]
Catanduanes Is.	- intrusive diorites, andesites	- numerous ages between 36 and 30 Ma: 35.4 ± 0.8, 32.2 ± 0.8, 32.8 ± 0.8, 33 ± 0.7, 30.3 ± 0.7, 30.2 ± 0.7, 33.9 ± 1.4, 35.7, 33 (K/Ar)	- *David* [1994]
	- diorite (biotite)	- 33.3 ± 0.6 (Ar/Ar)	
	- ?	- 31–29 Ma	- *Ringenbach* [1992]
Caramoan Peninsula	- intrusive diorites	- 60–66 Ma (K/Ar)	*David* [1994]
	- tonalite	- 49.8 ± 1.1 Ma (K/Ar)	
	- andesite	- 39 ± 0.9 Ma (K/Ar)	
	- basaltic dyke	- 60.3 ± 1.4 Ma (K/Ar)	
	- gabbro	- 62.8 ± 1.4 Ma (K/Ar)	
	- gabbro	- 64.7 ± 1.7 Ma (K/Ar)	
Polillo Is. (Anawa F.)	volcanoclastic formation	Middle to late Eocene	*Billedo* [1994]
Polillo Is. (Polillo diorite)	- diorite	- 34.4 ± 1.2 Ma (Rb-Sr)	- *Knittel* [1985]
	- ?	- 31.8 Ma	- *Billedo* [1994]
	- gabbro	- 63.7 ± 1.8 Ma (K/Ar)	
Northern Sierra Madre (Caraballo F.)	island arc basalt	39 ± 2 Ma (K/Ar)	*Ringenbach* [1992]
Northern Sierra Madre (Coastal batholit)	- quartzic diorite (amphibole)	- 38.7 ± 1.3 Ma (K/Ar)	- *Billedo* [1994]
	- diorites	- 49–43 Ma (K/Ar)	- *Wolfe* [1981]
	- diorites	- 33–27 Ma (K/Ar)	- Metal Mining Agency
Northern Sierra Madre (Dibuluan river formation)	- basaltic dyke	- 28.8 ± 2 Ma (K/Ar)	- *Billedo* [1994]
	- basalt	- 28.6 ± 1.1 Ma (K/Ar)	
	- basic andesite	- 28.8 ± 0.8 (K/Ar)	
	- basaltic dyke	- 32.5 ± 0.9 Ma	- *Ringenbach* [1992]

Table 3. (continued)

