

Segmentation of the Manila subduction zone and slab tearing beneath the Philippine mobile belt

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ARTICLE INFO

Keywords:

Manila Trench
Philippine Fault
Segmentation
Slab tearing
Subduction zone

ABSTRACT

The Philippine Fault Zone (PFZ) is a key tectonic structure associated with crustal deformation and earthquakes throughout the Philippine Archipelago. Understanding its structures and related mechanisms can significantly mitigate seismic hazards. However, the complete structure of the PFZ, particularly its northwest termination in west Luzon, remains ambiguous. Based on newly acquired multichannel seismic reflection profiles and high-resolution bathymetric data, we have identified four roughly NW-SE trending fault zones off west Luzon, interpreted as branch faults of the northwestward prolongation of the inland PFZ. The southernmost branch could be the offshore extension of the principal NW-SE trending PFZ in central Luzon, terminating at the Manila Trench near $\sim 119^{\circ}\text{E}$ and $\sim 17.5^{\circ}\text{N}$ and segmenting the Manila Trench. A new transform fault could be formed to connect the northern and the southern Manila Trench segments. However, the trend of the Manila Trench has changed $\sim 35^{\circ}$ counterclockwise from north to south. Coinciding with the NW-SE trending PFZ in central Luzon, the Manila subducting slab beneath central Luzon has been torn, as revealed by seismic tomography and seismicity. The northern subducted slab dips 40° eastward, while the southern slab dips 80° eastward. The segmentation of the Manila subduction zone along the NW-SE trending principal PFZ could be due to the southeastward collision of the Palawan microcontinental block against the Philippine mobile belt near Mindoro and the northwestward docking of the Benham Rise. The segmentation of the Manila subduction zone and slab tearing could dominate regional kinematics and crustal deformation.

1. Introduction

The Philippine Archipelago is situated within a complex oblique convergence zone between the Philippine Sea Plate and the Eurasian Plate (Fig. 1). Near Luzon Island, the Philippine Sea plate moves northwestward at a high rate of ~ 85 m/yr relative to the Eurasian Plate (DeMets et al., 2010; Hsu et al., 2016; Hutchings and Mooney, 2024; Kreemer et al., 2000). To the east, the Philippine Sea Plate subducts northwestward beneath the Eurasian Plate along the Philippine Trench and the East Luzon Trough (Fig. 1). In contrast, to the west, the Eurasian Plate converges the Philippine mobile belt along the Manila-Sulu-Negros-Cotabato Trench system. The plate convergence developed a complex tectonic framework, causing the ~ 1200 km left-lateral strike-slip Philippine Fault Zone (PFZ) from southern Mindanao to northern

Luzon (e.g., Barrier et al., 1991; Bischke et al., 1990; Aurelio et al., 2000; Yu et al., 2013; Armada et al., 2012). The 2 to 2.5 cm/yr motion along the left-lateral strike-slip fault is predicted (Barrier et al., 1991). Over the years, large earthquakes of magnitude greater than six have occurred along the PFZ (Fig. 1), resulting in substantial loss of life and economic impacts (Llamas et al., 2024; Tsutsumi and Perez, 2013). The occurrence of the PFZ and the Philippine Trench was estimated at an age of 2 to 4 Ma when the Palawan microcontinental block collided with the Philippine mobile belt (Barrier et al., 1991). The existence of the PFZ is crucial in the oblique convergence between the Philippine Sea Plate and the Eurasian Plate (Aurelio, 2000; Fitch, 1972). It represents a primary response to the regional tectonic stress adjustments and serves as a significant source of seismic hazard in the region (Hsu et al., 2016; Llamas et al., 2024; Tsutsumi and Perez, 2013; Wu et al., 2017; Yoshida

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<https://doi.org/10.1016/j.jseaes.2025.106720>

Received 12 February 2025; Received in revised form 17 April 2025; Accepted 16 June 2025

Available online 18 June 2025

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et al., 2016; Yumul et al., 2008).

