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Identification of the Caroline Plate Boundary: Constraints from Magnetic Anomaly

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Abstract

The Caroline Plate is located among the Pacific Plate, the Philippine Sea Plate, and the India Australia Plate, and plays a key role in controlling the spreading direction of the Philippine Sea Plate. The Caroline Submarine Plateau (or Caroline Ridge) and the Eauripik Rise on the south formed a remarkable T-shaped large igneous rock province, which covered the northern boundary between the Caroline Plate and the Pacific Plate. However, relationship between these tectonic units and magma evolution remains unclear. Based on magnetic data from the Earth Magnetic Anomaly Grid (2-arc-minute resolution) (V2), the normalized vertical derivative of the total horizontal derivative (NVDR-THDR) technique was used to study the boundary of the Caroline Plate. Results show that the northern boundary is a transform fault that runs 1 400 km long in approximately 28 km wide along the N8° in E-W direction. The eastern boundary is an NNW-SSE trending fault zone and subduction zone with a width of tens to hundreds of kilometers; and the north of N4° is a fracture zone of dense faults. The southeastern boundary may be the Lyra Trough. The area between the southwestern part of the Caroline Plate and the Ayu Trough is occupied by a wide shear zone up to 100 km wide in nearly S-N trending in general. The Eauripik transform fault (ETF) in the center of the Caroline Plate and the fault zones in the east and west basins are mostly semi-parallel sinistral NNW-SSE–trending faults, which together with the eastern boundary Mussau Trench sinistral fault, the northern Caroline transform fault, and the southern shear zone of the western boundary, indicates the sinistral characteristics of the Caroline Plate. The Caroline hotspot erupted in the Pacific Plate near the Caroline transform fault and formed the West Caroline Ridge, and then joined with the Caroline transform fault at the N8°. A large amount of magma erupted along the Caroline transform fault, by which the East Caroline Ridge was formed. At the same time, a large amount of magma developed southward via the eastern branch of the ETF, forming the northern segment of the Eauripik Rise. Therefore, the magmatic activity of the T-shaped large igneous province is obviously related to the fault structure of the boundary faults between the Caroline Plate and Pacific Plate, and the active faults within the Caroline Plate.

Key words: Caroline Plate, magnetic anomaly, normalized vertical derivative of the total horizontal derivative, plate boundary, Caroline Ridge, Eauripik Rise

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1 Introduction

The Caroline Plate is located in the equatorial western Pacific Ocean, surrounded by the Philippine Sea Plate to the west, the Pacific Plate to the north and east, and the Indo-Australian Plate to the south (Fig. 1a). The kinematic relationship of the Caroline Plate to the Indo-Australian Plate and the Philippine Sea Plate significantly affected the spreading direction and rotation of the Philippine Sea Plate (Gaina and Müller, 2007; Wu et al., 2016). Therefore, the Caroline Plate is a key unit of reconstruction for the mutual movement between the Pacific Plate and the Philippine Sea Plate, and the tectonic evolution of the surrounding basins as well (Hall, 2002; Gaina and Müller, 2007; Wu et al., 2016).

Previous studies have identified magnetic lineations in the near E-W direction and determined the direction and era of the Caroline Plate spreading (36 Ma-25 Ma) (Gaina and Müller, 2007;

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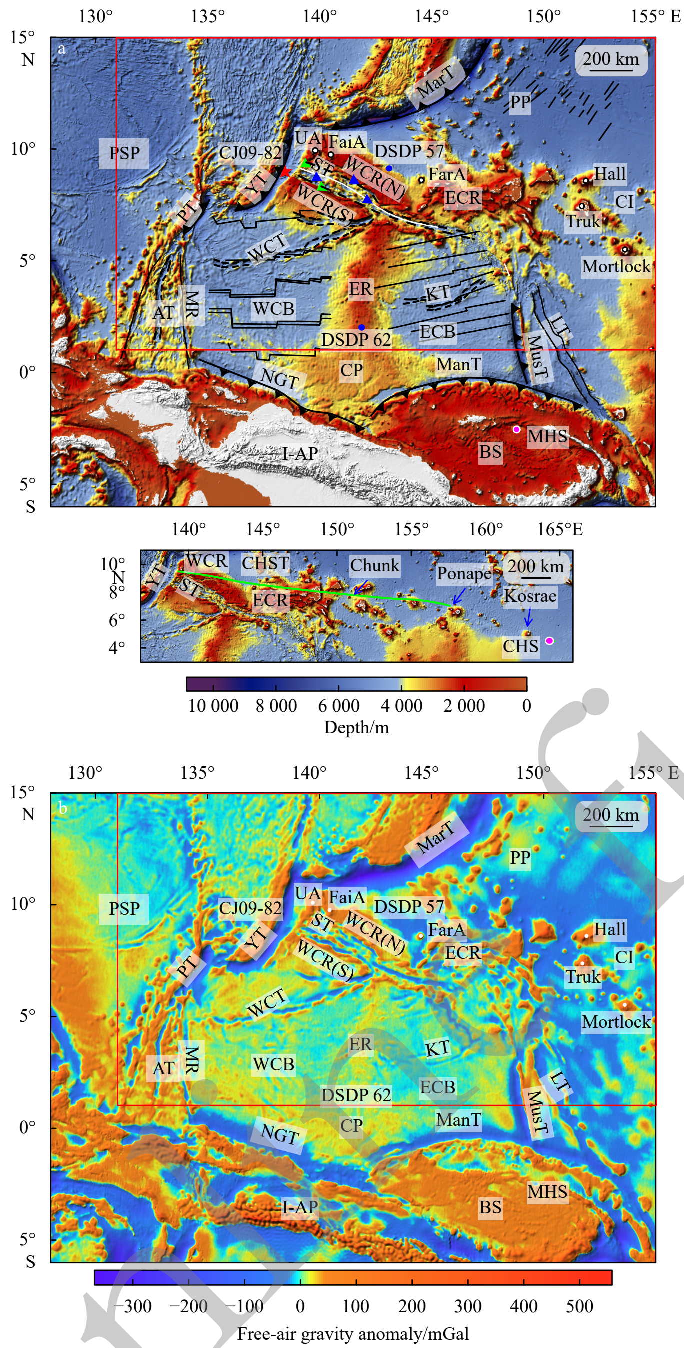

Fig. 1. a. Submarine topography and geological units in the research area. The topography data are from GEBCO Compilation Group (2022) GEBCO_2022 Grid. The magnetic lineation data in the Caroline Basin are from Gaina and Müller (2007). The magnetic lineation in the Pacific Plate is from Zhu et al. (2022). The white dots represent islands in the Federated States of Micronesia. The white dotted line is the presumed boundary between the Caroline Plate and the Pacific Plate. The green dashed line indicates the modeled track of the Caroline hot spot since 25 Ma, based on Wu et al. (2016). AT: Ayu Trough; BS: Bismark Sea; CHS: Caroline Hot Spot; CHST: Caroline Hot Spot Track; CI: Caroline Islands; CP: Caroline Plate; ECB: East Caroline Basin; ECR: East Caroline Ridge; ER: Eauripik Rise; FaiA: Fais Atoll; FarA: Faraulep Atoll; I-AP: Indo-Australian Plate; KT: Kiilsgaard Trough; LT: Lyra Trough; ManT: Manus Trench; MR: Mapia Ridge; MarT: Mariana Trench; MHS: Manus Hot Spot; MusT: Mussau Trench: NGT: New Guinea Trench; PP: Pacific Plate; PT: Palau Trench; PSP: Philippine Sea Plate; ST: Sorol Trough: UA: Ulithi Atoll; WCB: West Caroline Basin; WCR(N): West Caroline Ridge (North); WCR(S): West Caroline Ridge (South); WCT: West Caroline Trough; YT: Yap Trench. The red star indicates the Site CJ09-82 (Yan et al., 2022). The green triangles are dredge hauls by RV *Kexue* from the Institute of Oceanology, Chinese Academy of Sciences (Zhang et al., 2020). The blue triangles are dredge hauls by the RV "Vema" (hauls D19, D20, and D21) (Fornari et al., 1979). DSDP57 and DSDP62 are from Ian Ridley et al. (1974) and Den et al. (1971), respectively. b. The free air gravity anomaly (satellite altimetry gravity anomaly) mapof the research area. Data are from Sandwell et al. (2021). The names of geological units are the same as Fig.1a.