Location	Nature of the Rock	Age	Reference
Northern Sierra Madre (NSM batholit)	- diorite	- 31.1 ± 1.5 Ma to 22.3 ± 1.1 Ma (K/Ar)	- *Republic of the Philippines - Japan Project* (*RPJP*) [1977]
	- amphibole in diorite	- 21.9 et 26 Ma (Ar/Ar)	- *Billedo* [1994]
	- Dupax batholit	- 33–23 Ma (K/Ar)	- *RPJP* [1977]
	- Dupax batholit	- 32.5–27.4 Ma	- *Wolfe* [1981]
	- quartzic diorite	- 30.2 ± 0.7 Ma (K/Ar)	- *Billedo* [1994]
	- gabbro	- 33.6 ± 2.6 Ma (K/Ar)	
Northern Sierra Madre (Cordon syenite complex)	- ?	- 25 ± 1 Ma (Rb-Sr)	- *Knittel and Cundari* [1990]
	- porphyric syenite	- 23.3 ± 0.5 Ma (K/Ar)	- *Billedo* [1994]
	- basaltic dyke	- 24.0 ± 0.9 Ma (K/Ar)	
	- andesite	- 20.4 ± 0.4 Ma (K/Ar)	
	- andesite (amphibole)	- 21.9 ± 0.1 Ma (Ar/Ar)	
	- syenite (amphibole)	- 22 ± 0.2 Ma (Ar/Ar)	
	- amphibole	- 21.9 ± 0.1 Ma (Ar/Ar)	
Northern Sierra Madre (Palali F.)	- basalt	- 17.6 ± 1.0 Ma	- *RPJP* [1977]
	- basaltic dyke	- 17.1 ± 0.5 Ma (K/Ar)	- *Ringenbach* [1992]
	- basalt	- 17.2 ± 0.4 Ma (K/Ar)	
Southern SM (Kanan block, Maybangain F.)	- pelagic foraminifera	- middle Paleocene to middle/late Eocene	*Agadier* [1986], *Baumann et al.* [1976], *Haeck* [1987], *Schoell and Duyanon* [1988], and *Billedo* [1994]
Southern SM (Madlum F.)	andesitic rocks	middle Miocene	*Baumann et al.* [1976]
Southern SM (Antipolo diorite)	diorite	36.9 Ma	*Wolfe* [1981]
South Central Cordillera	volcanic rocks	- 1 group: 35–19 Ma (K/Ar)	- *Wolfe* [1981]
		- 1 group: 12–5 Ma (K/Ar)	- *Maleterre* [1989]
Central Cordillera (Balilli F.)		upper Oligocene-early Miocene	*Baker* [1983], *Sillitoe and Angeles* [1985], and *Ringenbach* [1992]
Central Cordillera (Bagon Batholit)	- trondhjemite (hornblende)	- 1 3 ± 0,8 Ma (K/Ar)	*Sillitoe and Angeles* [1985] and *Ringenbach* [1992]
	- trondhjemite (biotite)	- 12 ± 0,4 Ma (K/Ar)	
Central Cordillera (Agno Batholit)	- ?	- Oligocene	- *Balce et al.* [1981]
	- ?	- 18 à 7 Ma (K/Ar) (Miocene)	- *Wolfe* [1981]
	- diorite	- 17.9 Ma (K/Ar)	
	- dacite	- 17.3 Ma (K/Ar)	
	- gabbro	- 31.7 ± 15.3 Ma (K/Ar)	
	- diorite	- 30.3 Ma (K/Ar)	
	- ?	- 18.8, 13.8, 13.2, 12.2 Ma (K/Ar)	- *Maleterre* [1989]
Central Cordillera (Itogon ophiolite)	gabbros, diorites, trondhjemites	Oligocene to middle Miocene	*Wolfe* [1981]
Eastern part of Mindoro-Tablas	- calc-alkaline andesite	- 18 ± 0.4 Ma	*Bellon and Rangin* [1991]
	- calc-alkaline andesite	- 18.5 ± 0.4 Ma	
	- calc-alkaline rhyolite	- 19.9 ± 0.5 Ma	
Panay	- calc-alkaline diorite	- 29.7 ± 0.6 Ma (K/Ar)	*Bellon and Rangin* [1991]
	- andesite	- 23.7 ± 1.3 Ma (K/Ar)	
	- shoshonitic basalts	- 25.3 ± 0.7, 21.5 ± 0.5, 30.9 ± 0.6, 26.2 ± 0.5 Ma (K/Ar)	
	- calc-alkaline diorite	- 20.8 ± 0.6 Ma (K/Ar)	
	- grano-diorite calco-alcaline	- 19.5 ± 0.5 Ma (K/Ar)	
	- calc-alkaline basaltic andesite	- 22.9 ± 0.7 Ma (K/Ar)	
	- calc-alkaline basaltic andesite	- 14 ± 0.5, 13.1 ± 0.9, 12.4 ± 0.8, 13.3 ± 0.7, 13.7 ± 0.8, 13.8 ± 1.2 Ma (K/Ar)	

Table 3. (continued)

Location	Nature of the Rock	Age	Reference
Negros		30.2 Ma	*Walther et al.* [1981]
Bantayan Is.		28.7, 22.3, 20.3, 20 Ma	*Wolfe* [1981]
Samar/Leyte	- arc basalts and andesites	- Eocene to Miocene	- *Cole et al.* [1989]
	- arc gabbros (Leyte)	- 20.9 Ma (K/Ar)	- *Sajona et al.* [1997]
Eastern Mindanao	- volcanic debris	- Eocene	- *Moore and Silver* [1983]
	- ?	- 21 Ma	- *Wolfe* [1981]
NE Mindanao	arc diorite	32.3 ± 0.8 (whole rock), 31.4 ± 0.8 Ma (feldspar) (K/Ar)	*Sajona et al.* [1997]
Davao (Southeastern part of Mindanao)	- arc basalt	- 47.2 ± 1.6 Ma (K/Ar)	- *Sajona et al.* [1997]
	- arc diorite	- 46.1 ± 1.1 (K/Ar)	
	- arc diorite	- 18.1 ± 0.5 (whole r.), 17.5 ± 0.4 Ma (feldspar) (K/Ar)	
	- arc diorite	- 12.3 ± 0.4, 11.1, 12.9 Ma	- *Sajona et al.* [1994]
Mindanao (south of Daguma Range)	- diorite (arc tholeiite)	- 29.9 ± 2.1 Ma (K/Ar)	- *Bellon and Rangin* [1991]
	- calc-alkaline diorite	- 31.9 ± 3.9 Ma (K/Ar)	
	- calc-alkaline basalt	- 16.7 ± 1.2 Ma (K/Ar)	
	- arc diorite (tholeiite)	- 29.9 ± 2.1 Ma (K/Ar)	- *Sajona et al.* [1997]
	- andesite	- 59.2 ± 10.8 Ma (K/Ar) (altered sample)	
Eastern Halmahera	volcanic sequence	middle Oligocene and younger	*Hall et al.* [1988]
Western Halmahera	volcanic sequence	ante-middle Miocene	*Hall et al.* [1988]
Bacan	volcanic arc rocks	37–25 Ma	*Lanphere and Dalrymple* [1976]
Morotai	arc lavas and turbidites with volcanic debris	32.5–27 Ma	*Hall et al.* [1995a, 1995b, 1995c]
Sulu Sea (Cagayan ridge)	- DSDP site 769	- 20.3 ± 0.8, 20.8 ± 0.7 Ma	*Bellon and Rangin* [1991]
		- 19.5 ± 0.5, 20.1 ± 0.5 Ma	
		- 14.2 ± 0.8, 15.1 ± 0.9 Ma	
	- DSDP site 771	- 18.8 ± 2.4, 20.9 ± 2.9 Ma	
		- 14.2 ± 0.3, 13.8 ± 0.4 Ma	