Nevertheless, considerable uncertainties or unknowns of the Philippine Fault configuration remain, particularly the northern end of the Philippine Fault in west Luzon (Aurelio et al., 1997; Aurelio et al., 1991; Besana and Ando, 2005; Duquesnoy et al., 1994; Perez et al., 2023; Ringenbach et al., 1993; Tang et al., 2023; Tsutsumi and Perez, 2013). It is unclear whether the Philippine Fault extends offshore west of Luzon

and how it interacts with the Manila Trench. The answer is crucial for the prevention of large thrust earthquakes and tsunamis attacking the coastal zones around the South China Sea (Nguyen et al., 2014; Hsu and Deffontaines, 2009; Li et al., 2016; Megawati et al., 2009; Okal et al., 2011; Qiu et al., 2019).

In this study, we use multichannel seismic (MCS) reflection profiles and multi-beam bathymetry collected off west Luzon to understand the

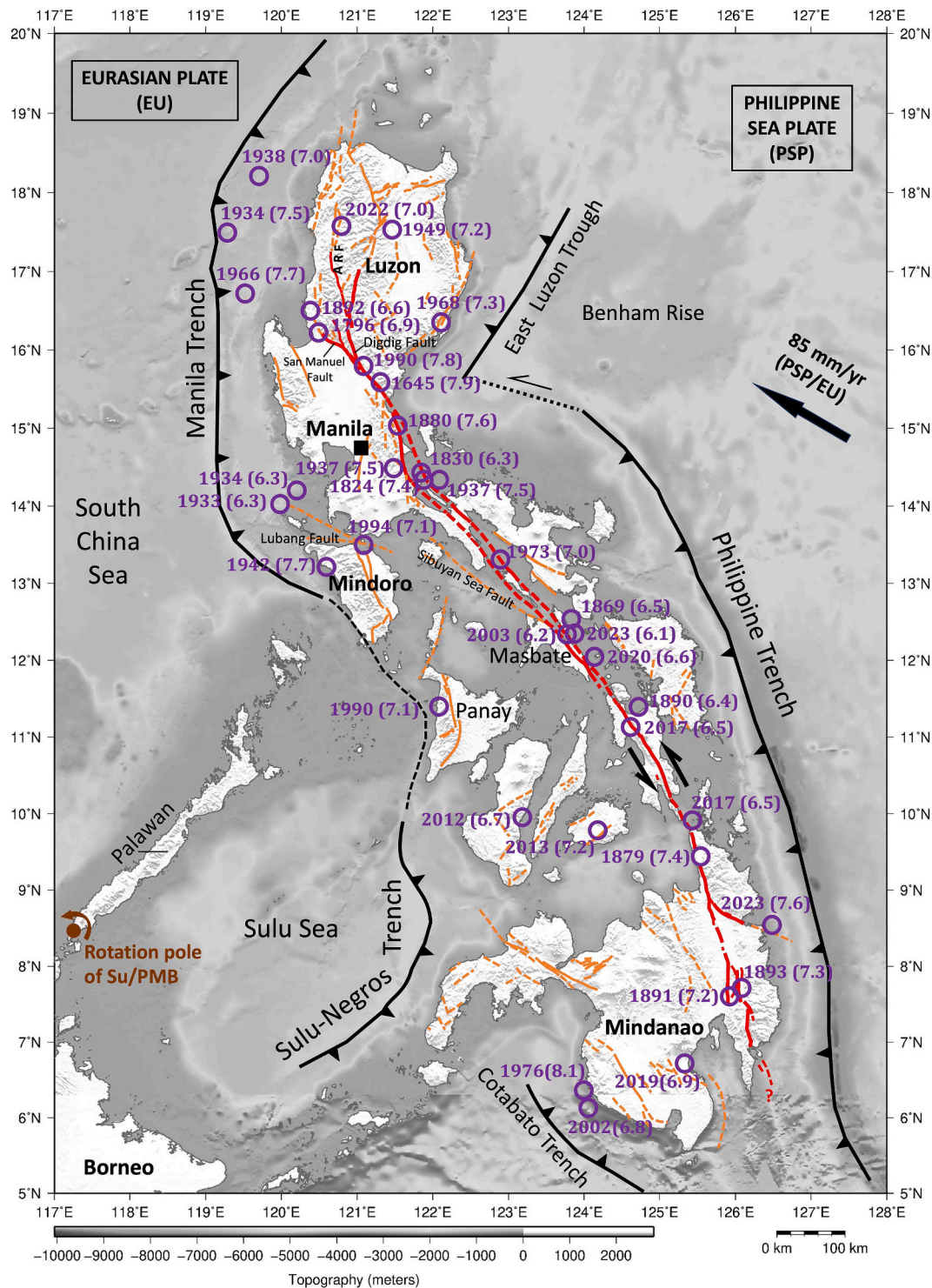


Fig. 1. Distribution of active faults in the Philippines from Phivolcs in April 2015. Large earthquakes with magnitudes in parentheses are displayed in purple. Noted that many large earthquakes occurred along the main Philippine Fault system in red. ARF: Abra River Fault. Su/PMB: rotation of Sunda Plate (Su) relative to the Philippine mobile belt (PMB) (Rangin et al., 1999). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

structures of the northern end of the Philippine Fault. The results can offer valuable constraints on understanding regional geodynamics and assessing the region's seismic and tsunami hazards.

2. Seismic data and processing

In this study, we use 8 MCS (multi-channel seismic) profiles and bathymetric data to identify the geological structure of the Philippine fault system off west Luzon. The locations of the MSC profiles are shown