Weissel and Anderson, 1978). However, the boundary between the Caroline Plate and the Pacific Plate has not been widely recognized in consensus. This is because in the north, the Caroline Ridge near E-W direction and the Eauripik Rise near S-N direction formed the T-shaped large igneous province that covered the boundary between the Caroline Plate and the Pacific Plate, and massive magmatic activity smeared the boundary between the near E-W magnetic lineations of the Caroline Plate and the NE magnetic lineations of the Pacific Plate; in the east, the southern part is the Mussau Trench and Lyra Trough, and the northern part is the disruptured zone composed of dense-fault belts and submarine volcanos, forming a boundary of 100 km wide in the nature of transformation (Hegarty and Weissel, 1988). Therefore, some scholars chose the paddle-shaped Sorol Trough as the plate boundary based on free space gravity anomaly, geomorphology, and tectonic features (Gaina and Müller, 2007; Hegarty and Weissel, 1988; Wu et al., 2016). However, the Sorol Trough should have developed after the formation of the Caroline Ridge, which is relatively late and currently active (Dong et al., 2018; Lee, 2004), although the free air gravity anomaly (Fig. 1b) and seabed topography (Fig. 1a) can be connected to the Mussau Trench to the southwest. In addition, the Sorol Trough cuts through the C12 magnetic lineation (33.1 Ma; Gaina and Müller, 2007) and the magnetic lineations in the Earth Magnetic Anomaly Grid (2-arc-minute resolution) (V2) magnetic anomaly map (Fig. 2), which all suggest that the Sorol Trough is not the plate boundary.

The distribution of T-shaped large igneous province not only helps to interpret the relative movement relationship between the Pacific Plate and Caroline Plate, but also raises an issue of magma source of the S-N Eauripik Rise. In this regard, the near E-W direction of the West Caroline Ridge and the East Caroline Ridge (Nagihara et al., 1989; Wu et al., 2016; Zhang et al., 2021; Fan et al., 2022), along with the eastern side of the Chuuk Island, and then the eastward islands of Pohnpei and Kosrae, formed a typical oceanic island volcanic chain (Jackson et al., 2016; Keating et al., 1984; Lee et al., 2001; Mattey, 1982; Tuzo Wilson, 1963; Wu et al., 2016; Zhang et al., 2020), which is the product of the Caroline hotspot movement (Wu et al., 2016; Zhang et al., 2020) and can provide reliable constraints of space-time relations for the movement of the Pacific Plate and Caroline Plate relative to the Caroline hotspot.

However, the northern end of the Eauripik Rise running in nearly S-N direction is perpendicular to the West Caroline Ridge and extends southward to the New Guinea Trench and Manus Trench at the southern boundary of the Caroline Plate. As the northern segment of the Eauripik Rise is closely connected to the West Caroline Ridge, both are related to hotspot magmatic activity (Fujiwara et al., 2000; Weissel and Anderson, 1978) and are likely formed by the same hotspot (Hegarty and Weissel, 1988). However clearly, the Caroline hotspot cannot provide sufficient magma for the E-W Caroline Ridge and S-N Eauripik Rise simultaneously in vertical direction. Therefore, some scholars suggested that the Manus hotspot might have played the role (Macpherson and Hall, 2001). Gaina and Müller (2007) proposed that the Manus hotspot first formed the West Caroline Ridge in the north, and then roughly migrated southward along the Eauripik Fault to the Manus Basin, forming the Eauripik Rise at last. Wu et al. (2016) emphasized that the Manus hotspot stayed at a relatively fixed position at the southern end, while the Caroline hotspot forms the Caroline Ridge and Caroline Island Chain at the northern end, but did not discuss the magma source of the Eauripik Rise. In the westward movement of the Pacific Plate and the tectonic evolution model of the Caroline Plate and the Philippine Sea Plate (Hall, 2002), how to interpret the Eauripik Rise is a question.

Therefore, the determination of the boundary between the Caroline Plate and the Pacific Plate and the discussion of the origin of the Eauripik Rise within the T-shaped large igneous province are a key factor for understanding the mutual movement between the Pacific Plate and the Philippine Sea Plate, and the tectonic evolution of the surrounding sea basins. In this paper, based on the magnetic potential field data, the edge recognition technology of the normalized vertical derivative of the total horizontal derivative (NVDR-THDR) (Wang et al., 2009) was used to study the fault distribution of the Caroline Plate, determine its boundary with the Pacific Plate, and then based on the spatial relationship between the northern boundaries of Caroline Plate to the East Caroline Ridge, West Caroline Ridge, and Eauripik Rise, and the coupling relationship between fault structure and magmatic activity was discussed to provides a new insight to exploring the magma source of the Eauripik Rise.

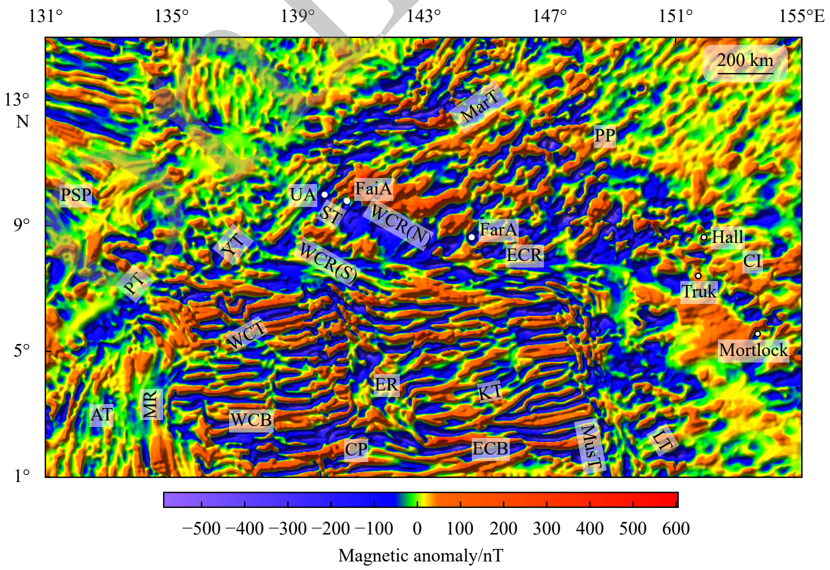

Fig. 2. ΔT magnetic anomaly map of the research area. The geological unit names are the same as Fig.1a.

2 Geolgical background

2.1 *Pacific Plate*

The plate reconstruction shows that, the Pacific Plate began to form from the center of the ancient Pacific Ocean (Panthalassa) at about 190 Ma, and the oldest oceanic crust exists in the east of the Mariana Trench (Dietmar Müller et al., 2008; Li et al., 2019). The drift direction of the Pacific Plate shifted from the previous NNW direction to the current NWW direction at about 43 Ma (Koppers et al., 2003). This led to the subduction of the Pacific Plate beneath the Philippine Sea Plate, but there was no subduction zone between the Pacific Plate and the Caroline Plate, instead of a 200 km wide boundary in transitional characteristics (Hegarty and Weissel, 1988).

The West Caroline Ridge (divided into the North Caroline Ridge and the South Caroline Ridge by the Sorol Trough) and the East Caroline Ridge developed in the area adjacent to the Pacific Plate in the north of the Caroline Plate are prominent high submarine reliefs, which are currently subducting beneath the Yap Trench at a slow speed (Nagihara et al., 1989; Wu et al., 2016). The two ridges have a about 30° difference in the trending, implying a possible change in the plate movement direction. Meanwhile, it shows no relationship between the Sorol Trough and the East Caroline Ridge on the subtopography and gravity maps (Figs 1a and 1b).

The age of the West Caroline Ridge is estimated to be 30 Ma (Wu et al., 2016), the K-Ar age of the basalt from the DSDP Site 57 site at the eastern end of the ridge is 23.5 Ma (Ian Ridley et al., 1974), and the ^{40}Ar-^{39}Ar age of basalt (sample M17-14) is 19.3 Ma (Zhang et al., 2020), which is consistent with the paleontological age of the overlying Upper Oligocene sedimentary rock (Heezen et al., 1971). The volcanic rocks of Chuuk Island in the Caroline Islands are approximately 10-11 Ma old, and the Pohnpei and Kosrae volcanic rocks further eastward are ~5 Ma and ~1.2 Ma-2.6 Ma old, respectively, forming a typical oceanic island volcanic chain (Jackson et al., 2016; Keating et al., 1984; Lee et al., 2001; Mattey, 1982; Tuzo Wilson, 1963; Wu et al., 2016; Zhang et al., 2020), which is surely the product of the Caroline hotspot (Wu et al., 2016; Zhang et al., 2020).

2.2 *The Philippine Sea Plate*

The Philippine Sea Plate is located between the Japan-Ryukyu-Taiwan-Philippines trench-arc system and the Izu-Ogasawara-Mariana-Yap trench arc system in the western Pacific Ocean (Karig, 1975; Mrozowski et al., 1982). The Philippine Sea Plate can be divided into three spreading stages (Austria et al., 2022), during which several clockwise rotation movements occurred. Hall et al. (1995) and Hall (2002) believed that the Philippine Sea Plate rotated 50° clockwise during 50 Ma-40 Ma, and continued to rotate 40° clockwise and move northward during 25 Ma-0 Ma. Some scholars also believed that the Philippine Sea Plate experienced a strong clockwise rotation during 53 Ma-45 Ma, while there was no obvious rotation during 44 Ma-25 Ma (Deschamps and Lallemand, 2002; Wu et al., 2016). In the late Oligocene, the Caroline Ridge subducted beneath the Philippine Sea Plate along the Yap Trench, which may have induced the turning of back-arc spreading of the Parece Vela Basin at ~19 Ma in direction from the initial E-W spreading at about 30 Ma by subduction of the Pacific Plate to NE-SW spreading (Fujiwara et al., 2000).