[a] See Figure 13 for location of samples.

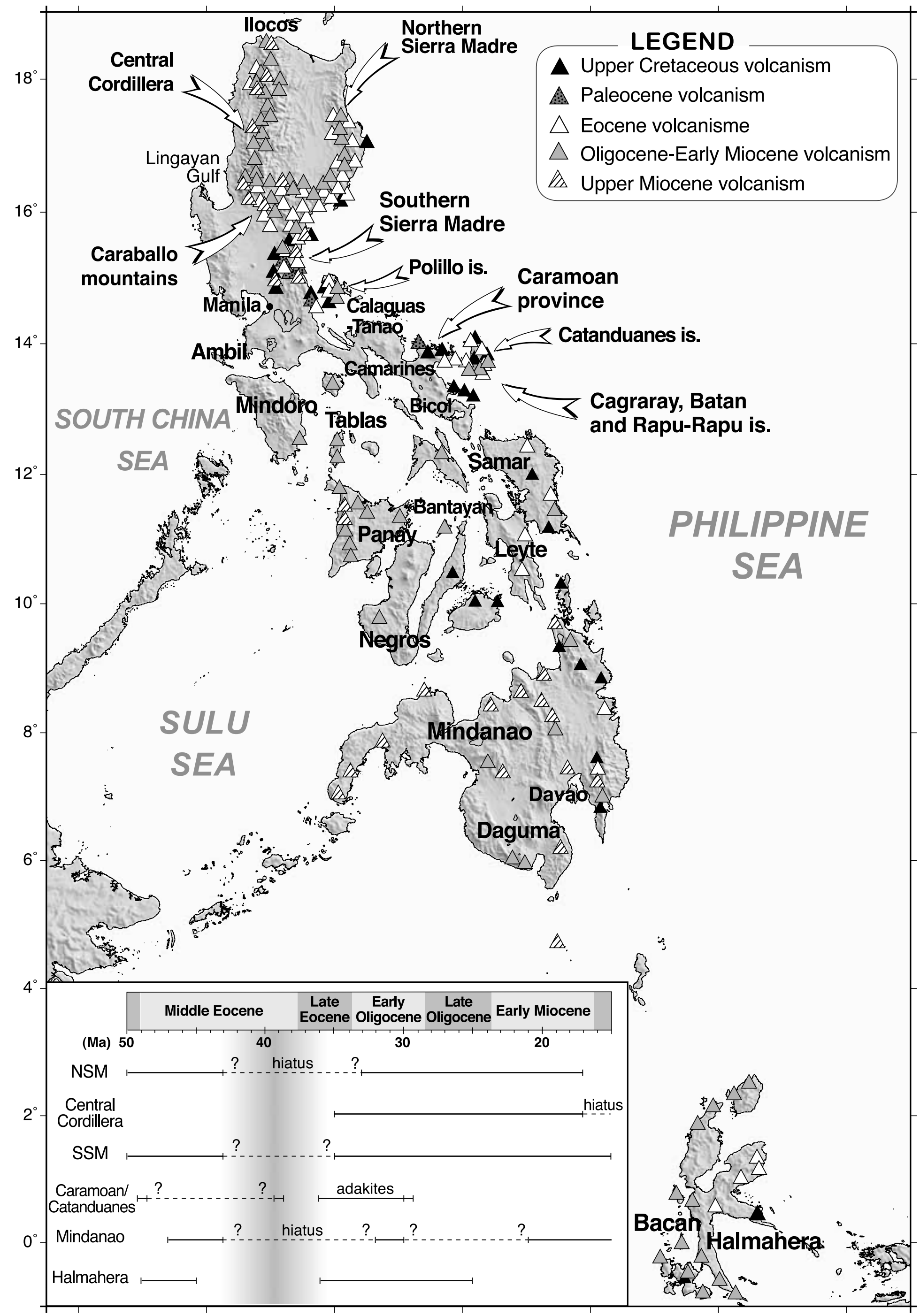

Figure 13. Age of arc volcanism earlier that Late Miocene in the Philippine archipelago and in Halmahera. Detailed information about these ages is given in Table 3. Diagram in insert shows the apparent lack of 43 to 36 Ma volcanic rocks which could suggest a cessation of the subduction along the Philippine archipelago during this epoch. NSM = Northern Sierra Madre, SSM = Southern Sierra Madre.