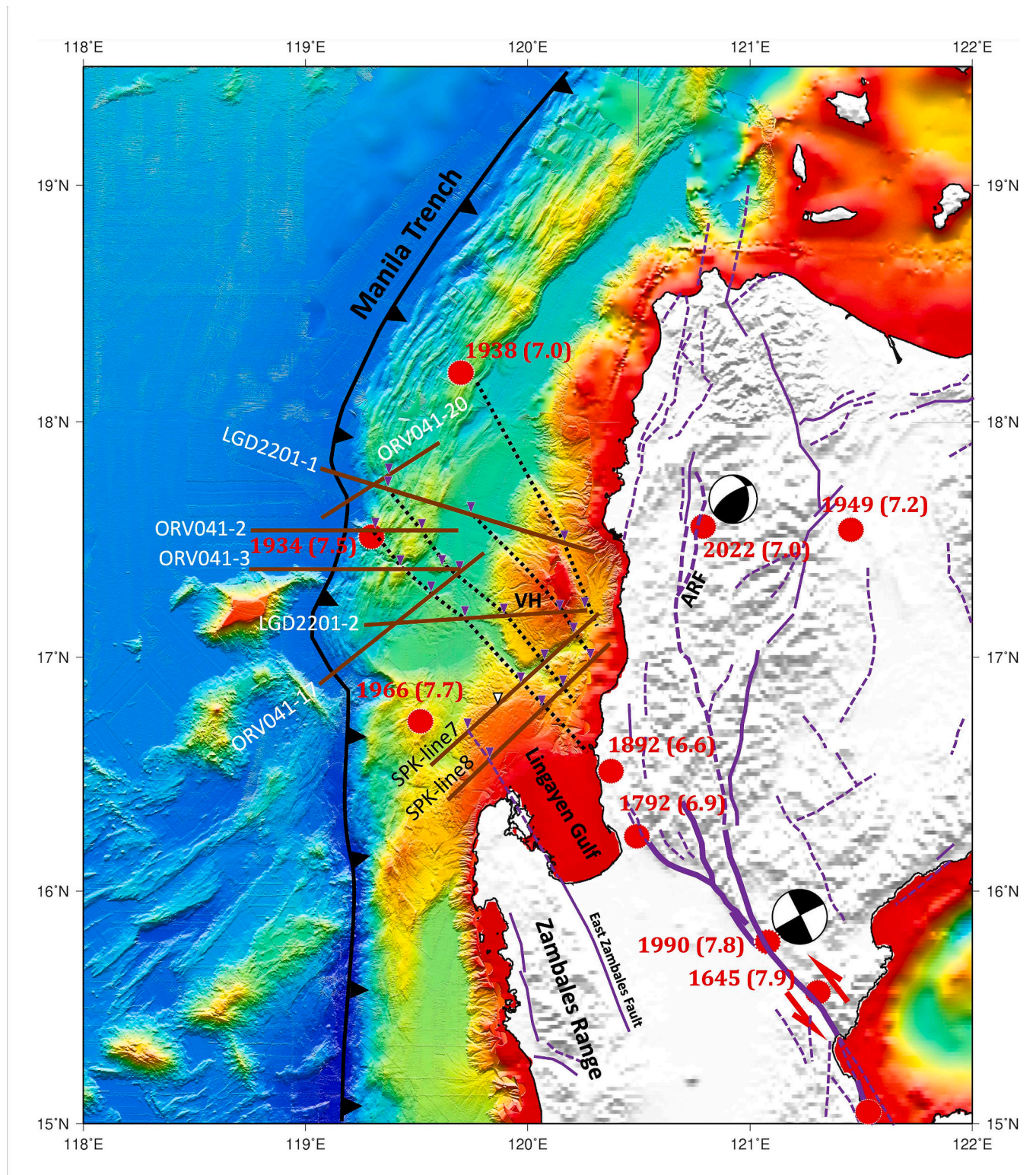


Fig. 2. The locations of the multichannel reflection seismic profiles (brown lines) used in this study are shown in the bathymetric map. Purple triangles indicate identified fault zones in Fig. 3. Black dashed lines indicate traces of fault zones. VH: Vigan High. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in the brown lines in Fig. 2. The MCS profiles were acquired in 2014, 2022, and 2023, respectively.

Four MCS profiles (ORV-041-2, ORV-041-3, ORV-041-17, and ORV-041-20) were collected during the ORV-041 cruise onboard the R/V Ocean Research V in June 2014 (Fig. 2). The data acquisition employed an air-gun array with a total volume of 975 cubic inches, a shot interval of 15 s, equivalent to approximately 37.5 m along the profile, with a vessel speed of 4–5 knots. A 24-channel streamer with a 12.5 m group interval and a sampling rate of 2 ms was used to record the seismic data. The recording length for each shot is 10 s.

Two MCS profiles (LGD-2201-1 and LGD-2201-2) were collected

during the LGD-2201 cruise onboard the R/V Legend in March 2022 (Fig. 2). The air-gun source had a total volume of 2000 cubic inches. The shots were fired at a 50 m interval, controlled by a differential global position system. Data were recorded using a 192-channel streamer with a 12.5 m group interval, with a sampling rate of 2 ms and a recording length of 15 s. Besides, two 24-channel Sparker seismic profiles (SPK-line7 and SPK-line8) were collected with a source of 4 k Joules in 2023.

All MCS data were processed using the Paradigm Echos seismic processing software. Data processing steps followed established seismic processing workflow before time migration (e.g., Armada et al., 2021; Lin et al., 2021). The processing sequence included (1) SEG-D data