Although there are different models for the movement of the Caroline Plate, both Gaina and Müller (2007) and Wu et al. (2016) emphasized the influence of Caroline Plate subduction on the movement direction of the Philippine Sea Plate.

2.3 *Caroline Plate*

At present, it is generally believed that the Caroline Plate was formed in the back arc spreading environment of the Indo-Australian Plate subducting northward (Bracey, 1983; Hill and Hall, 2002; Hill and Hegarty, 1988; MacLeod et al., 2017). However, Gaina and Müller (2007) believed that in the late Eocene, the Pacific Plate subducted northward under the Philippine Sea Plate, forming the Caroline Arc, and then the seafloor began to spread into east and west sub-basins in S-N spreading divided by the Eauripik transform fault (ETF). The magnetic lineation results (Gaina and Müller, 2007) show that the West Caroline Basin was formed during seafloor spreading between 36 Ma and 25 Ma; the spreading center switched twice from south to north at 33.1 Ma and 28.7 Ma, respectively, and arrived at the West Caroline Trough at 26.6 Ma. The East Caroline Basin was formed persistently during seafloor spreading (35 Ma-25 Ma) with the Kiilsgaard Trough as its ridge. Along the ETF developed the Eauripik Rise extending over 1 000 km, which is an aseismic ridge (Den et al., 1971). It is widely believed that the magma from Eauripik Rise was originated from deep hotspots (Gaina and Müller, 2007; Macpherson and Hall, 2001).

Morphologically, the West and East Caroline Ridges and Eauripik Rise formed an irregular T-shaped large igneous province, especially in the north. Eauripik Rise and West Caroline Ridge are closely connected. Therefore, some scholars proposed that the T-shaped large igneous province might be formed by the same hotspot (Hegarty and Weissel, 1988). However, based on different geophysical fields and deep structures, some scholars believed that the two are not homologous (Li et al., 2021; Li and Wang, 2016).

2.3.1 *Boundary between Caroline Plate and Philippine Sea Plate*

The boundary between the Caroline Plate and the Philippine Sea Plate is clear: from north to south, there are the Yap Trench and Palau Trench, and then to south, there is the slowly expanding Ayu Trough (Fig. 1a).

In the early Miocene or late Oligocene, the Caroline Plate began to subduct beneath the Philippine Sea Plate along the Yap Trench. The late Oligocene Caroline hotspot volcanism formed the West Caroline Ridge (Wu et al., 2016). The subduction or collision of this submarine plateau significantly slowed down the plate subduction process, leading to the cessation of the Yap island-arc volcanic activity (Nagihara et al., 1989). The Yap subduction zone is a young initial subduction zone (Kim et al., 2009; Lee and Kim, 2004), with small spacing (~50 km) between island arc and trench, weak seismicity, no active island-arc volcanic activity, and submarine plateau subduction (Dong et al., 2018; Fan et al., 2022).

The Palau Trench may have the same origin as the Yap Trench (Kobayashi, 2004). The northern part of the Palau Trench is in S-N direction, while the central and southern parts are N30°E oriented. The southernmost end is overlaid with an active spreading center of the Ayu Trough (Fujiwara et al., 1995).

The Ayu Trough is centered around the S-N oriented central rift valley, symmetrical on both sides, exhibiting a trapezoidal or fan-shaped shape that is narrow in the north and wide in the south. It may have formed after the Caroline Plate stopped spreading (about 25 Ma) (Fujiwara et al., 1995; Fujiwara et al., 2000; Weissel and Anderson, 1978), and spread slowly but persistently (Fujiwara et al., 1995), making it a slowly growing basin. The central rift valley may be an active mid-ocean ridge, but no evidence of magnetic lineations was obtained (Hong and Lee, 2002; Lee and Kim, 2004). Some scholars believe that the counterclockwise rotation of the Caroline Plate led to the spreading of the Ayu Trough and the formation of the Mussau subduction zone (Bracey, 1983; Fujiwara et al., 2000).

2.3.2 *Boundary between Caroline Plate and Pacific Plate*

The border area between the northern side of the Caroline Plate and the Pacific Plate is affected by the T-shaped large igneous province, and thus the northern boundary of the Caroline Plate is ambiguous. If the Sorol Trough was used as the northern boundary of the Caroline Plate (Bird, 2003; Gaina and Müller, 2007; Hegarty and Weissel, 1988; Weissel and Anderson, 1978; Wu et al., 2016), it would obviously cut known magnetic lineations (Gaina and Müller, 2007; Wu et al., 2016), which is unreasonable. Moreover, the rifting time of the Sorol Trough may be between 24 and 10 Ma (Dong et al., 2018; Lee and Kim, 2004; Yan et al., 2022), indicating a late-coming geological body.

The Sorol Trough may be an active oblique tension fracture transformation system with strike slip and extensional properties (Weissel and Anderson, 1978), has strong shear action (Fornari et al., 1979; Perfit and Fornari, 1982), and is a sinistral shear fault zone (Dong et al., 2018; Zhang et al., 2021). Therefore, the Sorol Trough may also be formed from the initial splitting of the Pacific Plate. This may be because a large amount of magmatic activity provided by hotspot disrupted the structure of the lithosphere after the formation of the Caroline submarine plateau, making the overlying plates fragile. It is also supported by the basalt samples from the Sorol Trough in the Yap Trench showing ocean island basalt (OIB)-like geochemical characteristics (Yan et al., 2022). Therefore, the tension of the subduction of the northern plate caused the opening of the Sorol Trough, which is also a two-stage hotspot magmatic activity pattern of the formation and rifting of a submarine plateau (Campbell et al., 1989; Campbell, 2007; Richards et al., 1991).

The area bordering the Pacific Plate in the east of the Caroline Plate is a transformational tectonic zone, with Lyra Trough and Mussau Trench in the south, and a disruptured zone divided by dense fault zones (Hegarty and Weissel, 1988) and hidden faults in the north. Submarine volcano is developed along the fracture zone and hidden fault, which is the southward extension part of the East Caroline Ridge. The Mussau Trench is currently an active subduction zone (Gaina and Müller, 2007). However, the indistinct magnetic lineations between the Mussau Trench and the Lyra Trough, as well as the hidden fault zone in the north, suggest that the Lyra Trough may be a plate boundary (Hegarty et al., 1983).

3 Data and methods

3.1 *Data*

The ΔT magnetic anomaly data used for this study are derived from the Earth Magnetic Anomaly Grid (2-arc-minute resolution) (V2) that are released by the National Geographic Data Center (NGDC) of the United States. It combines satellite magnetic, ocean magnetic, and airborne magnetic data. The observation surface of the data is transformed to 4 km above sea level, with a spatial resolution of 2′×2′ (Maus et al., 2009; Meyer et al., 2017). Due to the lack of magnetic data in the Papua New Guinea land area south of the Caroline Plate, the southern boundary of the Caroline Plate was not included in this study.

3.2 *Methods*

This article conducts a comprehensive interpretation of geology and geomagnetism, using geophysical method with geological constraint and geomagnetic interpretation to study the boundaries of the Caroline Plate. To eliminate the interference information and obtain richer geological understanding, relevant technologies are needed to process geomagnetic anomaly, including:

(1) The observation surface of the ΔT magnetic anomaly was converted to 4 km above sea level. To improve the resolution, the downward continuation technique was used (Liu et al., 2019) to obtain the ΔT magnetic anomaly at sea level (Fig. 2). The research area is located in the equatorial areas, with a latitude span of 16° and a longitude span of 24°. Therefore, the reduction-to-pole (RTP) technique with fully variable inclinations in low latitude areas (He et al., 2022) was used to process data under the condition of considering induced magnetization only, by which the RTP magnetic anomaly in the research area was obtained (Fig. 3).

(2) For the boundary of geological body (fault or rock bound-

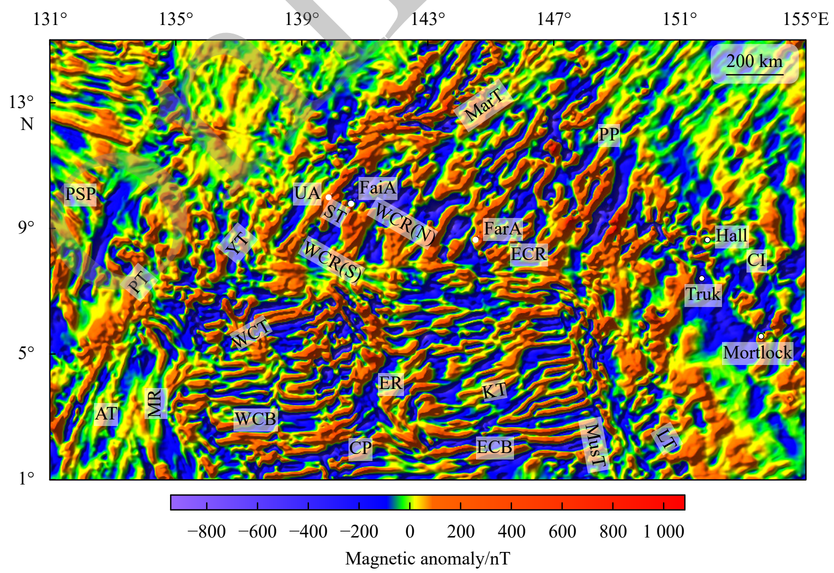

Fig. 3. The RTP magnetic anomaly in the research area. The geological unit names are the same as Fig.1a.

aries), the edge recognition method of gravity and magnetic potential field data has unique advantages; for examples, the directional derivative of gravity and magnetic potential field data can highlight the characteristics of gravity and magnetic anomalies in a certain direction. The NVDR-THDR edge recognition method (Wang et al., 2009) has advantages of stronger lateral resolution ability, edge enhancement function, and simple, clear, and easy to recognize images. This method has been widely used in the study of rock mass boundaries and fault distribution (Ma et al., 2021; Zhu et al., 2021; Luo et al., 2018; Zhu et al., 2022). The maximum position and its dislocation position in the NVDR-THDR map are used to identify the fault plane position. If the maximum extension of NVDR-THDR is long and exhibits linear characteristics, it reflects the distribution of faults; otherwise, if the extension is short and characterized by arc-shaped trap or semi-trap, it reflects the boundaries of rocks or seamounts.