1986]. It is possible that the north Australian margin was bordered by one or several marginal basins of Cretaceous or older age [*Hall*, 1998, 2002]. The opening of the WPB would be related to northward subduction of one of these basins along the Philippine Arc. Subduction also occurred along the northernmost part of the Palau-Kyushu Ridge since 55 Ma. The initiation of this subduction may have been linked to a major change of the Pacific Plate motion inferred in the Early Eocene [*Scholl et al.*, 1986; *Norton*, 1995]. The southern proto-PKR was a transform fault separating the PSP and the Pacific Plate. Strike-slip movement along this boundary accommodated the opening of the WPB during the first 10 m.y. of the basin's formation.

6.2. 50 Ma Stage

[32] After 50 Ma, a second spreading axis propagated from east-northeast to west-southwest in the basin (Figure 14).

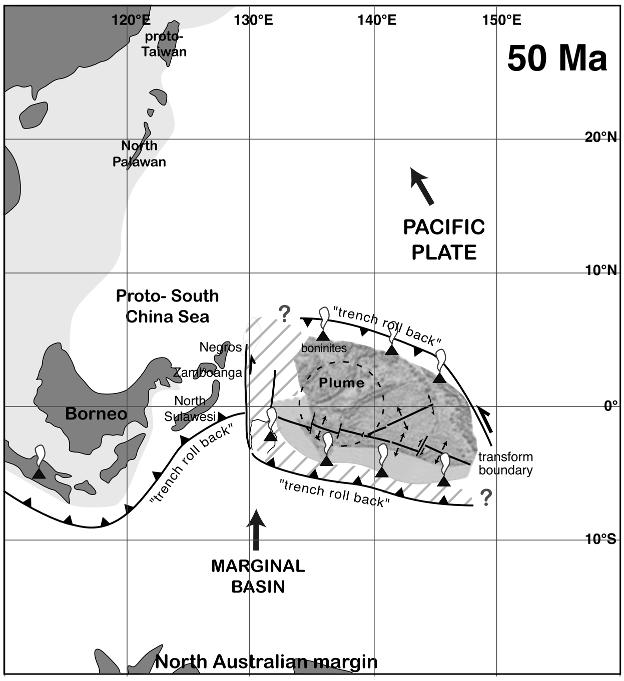

Figure 14. Evolutionary model of the West Philippine Basin, stage at 50 Ma.

The segment of the former spreading axis that parallels the Philippine Arc east of the R-R-R triple junction became inactive. The spreading rate along the new axis stabilized at 4.4 cm/yr. The Oki-Daito escarpment marks the transition between seafloor that was formed at two different spreading axes. The direction of opening progressively rotated counter-clockwise between 50 and 45 Ma, always remaining parallel to the Luzon-Okinawa Fracture Zone, and to the Gagua and Palau-Kyushu ridges. We suggest that the opening was accommodated by strike-slip faulting along these two last features. The Gagua Ridge is considered as a transform margin, as is the southern part of the Palau-Kyushu Ridge. The difference between these two margins is that volcanism occurred along the Palau-Kyushu Ridge when it developed.

[33] The Urdaneta and Benham plateaus started to form by excess of volcanism at the spreading axis due to the presence of a hot spot. Overlapping spreading centers developed in the vicinity of these plateaus and in the eastern part of the basin [*Okino et al.*, 1999; *Deschamps*, 2001].

[34] The two opposed subduction zones that fringed the PSP were still both active. The Early Eocene period coincided with widespread boninitic volcanism along the Izu-Bonin-Mariana (IBM) Arc. These eruptions may be related to the presence of a mantle plume in the region [*Macpherson and Hall*, 2001] which also explains the occurrence of numerous basaltic sills in the Amami-Oki-Daito region [*Hickey-Vargas*, 1998] as well as its uplift [*Tokuyama et al.*, 1986].

[35] We suggest a strong southward retreat of the subduction trench that was bordering the Philippine Arc between 53 and 43 Ma, in accordance with paleomagnetic data [*Ali and Hall*, 1995]. We suggest that during this period of time the main driving force for the WPB opening was provided by this southward retreat of the trench. This explains why the first spreading axis in the basin was trending parallel to the Philippine archipelago (Figure 7).

