Propagators and ridge jumps in a back-arc basin, the West Philippine Basin

Anne Deschamps,1 Ryuichi Shinjo,2 Takeshi Matsumoto,2 Chao-Shing Lee,3 Serge E. Lallemand,4 Shiguo Wu5 and Scientific party of KR03-04 and KR04-14 cruises6

1Université Européenne de Bretagne, Université de Brest/CNRS, UMR 6538 Domaines Océaniques, IUEM, Place N. Copernic, 29280 Plouzané, France; 2Department of Physics and Earth Sciences, University of the Ryukyus, Senbaru-1, Okinawa 903-02313, Japan; 3Institute of Applied Geophysics, National Taiwan Ocean University, 2 Pei-Ning Road, Keelung 202, Taiwan; 4Géosciences Montpellier, Université Montpellier 2, CC.60, Place E Bataillon 34095 Montpellier Cedex 05, France; 5Institute of Oceanology, Chinese Academy of Sciences, 7 Nanhai Road, Qingdao 266071, China; 6KR03-04 and KR04-14 Cruises Scientific Party: M. Shirahashi (Univ. Ryukyus: UR), S. Inoue (UR), Y. Mauda (UR), R. Matsumura (UR), M. Miyamoto (UR), H-M. Kao (National Taiwan Ocean Univ.: NTOU), J. Lee (NTOU), C-H. Tsai (NTOU), T. No (Nippon Marine Enterprises, Ltd.: NME), S. Hosoya (NME), H. Shibata (NME), T. Kodera (NME), Y. Sato (Marine Works Japan, Ltd.: MWJ), Y. Sagawa (MWJ), O. Cabrera (Dept Foreign Affairs, Maritime and Ocean Affairs Center, Philippines)

ABSTRACT

We explore the tectono-magmatic processes in the western West Philippine Basin, Philippine Sea Plate, using bathymetric data acquired in 2003 and 2004. The northwestern part of the basin formed through a series of northwestward propagating rifts. We identify at least five sequences of propagating rifts, probably triggered by mantle flow away from the mantle thermal anomaly that is responsible for the origin of the Benham and Urdenata plateaus. Gravitational forces caused by along-axis topographic gradient and a ~30° ridge reorientation appear to also be driving the rift propagations. The along-axis mantle flow appears to be reduced and deflected along the Luzon-Okinawa fracture zone, because the spreading system remained stable west of this major fault zone. North-east of the Benham plateau, a left-lateral fracture zone has turned into a NE–SW-trending spreading axis. As a result, a microplate developed at the triple junction.

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Introduction

The West Philippine Basin (WPB) is a currently inactive back-arc basin belonging to the Philippine Sea Plate (PSP). It has developed between two opposed subduction zones in the Eocene-Oligocene time. Opening is supposed to have occurred from 55 to 30 Ma, with a short episode of amagmatic extension at 30–26 Ma in the central part of the basin, according to Deschamps and Lallemand (2002) or from 58 to 33 Ma according to Hilde and Lee (1984). Development history of the basin is still controversial, mainly because of the lack of reliable age data. According to Hilde and Lee (1984), the WPB results from two stages of opening along the Central Basin Spreading Center (CBSC): (1) from 58 to 45 Ma (magnetic lineations 26–20), spreading occurred in a NE–SW direction at a half-rate of 44 mm yr\(^{-1}\) and (2) at 45 Ma (amagnematic). Subsequently, the former NW–SE CBSC was reorganized into numerous, short, E–W spreading segments offset by N–S transform faults and non-transform discontinuities. Spreading then ceased at 35 Ma. Deschamps and Lallemand (2002) proposed that the spreading history has been strongly affected by (1) a general rotation of the spreading system (Taylor and Goodliffe (2004) calculate 100° of rotation) and (2) the presence of a hot-spot. The spreading pattern is more complicated in the western part of the WPB than in its eastern part, because of the presence of this mantle thermal anomaly during spreading. The Urdenata plateau in the northwestern basin and the Benham plateau in the southwestern basin result from the interaction of such a plume upwelling with the western part of the spreading system (Okino et al., 1999; Deschamps and Lallemand, 2002). As the result of this interaction, propagating rift systems developed and several ridge jumps occurred towards the hot region and the western part of the WPB displays (1) rough morphology, (2) complicated magnetic pattern, (3) excess of magmatism, (4) several failed rifts and associated discordant fabric (Yoshida et al., 2000) and (5) a microplate characterized by fan-shaped seafloor structures (Deschamps and Lallemand, 2002; Okino and Fujioka, 2003). Conversely, in the eastern part of the basin, spreading occurred from a single and steady-state spreading centre.