4 Result

The NVDR-THDR of RTP magnetic anomaly (Fig. 4) exhibits rich information: within each plate, it mainly shows linear features in different orientations, reflecting the characteristics of oceanic crust magnetic lineations; in the Mariana Trench, Yap Trench, Palau Trench, and Ayu Trough, there are turns and discontinuities of the lineament-magnetic lineation belt, which manifested their boundaries; in the Caroline Ridge area, there is a boundary between the Caroline Plate E-W magnetic lineation and the Pacific Plate S-N magnetic lineation; and local small-scale arc-shaped traps serve as boundaries for volcanic rocks.

4.1 *The fault zone within the Caroline Plate*

The clear and continuous NVDR-THDR of RTP magnetic anomaly within the Caroline Plate reflects the near E-W magnetic lineation, and overall, the NNW fault zone cuts the magnetic lineation. Based on the characteristics of deformation and cutting of magnetic lineations, the ETF with a nearly parallel NNW-SSE strike, and faults within the East and West Caroline basins with sinistral features, were identified (Fig. 4).

The ETF is located in the center, running north-south, and separating the East Caroline Basin from West Caroline Basin. It is relatively large and has a maximum width of approximately 38 km in the north. In the northern area near the plate boundary and to the east of the ETF, a set of NNE faults is developed, which is closely related to the Eauripik Rise, known as the northern Eauripik Rise fault (NERF). It should be pointed out that in the northern part of the Caroline Plate, the ETF and Eauripik Rise are roughly symmetrical in the S-N axis, and southward near N3°, the Eauripik Rise gradually merges with the ETF.

The faults in the East Caroline Basin (East Caroline Basin fault, ECBF) are a set of parallel NNW trending faults, parallel to the ETF and the eastern boundary fault zone of the Caroline Plate (the northern segment is the disruptured zone DZ, and the southern segment is the Mussau Trench MT). The extension of the fault zone is discontinuous, and the offset of the magnetic lineation being cut is relatively short. In the area bordering the Pacific Plate, NWW-SEE trending Sorol Trough fault (STF) is developed.

The trending of faults in the West Caroline Basin (West Caroline Basin fault, WCBF) gradually shifted from NNW to near S-N from east to west. This also implies that the western part of the basin experienced stronger shear deformation compared to the eastern part of the basin. The activity of NNW to near S-N trending fault is strong, extending continuously from north to south in the West Caroline Basin. The development of NW trending faults is speculated to be conjugate faults of NNW or S-N trending faults. The NW trending fault is relatively small in scale, but there is a fault close to the Palau subduction zone in the west, running through the ETF in the east, and extending into the East Caroline Basin.

4.2 *The fault on the northern boundary of the Caroline Plate*

In the border area between the northern Caroline Plate and the Pacific Plate, a 1 400 km-long and 28-km wide fault zone

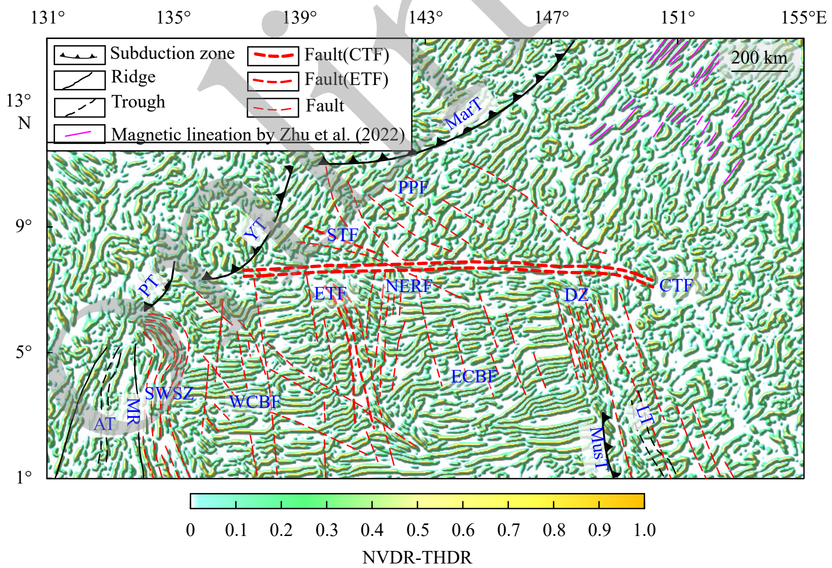

Fig. 4. The distribution of the Caroline Plate fault. The yellow-and-green lines are NVDR-THDR of RTP magnetic anomaly. The purple line in the upper right corner is the magnetic lineation recognized by Zhu et al. (2022). CTF: Caroline Transform Fault; DZ: Disruptured zone in the northern section of the eastern boundary of the Caroline Plate; ECBF: NNW trending fault in the East Caroline Basin; LT: Lyra Trough; MusT: Mussau Trench; ETF: Eauripik Transform Fault; NERF: northern Eauripik Rise fault; PPF: NW trending fault zone in the Pacific Plate; STF: Sorol Trough Fault zone; SWSZ: Southwest shear zone; WCBF: Fault zone within the West Caroline Basin.

(Fig. 4) is developed along the N8° in east-west direction, which extends eastward from the east of Yapu Trench to the south of West Caroline Ridge, the Sorol Trough, East Caroline Ridge, and Caroline Islands, and finally extends to the Pacific Plate. On the north and south sides are respectively the EW-oriented magnetic anomaly of the Caroline plate and the NE-oriented magnetic anomaly of the Pacific Plate, which indicates that it is the boundary between the Caroline Plate and the Pacific Plate. It is speculated that it is the transform fault zone of shear boundary of the plate, called the Caroline transform fault (CTF, Fig. 4).

As a plate boundary, the CTF is also reflected in the change of the width of the Sorol Trough, which indicated that the Sorol Trough, which was initially split from the Pacific Plate, is like an oar in plane shape. In the area where it intersects with the CTF, the width of the trough is suddenly reduced from 81 km in the west to 26 km wide in the east (Figs 1a, 1b, and 4), which is like the transition zone between oar paddle and grip in shape. This suggests that there are two geological bodies on the north and south sides of the CTF, and the forces that formed the Sorol Trough have attenuated on the fault surfaces of both geological bodies. Therefore, although they continue to develop within the Caroline Plate, the width of the Sorol Trough has been significantly decreased.

Within a width of approximately 100 km from the south of the CTF to the approximately N7° latitude line, the NVDR-THDR of RTP magnetic anomaly is intermittently connected, and characterized by a fault zone, which is speculated to be a shear zone associated with the CTF.

In the Pacific Plate near the CTF, despite the influence of igneous rock of the West Caroline Ridge and the East Caroline Ridge, the magnetic lineation still maintains a stable NE trend. In addition to the shear deformation of the Sorol Trough, a group of echelon NWW fault zones (Pacific Plate Fault, PPF) was also developed, suggesting shearing strain, but only the Sorol Trough Fault zone (STF) crosses the CTF, extends towards the SEE direction in the East Caroline Basin. In fact, strong sinistral shearing in the development of the Sorol Trough has been confirmed by structural interpretation (Weissel and Anderson, 1978), metamorphic structures of submarine rocks (Fornari et al., 1979; Perfit and Fornari, 1982), seismic profile interpretation (Dong et al., 2018; Zhang et al., 2021), and seismic distribution (Schellart et al., 2008). The seismic distribution of the Sorol Trough shows the nature of strike slip, which is consistent with the relative movement between the Pacific Plate and the Caroline Plate (Schellart et al., 2008). GPS measurement data (Kotake, 2000; Lee, 2004) also confirmed the existence of strike slip earthquakes between Ulithi Atoll and Fais Atoll north of the Sorol Trough, possibly involving a sinistral strike slip fault. Earthquakes distributed along this fault indicate that it has cut through the lithosphere.

The shear zone of the Sorol Trough, CTF, and the northern shear zone of the Caroline Plate constituted a 200-km wide shear boundary zone between the Caroline Plate and the Pacific Plate (Fig. 4).