[36] We also suggest a northward retreat of the subduction zone that was bounding the northern Palau-Kyushu Ridge. It also provided a driving force for the opening of the WPB. At 50 Ma, the Pacific Plate was moving toward the N-NW [*Clague and Dalrymple*, 1989] such that southward subduction was apparently less active along the IBM subduction zone. *Seno* [1984], *Seno and Maruyama* [1984], and *Hall* [1997], therefore, invoked the southward movement of the "North New Guinea Plate" toward the IBM subduction zone to explain convergence that occurred along this margin of the PSP. But it is possible that the trench roll-back along the IBM subduction zone counterbalanced the trench-normal component of the NW motion of the Pacific Plate with respect to the PSP. We propose that the Pacific Plate dragged northward the northern part of the PSP, providing another driving force for the opening of the WPB. In such a context, there is no need of a hypothetical "North New Guinea Plate".

6.3. 45/43 Ma Stage

[37] Spreading continued parallel to the Gagua and Palau-Kyushu ridges (Figure 15). The presence of a hot spot in the western part of the WPB resulted in an excess of volcanism in this region, and successive southward ridge jumps. This phenomenon explains the asymmetry of the western part of the basin with respect to the spreading axis, and the presence of several fossil rift valleys [*Yoshida et al.*, 2000; *Deschamps*, 2001]. The perturbation of the spreading system due to the hot spot results in the disorganization of the magnetic pattern in this part of the basin (Figure 10). We interpret the NE-SW to NNE-SSW trending normal faults and abyssal hills close to the northeastern border of the Benham Rise as seafloor created along a second spreading

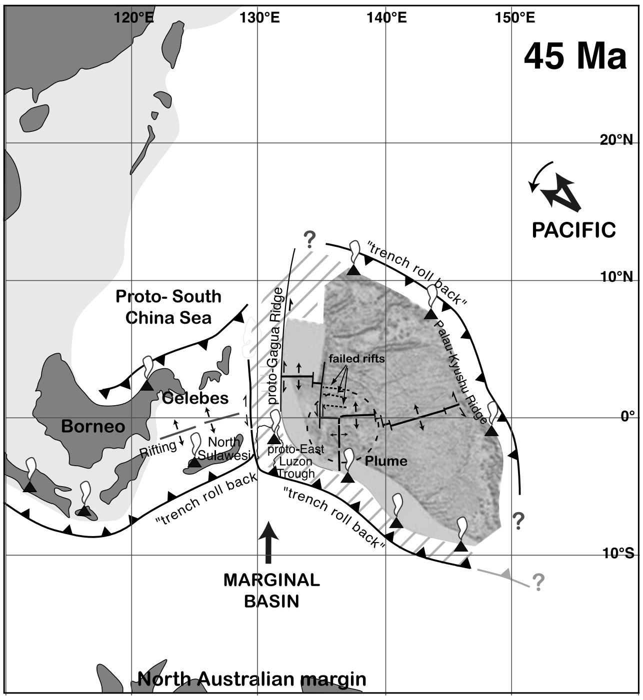

Figure 15. Evolutionary model of the West Philippine Basin, stage at 45 Ma.

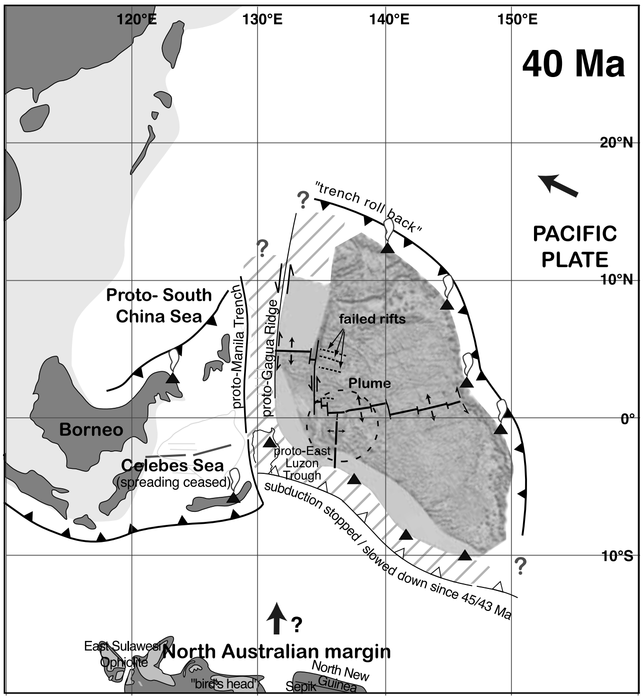

Figure 16. Evolutionary model of the West Philippine Basin, stage at 40 Ma.