Several oceanographic cruises collected bathymetric, magnetic and gravity data since 1984 (Oshima et al., 1988; Matsumoto et al., 1993; Ohara et al., 1997; Lallemand and Liu, 1997; Deschamps et al., 1998, 1999, 2000; Fujioka et al., 1999; Okino et al., 1999; Fujioka et al., 2000; Okino and Fujioka, 2003). Most of these cruises were conducted in the vicinity of the CBSC in the central and eastern parts of the WPB. In the northwestern part of the basin, the Hydrographic Department, Japan maritime Safety Agency, has conducted geophysical surveys including seabeam mapping, gravity and magnetic anomalies (Yoshida et al., 2000). On the basis of these results, Yoshida et al. (2000) identified at least three areas of seafloor fabric formed between...
overlapping spreading centres. However, the unequal quality of the data prevents the authors to characterize fully the spreading processes in this northwestern part of the basin all the more as no reliable age data exist.

To characterize better the spreading processes in the northwestern part of the WPB, we conducted two sampling and geophysical cruises in 2003 and in 2004 mostly east of the NNE-SSW-trending Luzon-Okinawa Fracture zone (LOFZ). In this article, we present bathymetric data acquired during these cruises as they provide important information about the spreading processes. Magnetic data were also collected, but not shown here. They are currently being processed and will be interpreted in the light of radiometric ages when available.

**Seafloor morphology at the northwestern part of the West Philippine Basin**

The bathymetric data acquired by the R/V Kairei of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) are shown in Fig. 1. They are mixed with previous data shown in Deschamps and Lallemand (2002). The depth of the basin in this area ranges between ~1200 m close to the Benham Rise and ~6800 m in the Ryukyu subduction trench. Seafloor shallows at ~3400 m at the Urdenata plateau.

In the survey area, the seafloor lineations are clearly visible and mainly correspond to large rectilinear scarps, most often 200–300 m high. They generally trend NW-SE, that is perpendicular to the LOFZ. Their orientation progressively changes from ~N133E in the northern part of the survey area till ~N105E toward the south, close to the most recent locus of spreading.

The western termination of the CBSC, marked by a well-expressed NW-SE rift valley, is clearly expressed at 127°30’E/18°30’N (e.g., Fujioka et al., 1999; Deschamps et al., 2002). Our data also show the presence of another WNW-ESE -trending valley at ~18°30’N/126°E. This valley is 20-km wide and 2100-m deep with respect to the surrounding seafloor.

The LOFZ consists of several linear and parallel faults such that it is reaches ~60 km in width. The orientation of its eastern branches varies from 040 north of the survey area to 010 south of the area, such that keeps roughly perpendicular to the spreading fabric to the east. Conversely, its western branches keep a stable 030 orientation all along the fault such that it remains strictly perpendicular to the N120E-trending spreading fabric west of the LOFZ. Between 21°30’N and 23°N, the LOFZ displays prominent linear to rounded reliefs.

At the vicinity of 18°30’N/126°E and 19°30’N/127°30’E, we observe an area of seafloor fabric, valleys, and prominent seamounts (up to ~2900 m with respect to the surrounding seafloor), which trend ~070 and bound to the northwest of the microplate centred at ~18°30’N/128°E evidenced by Deschamps and Lallemand (2002). These 070-trending abyssal hills are bounded by fault scarps up to ~1500 m in height.

Except at the location of the microplate, we identify six areas of ‘discordant’ fabric (named here D1–D6)
bordered by a series of curved scarps. These scarps delimit grabens that reach 15 km in width and 1700 m in depth relative to surrounding seafloor (Figs 1 and 2). Within these areas, abyssal hills generally trend 050–095.

West of the LOFZ, the trend of abyssal hills remains relatively constant with a N120E value. Small size seamounts are observed within this area.