In addition, the shear strength of the northern and southern sides of the CTF is significantly different. The shear deformation of the Pacific Plate is relatively weak, while that of the Caroline Plate is strong, which may be related to the lithospheric strength of the two plates. The Pacific Plate in the research area is older than 140 Ma, which is an ancient oceanic lithosphere (Dietmar Müller et al., 2008) while the age of Caroline Plate is 30 Ma, thus effective elastic thickness of the Pacific Plate is larger. Research shows that the effective elastic thickness of the Pacific Plate is 20-30 km and that of Caroline Plate is 5-10 km (Yang and Fu, 2018). Therefore, under the shearing on both sides of the CTF, the weak Caroline Plate has strong deformation, while the strong Pacific Plate has relatively weak shear deformation, and the magnetic lineation remains stable.

4.3 *Eastern boundary of the Caroline Plate*

Based on the interpretation of topography and seismic profiles, Hegarty et al. (1983) proposed that the Lyra Trough was once a subduction zone where the Pacific Plate subducted to the Caroline Plate, and later stopped working. The latest activity was the eastward subduction of the Mussau Trough. Therefore, the oceanic crust between the Lyra Trough and the Mussau Trough should belong to the Caroline Plate. This view is also supported by the recognition of intermittent magnetic lineations connected to the Caroline Plate in the fracture zone on the north side of the Mussau Trough. Hegarty and Weissel (1988) further pointed out that in the northern fracture zone, the Caroline Plate showed the feature of eastward subduction, indicating the polarity reversal of this initial subduction zone relative to the Mussau Trench. Gaina and Müller (2007) believed that the eastern part of the Caroline Plate is separated from the Pacific Plate by a series of transform faults, the oldest of which is the Lyra Trough, and the transform fault on the western side has been transformed into a trench, just like the oceanic crust of the Caroline Plate at the Mussau Trench subducted to the Pacific Plate in the recent period (Hegarty et al., 1983).

According to the NVDR-THDR of RTP magnetic anomaly there are NNW trending fracture zones and Mussau Trench between the E148° and E150°, while the striking of the NVDR-THDR of RTP magnetic anomaly is in NNW, which nearly perpendicularly cuts the magnetic lineations in near E-W trending within the Caroline Plate. The dense trend lines indicate the development of large-scale fault zones in this area. In the area between the E149°-E152° further east, the NNW trending fault zone is connected to the Lyra Trough to the south. From the RTP anomaly map (Fig. 3) and the NVDR-THDR map (Fig. 4), it can be seen that there are obvious magnetic lineations between the Mussau Trench and the Lyra Trough, which could dimly be connect to the magnetic lineations of the Caroline Plate towards the west, indicating that the area between the Mussau Trench and the Lyra Trough should be a part of the Caroline Plate. Further to the east, it is the Ontong Java igneous province (Godfrey Fitton and Godard, 2004; Taylor, 2006; Tejada et al., 2013). The NVDR-THDR of RTP magnetic anomaly showed no obvious trend characteristics.

Therefore, similar to the transform faults and shear zones at the northern boundary, there is a 200 km wide tectonic zone in the eastern part of the Caroline Plate, and the southern section to the west is the Mussau Trench (MT), the northern section is the disruptured zone (DZ), and the Lyra Trough and hidden faults situated to the east (Fig. 4). This point of view is proved by the mineralogical and geochemical analyses of basalts and serpentinized peridotites from the Mussau Trench (Zhang et al., 2023).

4.4 *The shear zone in the southwest of the Caroline Plate*

To the east of the Mapia Ridge on the eastern side of the Ayu Trough is the Caroline Plate, but the RTP magnetic anomaly (Fig. 3) shows that to the east of the Mapia Ridge, from the border of the Palau Trench on the north side to the southern edge of the research area, it is a strong magnetic anomaly zone in reverse S or kinked shape, up to 100 km wide, almost perpendicular to the near E-W magnetic lineation of the Caroline Plate on the east side. Wu et al. (2016) noticed this phenomenon and proposed the hypothesis that there may be eastward spreading of the Caroline Plate spreading ridge.

In the NVDR-THDR map of RTP anomaly (Fig. 4), there is a relatively weak and short magnetic anomaly to the west of the Mapia Ridge. However, between the E-W magnetic lineation of the Caroline Plate and the blurry S-N magnetic anomaly of the Ayu Trough, 5-6 parallel distributed reverse S-shaped NVDR-THDR trend lines are developed in the area east of Mapia, which tightly bend and extend eastward at the southern border of the Palau Trench and southward near the E135° longitude. Therefore, there is a kinked feature between the N6°~N4°, expanding gradually in width southwards, and the width of the southern boundary in the research area has reached about 126 km. Based on the geological characteristics and NVDR-THDR characteristics of RTP anomaly, it is speculated that it is a magnetic anomaly characteristic of a strong deformation shear zone, rather than a magnetic lineation, and is the southwest shear zone (SWSZ) of the Caroline Plate. Based on the spreading environment of the Ayu Trough, it is suggested that the shear zone in the southwest section is a tensional shear zone (Fig. 4).

In fact, to the east of the Palau Trench and to the north of the western shear zone of the Caroline Plate, there are significant deformations in both RTP anomaly and its NVDR-THDR. Especially, NVDR-THDR is notable for its continuous short lines and large changes in extension direction, which may indicate the development of strong shear deformation in the protruding area of the Caroline Plate to the east of the Palau Trench.

The age of the Caroline Plate is even older than the spreading age of the Ayu Trough (<20-25 Ma). Relevant study (Yang and Fu, 2018) has shown that the effective elastic thickness (Te) of the lithosphere of the Caroline Plate near the western boundary (about 10 km) is also greater than the Te value of the Ayu Trough (about 5-7 km). However, the shear zones with strong deformation are mainly developed within the Caroline Plate, and the NVDR-THDR of RTP magnetic anomaly in the Ayu Trough does not show any signs of strong deformation. This may require further research to explain this phenomenon.

5 Discussion

5.1 *The sinistral characteristics of the Caroline Plate fault system*

In early studies, Weissel and Anderson (1978) and Hegarty and Weissel (1988) proposed that the counterclockwise rotation of the Caroline Plate led to the formation of the Ayu Trough to the southwest, the compression/subduction of the Yapu Trench in its northwest, and the Mussau Trench in its southeast. However, Gaina and Müller (2007) believed that since the late Miocene (10-0 Ma), the Philippine Sea Plate and the Caroline Plate continued to rotate clockwise, resulting in the recent activity of the eastern section of the Mussau Trench on the south side of the Caroline Plate and the New Guinea Trench, as well as the Mussau Trench on the east side and the fracture zone on the north side.

The Eauripik Transform Fault, the eastern boundary fault zone, and the fault zones within the Caroline Plate identified in this study exhibit an overall NNW-SSE direction and are nearly parallel. From the direction of the magnetic lineation displacement, it can be determined that the faults within the two basins are sinistral. The northern shear transform fault and western boundary shear zone of the Caroline Plate, with a width of up to 100 km, indicate that the Caroline Plate has undergone a prolonged period of shearing.

The metamorphic structure of submarine rocks in the North Sorol Trough, north of the Caroline Plate, manifests firmly a strong shearing (Fornari et al., 1979). In addition, the negative flower shaped structure on the seismic profile (Dong et al., 2018; Zhang et al., 2021) and seismic distribution (Schellart et al., 2008) support the strong sinistral shearing developed in the Sorol Trough. GPS measurement data (Kotake, 2000; Lee, 2004) also confirmed the existence of strike slip earthquakes between Ulithi Atoll and Fais Atoll north of the Sorol Trough, possibly involving a sinistral strike slip fault. Earthquakes distributed along this fault indicate that it has cut through the lithosphere.

The Caroline Plate subducts westward on the north side of the western boundary along the Yapu Trench beneath the Philippine Sea Plate (Bird, 2003). The Ayu Trough on the south side is narrow in the north and wide in the south, spreading towards the east and west, indicating that the Caroline Plate is moving eastward in this area. Therefore, the Caroline Plate subducts westward relative to the Philippine Sea Plate in the north and separates eastward in the south. It can be inferred that there is counterclockwise rotation between them.

The results of plate reconstruction (Seton et al., 2012) and GPS survey data (Schellart et al., 2008) indicate that the Pacific Plate is moving northwest relative to the Caroline Plate, and the eastern boundary of the Caroline Plate should be in a stress field of sinistral shear.

Therefore, the shear zone north of the Caroline Plate, the shear boundaries of the north and west, the sinistral fault zone within the plate, the spreading of the Ayu Trough, and the development of the Mussau Trench, all support the counterclockwise rotation of the Caroline Plate (Fig. 5).

Based on the counterclockwise rotation model of the Caroline Plate, Zhang et al. (2022) believed that the compression of the Pacific Plate and Caroline Plate on the East Caroline Ridge formed an arc seamount chain, which is also a significant submarine topographic feature.