axis (Figures 4 and 7) [*Karig et al.*, 1975; *Deschamps*, 2001]. The crust generated along this secondary axis most likely explains that this part of the basin is about 200 km larger than its northern part, when measuring the distance separating the Luzon-Okinawa FZ and the Palau-Kyushu Ridge at different times (Figure 15). The incomplete data coverage of the seafloor does not allow us to estimate with precision the area formed along this secondary axis. We infer its activity during about 10 Ma and a very slow rate of spreading. This information is provided by a correlation between the age of spreading inferred from magnetic anomalies and datings of rock samples, and the evolution of the width of the southern part of the plate between 45 and 35 Ma. The inferred duration of spreading is consistent with ages of rocks that were recovered in the vicinity of the Benham Rise. The simultaneous activity of two spreading axes in the WPB resulted at least in the formation of a microplate starting shortly after 35 Ma (Figure 17).

[38] Numerous authors invoke major plate reorganization at 45/43 Ma [e.g., *Clague and Dalrymple*, 1989]. This event has been reported from SE Asia through the western Pacific to the Australian margins east of Australia [*Hall*, 2002]. Since this time, the northward movement of Australia increased significantly (4–5 cm/yr) [*Veevers*, 1986]. A major tectonic event occurred in the Philippine archipelago [*Hall et al.*, 1995a]. We suggest a cessation or a slowing down of the northward subduction along the archipelago. The convergence between Australia and the Philippine Arc may have then been accommodated along another subduction zone, located in the vicinity of North New Guinea.

[39] Our study of the spreading processes in the WPB shows a slowing down of the rate of spreading at 43 Ma. We suggest that after the Middle Eocene, there was no driving mechanism for the opening of the basin, south of it. This is consistent with paleomagnetic data from the southern part of the plate which show no southward movement of this region since the Middle Eocene [*Hall et al.*, 1995a]. The northward retreat of the IBM trench caused the opening of the basin. This is consistent with paleomagnetic data that show clockwise rotation and northward movement of the northern part of the plate after 43 Ma. We suggest that during this period of time, the spreading system became relatively independent of lithospheric constraints. Since the beginning of the opening, the basin was subjected to widespread intraplate magmatism as shown by the occurrence of boninites along its eastern margin and of OIB source-derived basalts inside the basin. This indicates that active mantle upwelling was able to sample a deep and undepleted mantle and thus the presence of a widespread thermal anomaly in the upper mantle below the WPB. Like in the North Fiji Basin [*Lagabrielle et al.*, 1997], lithosphere emplacement would thus be not only the consequence of horizontal traction due to island arc migration, but also the result of the upwelling of hot asthenosphere. The resulting relative independence of the spreading system from the lithospheric constraints can explain why spreading continued in the basin, from an axis that was far from, and not parallel to, the subducting boundaries.

[40] As to why the subduction along the Philippine Arc ceased, we suggest that this is related to a global kinematic change rather than to a local event such as a microcollision along the Philippine Arc. The temporary locking of a subduction zone due to the arrival of a major high in the trench should lead relatively rapidly to the initiation of a new subduction zone located more to the south. This is not what we observe since arc volcanism that rejuvenated in the Philippine archipelago since 36 Ma occurred exactly at the same location than before, except in northern Luzon.

6.4. 40 Ma Stage

[41] The southern part of the PSP was stable in space at 40 Ma [*Ali and Hall*, 1995] (Figure 16). We suggest that there was still no subduction along the Philippine archipelago. The only external force for the opening of the basin was the northward retreat of the IBM trench. The half part of the WPB located south of the spreading axis remained fixed above the Benham hot spot from 44 Ma to 35 Ma approximately. The major part of the Benham Rise would have been formed during this period.

[42] We observe a change in the characteristics of spreading at about 37 Ma. The spreading rate strongly diminished and its direction underwent a rapid counter-clockwise rotation. The roughness of the seafloor increased significantly [*Deschamps*, 2001] and nontransform discontinuities developed. In the Philippine Arc, arc volcanism resumed since about 36 Ma, suggesting northward subduction restarted. However, this subduction would not provide an efficient driving force for the opening of the WPB as paleomagnetic data do not indicate any southward retreat of the trench. But this change of the geodynamic context within the southwestern boundary of the basin could partly explain the variation in the characteristics of spreading in the basin.