**Spreading in the northwestern part of the basin based on bathymetric data**

The overall orientation of abyssal hills in the northwestern part of the WPB as well as the trend of the LOFZ reveals a general NE–SW spreading direction with a counter-clockwise rotation of this direction south of ~22°N, in accordance with existing spreading models (e.g. Hilde and Lee, 1984; Deschamps and Lallemand, 2002; Taylor and Goodliffe, 2004) and with the general NW–SE trend of the CBSC. However, in detail, the spreading pattern appears to be more complicated in this part of the basin than within its central and eastern parts.

The WNW–ESE -trending elongated large graben observed at ~18°30’N/126°E probably represents the westward continuation of the CBSC as it parallels the N105E-trending surrounding seafloor fabric as well as the CBSC east of 127°30’E. The CBSC thus seems to be offset by a small, short-lived microplate (Hilde and Lee, 1984). This discordant 070 fabric is interpreted as the result of a NW–SE spreading episode in the vicinity of the Benham Rise during the last spreading stage in the WPB (Deschamps and Lallemand, 2002). We notice that within this area of discordant fabric, fault scarps generally face the elongated, prominent NE–SW-trending seamounts observed within this area. Seamounts locally present steep and relatively linear flanks suggesting partial control by faulting. These seamounts indicate dominant effect of magmatism relative to tectonics such that more lava stack vertically and generate a prominent volcanic relief as less magma accretes laterally because of a low spreading rate. We suggest that they are axial volcanoes and thus mark the last locus of the short episode of NW–SE spreading. Such prominent seamounts are indeed sometimes observed along slow or ultra-slow spreading centres (e.g. Dick et al., 2003; Garel et al., 2003) where lava production can locally be high enough and spreading rate low enough to allow the strong focusing of the magmatic activity and then prominent axial highs to develop. We hypothesize that NW–SE spreading occurred to form the 070-trending abyssal hills and seamounts at the location of a former left-lateral transform zone that previously offset the CBSC. Such evolution of a leaky transform towards a spreading ridge has already been observed along the Antarctic-Pacific boundary, for example (Symons et al., 2004). Numerical modelling of oceanic transform faults show that they are hottest and weakest near their centre, which enhances melting and promotes the migration of off-axis melts into the transform zone (Behn et al., 2007) all the more in the case the pipe-like along-transform flow.

The six areas D1–D6 of 050–095 abyssal hills bordered to the north by a series of deep, curved grabens are typical of a lithosphere formed within zones of overlap between -newly formed- propagating rifts and -dying-retreating rifts (e.g. Hey et al., 1988). Indeed, between dueling rifts that spread simultaneously for a time, lithosphere is progressively transferred from one plate to the other, producing a sheared zone with ‘discordant’ seafloor fabric. This fabric formed within such a small, short-lived microplate does not parallel the general trend of the ridge axis (e.g. Hey et al., 1988). The deep curved en echelon grabens that bound the rotated abyssal-hill fabrics to the north are interpreted as series of failed rifts curving southward towards a propagating rift. It is indeed shown that at mid-ocean ridge overlaps, rotation of the ridge-parallel tensile stresses favours rift propagation at more than 45° relative to the ridge trend (e.g. Neves et al., 2004). The northwestward or westward direction of inward curvature and jumps of the failing rift indicate encroaching of propagating rift at the same direction (Wilson, 1990). Similar system appears repeatedly toward the south. Each series reveal the abandonment of the spreading ridge and formation of a new one through northwestward propagation of a new ridge located more to the south. We identify five propagation rift systems (PRs) (D1–D5) in the study area and possibly a sixth one (D6) (Fig. 1). We observe that there is no change in the spreading fabric orientation north and south of the D1, D2 (Fig. 2) and D4 PRs. The abyssal hills orientation rotates counter-clockwise by approximately 8, 6 and 13° across the D3, D5 and D6 PRs, respectively. This suggests that these PRs did represent an opportunity to establish a new spreading centre with a distinct orientation.

West of the LOFZ, data reveal a relatively stable ~030 spreading direction, parallel to the western branches of the LOFZ. There are some evidences for excess of volcanism in the vicinity of the fracture zone, as well as along the fracture zone itself between 21°30’N and 23°N.