5.2 *Coupling mechanism between magmatic activity and structure in T-shaped large igneous province*

Different from the oceanic lithosphere where magnetic lineations are developed during seafloor spreading, the submarine plateau is generated by mantle plume volcanism (Coffin and Eldholm, 1994; Duncan and Richards, 1991; Richards et al., 1989), which forms a widely distributed igneous province on the seafloor. However, the magnetic lineations in the Tamu Massif in the spreading ridge at triple junction of the plate boundary indicate that this oceanic plateau is not a shield volcano, but was emplaced by voluminous and focused ridge volcanism (Sager et al., 2019). To the Shatsky Rise, if the magma source is a plume, it was closely connected to and controlled by seafloor spreading. At the same time, interaction between plate boundary ridges and hotspots also generates relatively abnormally thick crust (Whittaker et al., 2015). Wu et al. (2016) believed that the Caroline hotspot that occurred during the formation of the Caroline Plate resulted in a relatively and anomalously thick 10-25 km crust of the Caroline Ridge. The large-scale magmatic activity in the oceanic plate may be related to the shearing of deep asthenosphere caused by mantle convection (Conrad et al., 2011). In the interior of the oceanic plate, deep and large faults play an important role in the distribution of submarine volcano, and are obviously coupled with magmatic activity. Zhu et al. (2022) obtained the structural characteristics of the central western Pacific: intraplate volcanic activity is controlled by large-scale fault structures. The magnetic strip is separated or broken due to fracture and transform. The widely distributed and intersecting faults provide pathways for the eruption of magma in seamount areas and the over-

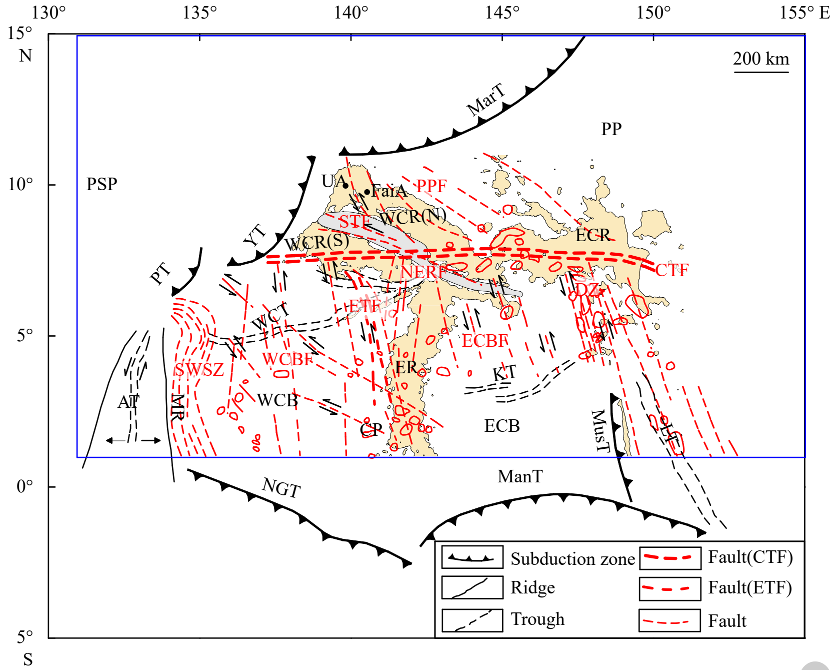

Fig. 5. Schematic diagram showing the sinistral movement of the Caroline Plate, the distribution of faults in the research area, and the locations of the West Caroline Ridge, East Caroline Ridge, and Eauripik Rise. The geological unit names are the same as in Fig. 1a, and the fault zone names are the same as in Fig. 4. The light-brown area is the enclosure of 3 000 m isobath, which is also the T-shaped large igneous province.

flow of magma in basin areas, which is consistent with Utkin (2006)'s understanding that strike slip fault zones controls volcanic activity zones.

According to the distributions of Caroline Plate boundary faults, intraplate faults and volcanoes in T-shaped large igneous province (Fig. 5), the early West Caroline Ridge obliquely intersects the Caroline Plate boundary transform fault at an angle of about 30°. Eauripik Rise moves southward along the fault on the east side of Eauripik Rise, and the East Caroline Ridge develops eastward along the CTF. On the east side of the West Caroline Trough, a small amount of magma intrudes along the fault zone. Similarly, in the northern segment of the eastern boundary of the Caroline Plate and north of the Lyra Trough, magma intruded along the fault zone. Therefore, there is obvious coupling between magmatic activity and fault structure in the T-shaped large igneous province. The fault is a channel for magma migration, and magma develops along the fault.

5.3 *The magma source of Eauripik Rise*

From a spatial perspective, the magmatic activity of the West Caroline Ridge is not connected to the northern segment of the ETF, thus the northern segment of the ETF lacks magma intrusion (Fig. 5). This also indicates that the magmatic activity of the early hotspot was located in the Pacific Plate. When the hotspot was located below the CTF, a large amount of magma invaded the interior of the Caroline Plate. Magma spewed southward along the NNE trending fault zone (northern Eauripik Rise fault, NERF) east of the ETF, forming the northern segment of the Eauripik Rise. The gradually decreasing height of the Eauripik Rise from north to south indicates that the scale of magma development gradually decreases from north to south, suggesting that the magma originated from the north. Therefore, the magma Eauripik Rise should also have originated from the Caroline hotspot.

However, the Caroline Plate and the Pacific Plate move from E to W relative to the Caroline hotspot, and the distance from the southern part of the Eauripik Rise from N to S is large. How to explain the magma source of the southern part of the Eauripik Rise is a difficult issue. Macpherson and Hall (2001) proposed a pattern of moving Manus hotspot that generally moved from north to south based on the extension characteristics of the Eauripik Rise in the southern part of the Caroline Plate. It migrated northward between 30 Ma and 25 Ma, providing magma for the Eauripik Rise, and then migrated towards SSE, forming an SEE extending rise in the East Caroline Basin. During 15 Ma -10 Ma, it migrated southward to the underside of the Manus Basin, and moved eastward to the present position from 10 Ma to 0 Ma. Similarly, using the moving-hotspot model, Gaina and Müller (2007) believed that the Manus hotspot provided a huge amount of magma for the West Caroline Ridge after 20 Ma, later formed the East Caroline Ridge, and then moved southward to form Eauripik Rise, but also pointed out that there was a possibility of magma origination from the southern subduction zone in the south of Eauripik Rise. However, the moving hotspot model cannot provide a reasonable explanation for the magma in the East Caroline Ridge and the Caroline Islands. Wu et al. (2016) proposed a model with the Caroline hotspot on the north side and the Manus hotspot on the south side, without in-depth discussion of the Eauripik Rise.

Considering the rapid but short spreading history of the Caroline Plate itself (with a spreading period of about 11 Ma and the modern north-south length of over 1 000 km), and the latest spreading center — the West Caroline Trough adjacent to the northern boundary, is it possible for the magma provided by the Caroline hotspot to accompany the spreading of the Caroline Plate and migrate southward along the NERF and the ETF? At the same time, only a small amount of magma continues to migrate towards SEE, forming the extension of the West Caroline Ridge in the East Caroline Basin? However, the ^{40}Ar-^{39}Ar age of 19.3 Ma (Zhang et al., 2020) of the igneous rock at DSDP-57 station in the east of the West Caroline Ridge indicates that the igneous rock in the east of the West Caroline Ridge was generated after the Caroline Plate stopped expanding, which does not support that the magma from Eauripik Rise migrated southward along the ETF with plate expansion.

Therefore, although the CTF, ETF, and NERF identified in this article support the view that the magma of Eauripik Rise is originated from the Caroline hotspot. However, the age of Caroline Plate spreading (Gaina and Müller, 2007) and the age of igneous rock at DSDP-57 station in the east of West Caroline Ridge (Zhang et al., 2020) cannot simultaneously support the southward migration of magma from Eauripik Rise with plate expansion.

Due to sediment coverage (Den et al., 1971), no igneous rocks from the Eauripik Rise are available at present. Therefore, it is necessary in the future to use gravity and magnetic inversion methods to determine its lithology.

6 Conclusions

This article is based on magnetic anomaly and uses NVDR-THDR technology to determine the boundaries and intraplate fault zones of the Caroline Plate, determine the direction of rotation, and analyze the coupling relationship between fault structures and magmatic activity.

The NVDR-THDR of RTP magnetic anomaly clearly presents the Caroline transform fault buried under the giant submarine volcano on the Caroline Ridge, the magnetic lineation of the Pacific Plate in NE direction in the north, and the magnetic lineation of the Caroline Plate in E-W direction in the south, so it is the boundary of the two plates.

The eastern boundary of the Caroline Plate is relatively vague, manifested as a NNW-SSE trending structural zone with a width of about tens to hundreds of kilometers, a fractured zone and hidden faults in the north, the Mussau Trench to the west in the south, and the Lyra Trough to the east.

The border area between the Caroline Plate and the Ayu Trough is a shear structural zone up to 100 km wide, showing an overall S-N direction. It borders the Palau Trench to the north and extends to the southern boundary of the research area to the south.

Within the Caroline Plate, the ETF and the fault zones in the east and west basins are generally semi-parallel NNW-SSE faults with sinistral characteristics.