6.5. 35 Ma Stage

[43] The spreading rate in the WPB diminished and the counter-clockwise reorientation of the spreading axis continued (Figure 17). Spreading at the axis that was located

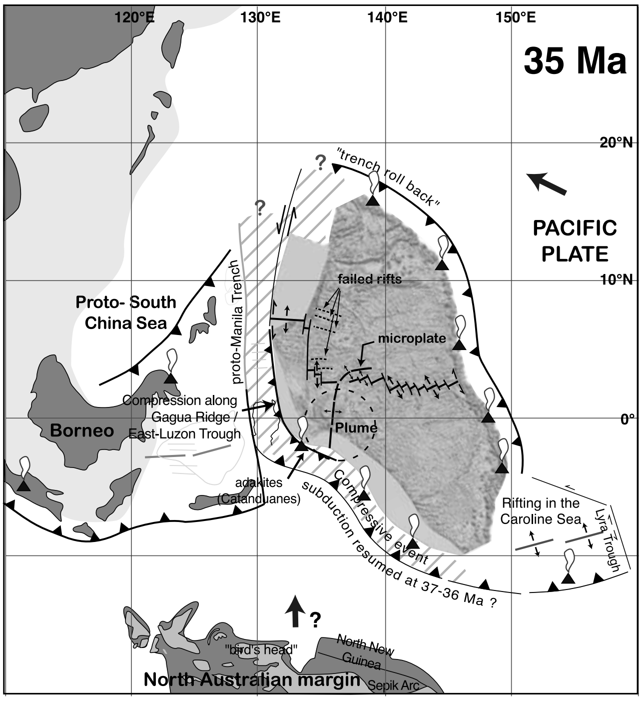

Figure 17. Evolutionary model of the West Philippine Basin, stage at 35 Ma.

above the Benham hot spot stopped, but young ages of rocks with OIB and E-MORB affinities show that the hot spot remained active at least until 25 Ma. In the central part of the basin, a microplate displaying well-marked fan-shaped structures developed during this last phase of spreading [*Deschamps et al.*, 1999; *Okino and Fujioka*, 2002].

[44] We suggest that a compressive episode occurred along the western margin of the WPB since 35 Ma, leading to the uplift of the Gagua Ridge [*Deschamps et al.*, 1998], and a short-lived subduction of the young crust of the WPB beneath the eastern coast of Luzon. This episode is marked by arc volcanism between 33 and 27 Ma in the Northern Sierra Madre and by adakitic volcanism in the Catanduanes Islands (Figure 18) [*Metal Mining Agency Japan* (*MMAJ*), 1977; *Wolfe*, 1981; *Ringenbach*, 1992; *David*, 1994]. Adakites are possibly due to the subduction of the young WPB created from the Benham spreading axis. The early Oligocene tectonic event may also have caused the incorporation of the Zambales ophiolites in eastern Luzon.

[45] The cause of the tectonic event mentioned above is still unclear. It could be related to the incipient collision between the northern part of the Philippine Arc with the Eurasian margin at 33/32 Ma [*Rangin et al.*, 1990]. Another cause could be a change of the movement of the Pacific Plate [*Norton*, 1995] which generated tectonic events on surrounding margins.

6.6. 30 Ma Stage

[46] The arc volcanism in the Northern Sierra Madre (Luzon) and in the Catanduanes Islands ceased at 27 and 30 Ma respectively, suggesting that the compressive episode along the Gagua Ridge and the eastern coast of Luzon stopped, perhaps due to the beginning of the subduction in the Manila Trench [*Rangin et al.*, 1990].

[47] Spreading ceased in the WPB at 33/30 Ma (Figure 18). Rifting began in the Shikoku and Parece-Vela basins since 30 Ma [*Okino*, 1998]. We suggest that the extensive stresses that provided driving forces for the opening of these basins were transmitted to the fossil but still hot and easily deformable spreading axis of the WPB, inducing a late and short stage of amagmatic extension accompanied by dextral strike-slip faulting along the rift valley. This last event occurred between 30 and 26 Ma.

7. Conclusion

[48] Our study of the West Philippine Basin and of its margins supports the following conclusions:

[49] 1. Age of spreading: spreading began at 54 Ma, and rifting at 55 Ma or few my before. The uncertainty about the age of the onset of spreading is due to the lack of information from the southern and northernmost parts of the WPB. Spreading ended at 33/30 Ma but a late and short episode of NE-SW extension occurred between 30 and 26 Ma. This almost amagmatic episode explains the great depth of the rift valley and its NW-SE orientation that cuts obliquely across the former spreading fabric. The opening of the Shikoku and Parece-Vela basins since 30 Ma along the eastern side of the WPB could be the origin of such an episode. This event was accompanied by dextral strike-slip faulting along the former rift valley.