**Discussion and conclusion**

Much of the northwestern part of the WPB, east of the LOFZ appears to have formed by a series of ridge propagation. Previously proposed mechanisms to explain the triggering and evolution of PRs include (1) mantle flow away from hotspots (e.g. Schilling et al., 1985; Hey et al., 1986; Brozena and White, 1990; Wilson and Hey, 1995; Rabinowicz and Briais, 2002), (2) ridge reorientation (e.g. Wilson et al., 1984; Menard, 1984; Lonsdale, 1989; Hey et al., 1995), (3) the propagation of the PR as a crack in an elastic material resulting from excess of gravity sliding stresses produced by the hotter and thus more buoyant asthenosphere and shallow seafloor associated with the hotspot compared to deeper regions (Phipps Morgan and Parmentier, 1985) and (4) very thin and weak lithosphere surrounding fast spreading centres that is susceptible to perturbation by relatively small mantle anomalies (Martínez et al., 1997). Martínez et al. (1997) emphasized the importance of temperature-dependant width of the ‘ductile deformation zone’ below the brittle lithospheric layer around the spreading axes relative to ridge offset, in which temperature is...
controlled by either spreading rate or thermal plume influence.

The presence of the Benham and Urdenata plateaus reflects excess of volcanism that is related to the presence of a hot mantle zone during basin development (e.g. Macpherson and Hall, 2001; Deschamps and Lallemand, 2002). Geochemical analyses of mafic lavas from the vicinity of the Benham Rise and Urdeneta Plateau (Hickey-Vargas, 1998; Shinjo et al., 2005; Hickey-Vargas et al., 2006) reveal deviation of these magmas from enriched sources similar to those for ocean island basalts (OIBs). Thus, we propose that PRs in the study area are at least partly because of the juxtaposition of hotspot activity. New rifts indeed tend to propagate away from hotspots as a result of the flow of partial melts or mantle plume material away from a hotspot (e.g. Hey et al., 1988). As the seafloor is shallower in the vicinity of the Benham and Urdenata plateaus, it is possible that an additional triggering force is the gravity caused by the along-axis topographic gradient. We observe changes in seafloor fabric orientation in the vicinity of PRs D3, D5 and D6. Kinematic changes thus also probably contribute to the development of PRs as the general spreading direction progressively changed from ~045 to ~015 during the WPB formation. Small changes in plate motion indeed lead to reorientation of ridges axes often accommodated through the mechanism of ridge propagation (e.g. Wilson et al., 1984; Briais et al., 2002).

Spreading pattern is contrasted in the western and eastern parts of the WPB. To the east, spreading occurred from a single and stable spreading centre and ridge reorientation occurred by smooth, continuous rotations of individual spreading segments and rather by propagation. Long ridge segments did break into shorter lengths, facilitating the ridge crest rotation and creating new transform faults (e.g. Hilde and Lee, 1984; Deschamps and Lallemand, 2002). No excess of volcanism that might be related to a mantle thermal anomaly is observed. Conversely, in the west, the spreading system has been highly unstable because of the presence of a mantle thermal anomaly. Much of this part of the WPB was formed by a series of ridge jumps through rift propagation coupled to rift retreat. At least five sequences of westward rift propagation are recognized. Rotation of the spreading direction has been accommodated by propagation rather than by rotation of the spreading centre. The 070°-trending spreading centre evidenced north-east of the Benham Rise is likely responsible for the development of the microplate evidenced by Deschamps and Lallemand (2002) at the triple junction.

We do observe few pieces of evidence for excess of volcanism west of the LOFZ. The spreading system seems, however, to be relatively stable as shown by the stable trend of abyssal hills, associated with the constant orientation of the western branches of the LOFZ. Georgen and Lin (2003) have investigated the effect of transform offsets in limiting along-axis flow of plume material. Modelling results predict that transform faults affect along-axis asthenospheric flow in two important ways: (1) transforms reduce along-axis flux, the longer the transform offset, the greater the reduction in across-transform flux relative to the zero-offset case and (2) transforms deflect shallow asthenospheric along-axis flow towards the direction of the next ridge segment. The age-offset across the LOFZ is not well-determined (e.g. Deschamps and Lallemand, 2002), but the propagating rift systems clearly end against the LOFZ, implying that this fault zone acted like a barrier to magma coming

![Fig. 2 Shaded seafloor topography of the areas of discordant fabric D1 and D2 (contours every 20 m) with the tectonic lineations within the same area. DF, discordant fabric; PR, propagating rift; FR, failing rift.](image-url)
from the hotspot. Second, the volcanic relief that we observe along the fault zone north of 21°30'N suggests that asthenospheric flow has been deflected along the LOFZ.

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