The geological features of the Caroline Plate, such as the fault zone within the Caroline Plate, the plate boundary shear zone, the sinistral strike slip movement of the Sorol Trough, and the peripheral shear zone, the fan-shaped spreading of the Ayu Trough towards the east and west sides, the eastward subduction of the Mussau Trough, and the westward subduction of the Yap Trough, all indicate the counterclockwise rotation of the Caroline Plate.

The Caroline hotspot erupted in the Pacific Plate and formed the West Caroline Ridge, and then transformed with the Caroline transform fault at the N8°. A large amount of magma surged along the Caroline transform fault and formed the East Caroline Ridge. At the same time, a large amount of magma developed southward through the NERF, forming the northern segment of Eauripik Rise. In the East Caroline Ridge, submarine volcanoes are developed along the eastern boundary fault zone. Therefore, the Caroline transform fault, the eastern boundary fault zone, and the northern fault zone of Eauripik Rise show obvious coupling with hotspot magmatic activity. The fault zone provides a channel for magma migration and affects the distributions of T-shaped large igneous provinces and submarine volcano.

References

Austria R S P, Parcutela N E, Reyes E M L, et al. 2022. Magnetic field characterization of Macolod Corridor (Luzon, Philippines): New perspectives on rifting in a volcanic arc setting. Tectonophysics, 822: 229179, doi: 10.1016/j.tecto.2021.229179

Bird P. 2003. An updated digital model of plate boundaries. Geochemistry, Geophysics, Geosystems, 4(3): 1027

Bracey D R. 1983. Geophysics and tectonic development of the Caroline basin. Bay St. Louis: US Naval Oceanographic Office.

Campbell I H. 2007. Testing the plume theory. Chemical Geology, 241(3-4): 153–176, doi: 10.1016/j.chemgeo.2007.01.024

Campbell I H, Griffiths R W, Hill R I. 1989. Melting in an Archaean mantle plume: heads it's basalts, tails it's komatiites. Nature, 339(6227): 697–699, doi: 10.1038/339697a0

Coffin M F, Eldholm O. 1994. Large igneous provinces: crustal structure, dimensions, and external consequences. Reviews of Geophysics, 32(1): 1–36, doi: 10.1029/93RG02508

Conrad C P, Bianco T A, Smith E I, et al. 2011. Patterns of intraplate volcanism controlled by asthenospheric shear. Nature Geoscience, 4(5): 317–321, doi: 10.1038/ngeo1111

Den N, Ludwig W J, Murauchi S, et al. 1971. Sediments and structure of the Eauripik-New Guinea Rise. Journal of Geophysical Research, 76(20): 4711–4723, doi: 10.1029/JB076i020p04711

Deschamps A, Lallemand S. 2002. The West Philippine Basin: An Eocene to early Oligocene back arc basin opened between two opposed subduction zones. Journal of Geophysical Research: Solid Earth, 107(B12): EPM1 1-1–EPM1 1-24

Dietmar Müller R, Sdrolias M, Gaina C, et al. 2008. Age, spreading rates, and spreading asymmetry of the world's ocean crust. Geochemistry, Geophysics, Geosystems, 9(4): Q04006

Dong Dongdong, Zhang Zhengyi, Bai Yongliang, et al. 2018. Topographic and sedimentary features in the Yap subduction zone and their implications for the Caroline Ridge subduction. Tectonophysics, 722: 410–421, doi: 10.1016/j.tecto.2017.11.030

Duncan R A, Richards M A. 1991. Hotspots, mantle plumes, flood basalts, and true polar wander. Reviews of Geophysics, 29(1): 31–50, doi: 10.1029/90RG02372

Fan Jianke, Zheng Hong, Zhao Dapeng, et al. 2022. Seismic structure of the Caroline plateau-yap trench collision zone. Geophysical Research Letters, 49(6): e2022GL098017, doi: 10.1029/2022GL098017

Fornari D J, Weissel J K, Perfit M R, et al. 1979. Petrochemistry of the Sorol and Ayu Troughs: implications for crustal accretion at the northern and western boundaries of the Caroline Plate. Earth and Planetary Science Letters, 45(1): 1–15, doi: 10.1016/0012-821X(79)90102-X

Fujiwara T, Tamaki K, Fujimoto H, et al. 1995. Morphological studies of the Ayu Trough, Philippine Sea-Caroline Plate boundary. Geophysical Research Letters, 22(2): 109–112, doi: 10.1029/94GL02719

Fujiwara T, Tamura C, Nishizawa A, et al. 2000. Morphology and tectonics of the Yap Trench. Marine Geophysical Researches, 21(1-2): 69–86

Gaina C, Müller D. 2007. Cenozoic tectonic and depth/age evolution of the Indonesian gateway and associated back-arc basins. Earth-Science Reviews, 83(3-4): 177–203, doi: 10.1016/j.earscirev.2007.04.004

Godfrey Fitton J, Godard M. 2004. Origin and evolution of magmas on the Ontong Java Plateau. Origin and Evolution of the Ontong Java Plateau, 229(1): 151–178

Hall R. 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. Journal of Asian Earth Sciences, 20(4): 353–431, doi: 10.1016/S1367-9120(01)00069-4

Hall R, Fuller M, Ali J R, et al. 1995. The Philippine Sea Plate: magnetism and reconstructions. In: Taylor B, Natland J, eds. Active Margins and Marginal Basins of the Western Pacific. Washington: American Geophysical Union, 371–404

He Tao, Xiong Shengqing, Wang Wanyin. 2022. Three-dimensional transformation of magnetization direction and magnetic field component at low latitudes based on vertical relationship. Applied Geophysics, 19(1): 91–106, doi: 10.1007/s11770-022-0928-4

Heezen B C, Gray C, Segre A G, et al. 1971. Evidence of foundered continental crust beneath the central Tyrrhenian Sea. Nature, 229(5283): 327–329, doi: 10.1038/229327a0

Hegarty K A, Weissel J K. 1988. Complexities in the development of the Caroline Plate region, western equatorial Pacific. In: Nairn A E M, Stehli F G, Uyeda S, eds. The Ocean Basins and Margins. Boston: Springer, 277–301

Hegarty K A, Weissel J K, Hayes D E. 1983. Convergence at the Caroline-Pacific plate boundary: collision and subduction. In: Hayes D E, ed. The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands: Part 2. Washington: American Geophysical Union, 27: 326–348

Hill K C, Hall R. 2002. Mesozoic-Cainozoic evolution of Australia's New Guinea margin in a West Pacific context. Defining Australia: the Australian Plate as Part of Planet Earth: Geological Society of America and Geological Society of Australia, joint publication, special paper, 1-43

Hill K C, Hegarty K A. 1988. Tectonic interactions between New Guinea and the Caroline Plate-Implications for backarc spreading, achievements in Australian geosciences. In: 9th Australian Geological Convention. Brisbane: Geological Society of Australia, 192–193

Hong J K, Lee S M. 2002. Reflection seismology in the southern Ayu Trough, a slow-spreading divergent boundary. Ocean and Polar Research, 24(3): 189–196, doi: 10.4217/OPR.2002.24.3.189

Ian Ridley W, Rhodes J M, Reid A M, et al. 1974. Basalts from leg 6 of the deep-sea drilling project. Journal of Petrology, 15(1): 140–159, doi: 10.1093/petrology/15.1.140

Jackson M G, Shirey S B, Hauri E H, et al. 2016. Peridotite xenoliths from the Polynesian Austral and Samoa hotspots: Implications for the destruction of ancient ^{187}Os and ^{142}Nd isotopic domains and the preservation of Hadean ^{129}Xe in the modern convecting mantle. Geochimica et Cosmochimica Acta, 185: 21–43, doi: 10.1016/j.gca.2016.02.011

Karig D E. 1975. Basin genesis in the Philippine Sea. Initial reports of the deep sea drilling project 31, 857-879.

Keating B H, Mattey D P, Helsley C E, et al. 1984. Evidence for a hot spot origin of the Caroline Islands. Journal of Geophysical Research: Solid Earth, 89(B12): 9937–9948, doi: 10.1029/JB089iB12p09937

Kim Y M, Lee S M, Okino K. 2009. Comparison of gravity anomaly between mature and immature intra-oceanic subduction zones in the western Pacific. Tectonophysics, 474(3-4): 657–673, doi: 10.1016/j.tecto.2009.05.004

Kobayashi K. 2004. Origin of the Palau and Yap trench-arc systems. Geophysical Journal International, 157(3): 1303–1315, doi: 10.1111/j.1365-246X.2003.02244.x

Koppers A A P, Staudigel H, Pringle M S, et al. 2003. Short-lived and discontinuous intraplate volcanism in the South Pacific: Hot spots or extensional volcanism?. Geochem. Geophys. Geosyst. , 4(10), 1089.https://doi.org/10.1029/2003GC000533.