[50] 2. Characteristics of spreading: spreading first occurred along an ENE-WSW axis close to and parallel to the Philippine Arc. After a few my, the spreading direction changed and spreading occurred in a NE–SW direction from a newly formed NW-SE-trending axis. The Oki-Daito escarpment was formed. The spreading direction continued to rotate counter-clockwise, toward a N–S and finally N10/20W direction. An extensional episode followed the end of

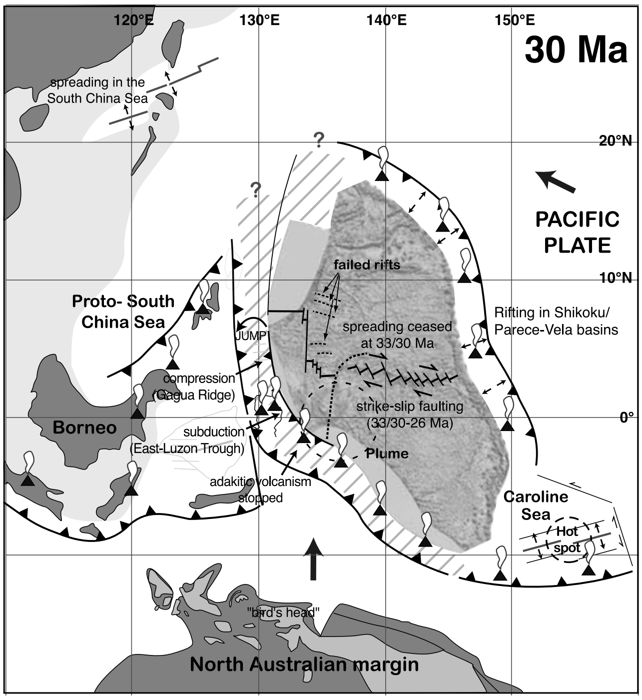

Figure 18. Evolutionary model of the West Philippine Basin, stage at 30 Ma.

spreading and occurred following a NE-SW direction. In the western part of the basin, the spreading system was disorganized due to the presence of a mantle plume. Such an interaction resulted in overlapping spreading centers, ridge jumps toward the hot spot, and the formation of a thick crust that displays N-MORB, E-MORB and OIB-like basalts.

[51] 3. Rate of spreading: most of the WPB crust was formed at a half spreading rate of 44km/Ma. This rate was maybe slightly higher before 50 Ma. It significantly diminished from 37 Ma until 33/30, as shown by the increasing spacing and height of abyssal hills when approaching the spreading axis.

[52] 4. Nature of the WPB boundaries during the opening: the eastern side of the basin (i.e., the Palau-Kyushu Ridge together with the Izu-Bonin Arc) was bounded by an active subduction zone. Strike-slip faulting occurred along the Palau-Kyushu Ridge accommodating the opening. Subduction was also active along the Philippine archipelago since the Late Cretaceous until the Miocene. We suspect a cessation of the northward subduction between 43 and 36 Ma. The Gagua Ridge accommodated the WPB opening by strike-slip deformation. This last boundary underwent a compressive episode in late Eocene-early Oligocene, maybe due to the incipient collision between the northern Philippine archipelago and rifted fragments from the Eurasian continental margin.

[53] 5. Driving forces for the opening: the northward retreat of the trench located along the Izu-Bonin Arc provided a driving force during the whole opening of the WPB. The southward retreat of the trench bounding the Philippine Arc also constituted another force for the opening but only before 43 Ma. We suggest that the opening of the WPB also resulted from the upwelling of hot asthenosphere beneath the basin, explaining why the spreading continued at a spreading axis that was far from, and not parallel to, the subducting boundaries since 50 Ma.

[54] 6. Nature of the West Philippine Basin: our study demonstrates that the WPB is a back arc basin in which extension was driven by horizontal traction due to island arc outward migration as well as by internal constraints that made its spreading center running efficiently for more than 20 my.

[55] Finally, the global study of the West Philippine Basin provides new information about the development of the basin. Compared to previous models, our model is able to propose a more precise history of spreading, giving details about the duration and direction of spreading, the location of triple junction traces, the presence of several distinct spreading axes, and the last event which is responsible for the structure of the extinct rift valley. By correlating the spreading characteristics within the basin, the paleomagnetic data and the tectonic and volcanic events that occurred within its margin, we can propose a consistent history of its opening, taking into account the presence of subduction zones and the related driving forces. Some inconsistencies that existed in previous models are partly solved. For example, the N–S spreading fabric evidenced in the oldest parts of the basin is much more consistent with an opening of the basin behind a subduction zone located along the Philippine archipelago (Figure 14) than is the NW–SE fabric that was previously inferred at the same locations from Hilde and Lee's model (1984). In the same way, the description of triple junction traces and of very discordant spreading fabrics close to the Benham Rise and their integration in a more global history provide valuable information about the basin development whereas previous models based on pure symmetric spreading fail to explain the geometry of the WPB.

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