Kotake Y. 2000. Study of the tectonics of Western Pacific region derived from GPS data analysis. Bulletin of the Earthquake Research Institute, University of Tokyo, 75: 229–334

Lee S M. 2004. Deformation from the convergence of oceanic lithosphere into Yap trench and its implications for early-stage subduction. Journal of Geodynamics, 37(1): 83–102, doi: 10.1016/j.jog.2003.10.003

Lee J I, Hur S D, Park B K, et al. 2001. Geochemistry and K-Ar age of alkali basalts from Weno Island, Caroline Islands, Western Pacific. Ocean and Polar Research, 23(1): 23–34

Lee S M, Kim S S. 2004. Vector magnetic analysis within the southern Ayu Trough, equatorial western Pacific. Geophysical Journal International, 156(2): 213–221, doi: 10.1111/j.1365-246X.2003.02125.x

Li Chunfeng, Wang Jian. 2016. Variations in Moho and Curie Depths and Heat Flow in Eastern and Southeastern Asia. Marine Geophysical Research, 37(1): 1–20, doi: 10.1007/s11001-016-9265-4

Li Chunfeng, Zhou Duo, Li Gang, et al. 2021. Geodynamic problems in the Western Pacific and future scientific drill targets. Earth Science (in Chinese), 46(3): 759–769

Li Sanzhong, Cao Xianzhi, Wang Guangzeng, et al. 2019. Meso-Cenozoic tectonic evolution and plate reconstruction of the Pacific Plate. Journal of Geomechanics (in Chinese), 25(5): 642–677

Liu Fen, Wang Wanyin, Ji Xiaolin. 2019. Influence factors and stability analysis of plane potential field continuation in space and frequency domains. Geophysical and Geochemical Exploration (in Chinese), 43(2): 320–328

Luo Xingang, Wang Wanyin, Zhang Gongcheng, et al. 2018. Study on distribution features of faults based on gravity data in the South China Sea and its adjacent areas. Chinese Journal of Geophysics (in Chinese), 61(10): 4255–4268

Ma Jie, Wang Wanyin, Du Xiangdong, et al. 2021. Study on system of faults in the gulf of Mexico and adjacent region based on gravity data. Acta Geologica Sinica-English Edition, 95(1): 305–318, doi: 10.1111/1755-6724.14643

MacLeod S J, Williams S E, Matthews K J, et al. 2017. A global review and digital database of large-scale extinct spreading centers. Geosphere, 13(3): GES01379.1

Macpherson C G, Hall R. 2001. Tectonic setting of Eocene boninite magmatism in the Izu-Bonin-Mariana forearc. Earth and Planetary Science Letters, 186(2): 215–230, doi: 10.1016/S0012-821X(01)00248-5

Mattey D P. 1982. The minor and trace element geochemistry of volcanic rocks from Truk, Ponape and Kusaie, eastern Caroline Islands; the evolution of a young hot spot trace across old Pacific Ocean crust. Contributions to Mineralogy and Petrology, 80(1): 1–13, doi: 10.1007/BF00376730

Maus S, Barckhausen U, Berkenbosch H, et al. 2009. EMAG2: A 2–arc min resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne, and marine magnetic measurements. Geochemistry, Geophysics, Geosystems, 10(8): Q08005

Meyer B, Saltus R, Chulliat A. 2017. EMAG2: Earth magnetic anomaly grid (2-arc-minute resolution) version 3. Washington: National Centers for Environmental Information, NOAA.

Mrozowski C L, Lewis S D, Hayes D E. 1982. Complexities in the tectonic evolution of the west Philippine Basin. Tectonophysics, 82(1-2): 1–24, doi: 10.1016/0040-1951(82)90085-3

Nagihara S, Kinoshita M, Fujimoto H, et al. 1989. Geophysical observations around the northern Yap Trench: Seismicity, Gravity and Heat flow. Tectonophysics, 163(1-2): 93–104, doi: 10.1016/0040-1951(89)90120-0

Perfit M R, Fornari D J. 1982. Mineralogy and geochemistry of volcanic and plutonic rocks from the boundaries of the Caroline Plate: Tectonic implications. Tectonophysics, 87(1-4): 279–313, doi: 10.1016/0040-1951(82)90230-X

Richards M A, Duncan R A, Courtillot V E. 1989. Flood basalts and hot-spot tracks: plume heads and tails. Science, 246(4926): 103–107, doi: 10.1126/science.246.4926.103

Richards M A, Jones D L, Duncan R A, et al. 1991. A mantle plume initiation model for the Wrangellia flood basalt and other oceanic plateaus. Science, 254(5029): 263–267, doi: 10.1126/science.254.5029.263

Sager W W, Huang Yanming, Tominaga M, et al. 2019. Oceanic plateau formation by seafloor spreading implied by Tamu Massif magnetic anomalies. Nature Geoscience, 12(8): 661–666, doi: 10.1038/s41561-019-0390-y

Sandwell D T, Harper H, Tozer B, et al. 2021. Gravity field recovery from geodetic altimeter missions. Advances in Space Research, 68(2): 1059–1072, doi: 10.1016/j.asr.2019.09.011

Schellart W P, Stegman D R, Freeman J. 2008. Global trench migration velocities and slab migration induced upper mantle volume fluxes: Constraints to find an Earth reference frame based on minimizing viscous dissipation. Earth-Science Reviews, 88(1-2): 118–144, doi: 10.1016/j.earscirev.2008.01.005

Seton M, Müller R D, Zahirovic S, et al. 2012. Global continental and ocean basin reconstructions since 200 Ma. Earth-Science Reviews, 113(3-4): 212–270, doi: 10.1016/j.earscirev.2012.03.002

Taylor B. 2006. The single largest oceanic plateau: Ontong Java-Manihiki-Hikurangi. Earth and Planetary Science Letters, 241(3-4): 372–380, doi: 10.1016/j.epsl.2005.11.049

Tejada M L G, Suzuki K, Hanyu T, et al. 2013. Cryptic lower crustal signature in the source of the Ontong Java Plateau revealed by Os and Hf isotopes. Earth and Planetary Science Letters, 377–378: 84–96

Tuzo Wilson J. 1963. A possible origin of the Hawaiian Islands. Canadian Journal of Physics, 41(6): 863–870, doi: 10.1139/p63-094

Utkin V P. 2006. Role of strike-slip faulting of the oceanic lithosphere in the formation of Pacific volcanic belts. Doklady Earth Sciences, 409(1): 692–296, doi: 10.1134/S1028334X06050023

Wang Wanyin, Pan Yu, Qiu Zhiyun. 2009. A new edge recognition technology based on the normalized vertical derivative of the total horizontal derivative for potential field data. Applied Geophysics, 6(3): 226–233, doi: 10.1007/s11770-009-0026-x

Weissel J K, Anderson R N. 1978. Is there a Caroline plate? Earth and Planetary Science Letters, 41(2): 143–158

Whittaker J M, Afonso J C, Masterton S, et al. 2015. Long-term interaction between mid-ocean ridges and mantle plumes. Nature Geoscience, 8(6): 479–483, doi: 10.1038/ngeo2437

Wu J, Suppe J, Lu Renqi, et al. 2016. Philippine Sea and East Asian plate tectonics since 52 Ma constrained by new subducted slab reconstruction methods. Journal of Geophysical Research: Solid Earth, 121(6): 4670–4741, doi: 10.1002/2016JB012923

Yan Shishuai, Yan Quanshu, Shi Xuefa, et al. 2022. The dynamics of the Sorol Trough magmatic system: Insights from bulk-rock chemistry and mineral geochemistry of basaltic rocks. Geological Journal, 57(10): 4074–4089, doi: 10.1002/gj.4529

Yang An, Fu Yongtao. 2018. Estimates of effective elastic thickness at subduction zones. Journal of Geodynamics, 117: 75–87, doi: 10.1016/j.jog.2018.04.007

Zhang Zhengyi, Dong Dongdong, Sun Weidong, et al. 2021. The Caroline Ridge fault system and implications for the bending-related faulting of incoming oceanic plateaus. Gondwana Research, 92: 133–148, doi: 10.1016/j.gr.2020.11.018

Zhang Zhen, Li Sanzhong, Wang Guangzeng, et al. 2022. Plate boundary processes of the Caroline Plate. Science China Earth Sciences, 65(8): 1554–1567, doi: 10.1007/s11430-021-9919-6

Zhang Guoliang, Yao Junhua, Xu Feng, et al. 2023. Origin of the Mussau Trench in the Western Pacific: Geochemical and mineralogical constraints from basalts and serpentinized peridotites. Chemical Geology, 642: 121798, doi: 10.1016/j.chemgeo.2023.121798

Zhang Guoliang, Zhang Ji, Wang Shuai, et al. 2020. Geochemical and chronological constraints on the mantle plume origin of the Caroline Plateau. Chemical Geology, 540: 119566, doi: 10.1016/j.chemgeo.2020.119566

Zhu Yingjie, Wang Wanyin, Farquharson C G, et al. 2021. Normalized vertical derivatives in the edge enhancement of maximum-edge-recognition methods in potential fields. Geophysics, 86(4): G23–G34, doi: 10.1190/geo2020-0165.1

Zhu Yingjie, Wang Wanyin, Kim Welford J, et al. 2022. Structural features in the mid-latitude Western Pacific based on gravity and magnetic anomalies. Chinese Journal of Geophysics (in Chinese), 65(5): 1712–1731