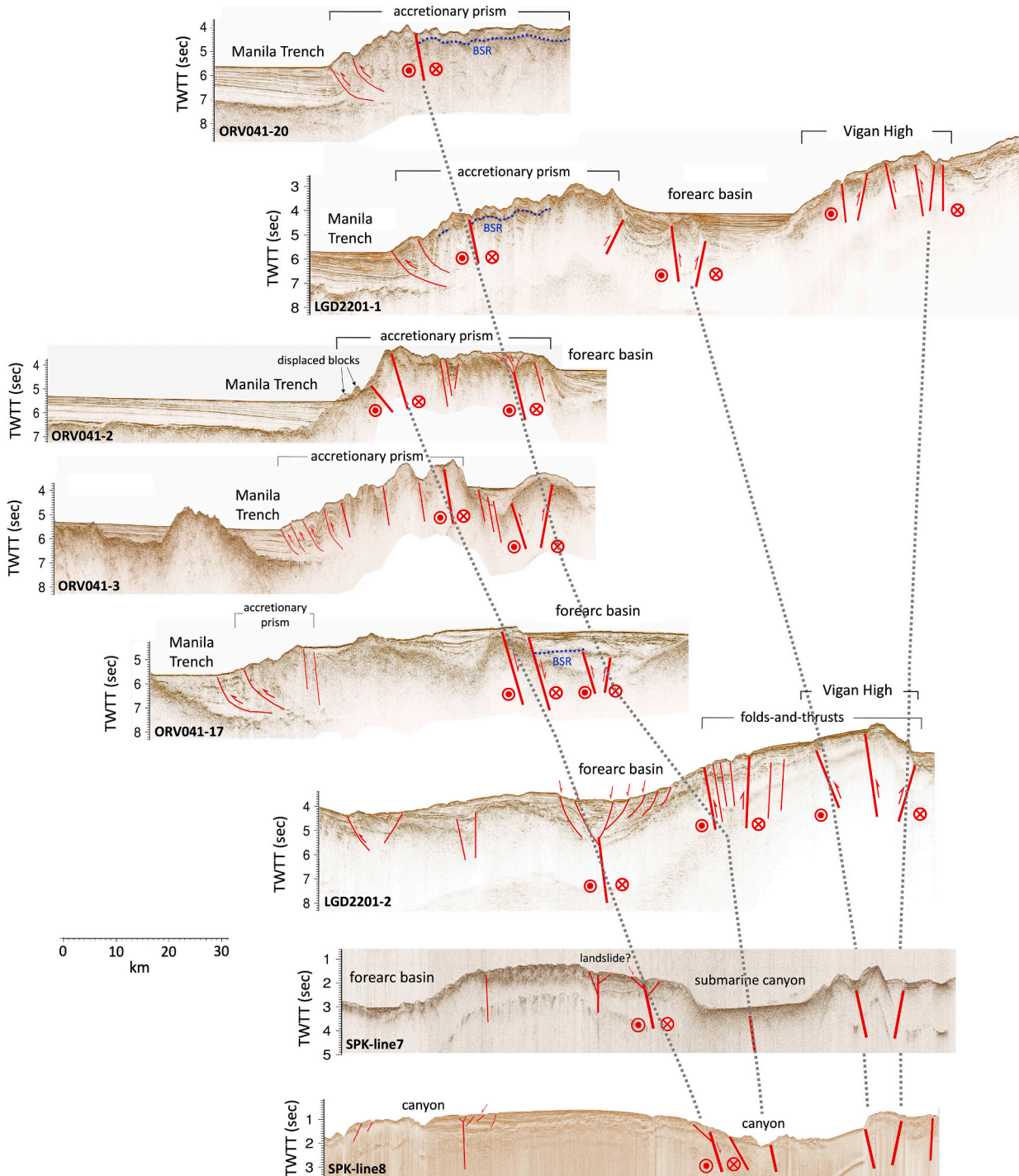


Fig. 3. Interpretations of the seismic profiles shown in Fig. 2. The identified fault zones have cut through forearc basin and/or accretionary prism. Notably, the submarine Vigan High has been uplifted, probably due to tectonic transpression. Some BSR (Bottom-Simulating Reflector) distributions are constrained by faults.

input, (2) streamer geometry definition accounting for feathering and common-mid-point sorting, (3) zero-phase band-pass filtering, (4) denoising, (5) source signature deconvolution, (6) predictive deconvolution in the Tau-P domain, (7) de-multiplying, and (8) trace amplitude balancing. We applied a 2–16–64–120 Hz zero-phase band-pass filter to suppress random noise for each profile. The bubble effects caused by the air-gun reverberation were minimized using deconvolution.

For the 192-channel data, velocity sections were obtained using semblance velocity analysis. The subsequent steps involved de-multiplying, normal moveout correction, amplitude correction for spherical divergence, pre-stack Kirchhoff time migration, and stacking. For the 24-channel dataset, a water velocity of 1500 m/s was applied during normal moveout corrections, followed by stacking, spherical divergence amplitude corrections, and post-stack Kirchhoff time migration. The final time-migrated sections were exported in SEG-Y formation for plotting and interpretation (Fig. 3).

In addition to the MCS profiles, we used multi-beam bathymetry and topography data compiled by Armada et al. (2020) to show the seafloor morphology, which helps identify fault traces at the seafloor (Fig. 2).

3. Results and Discussions

3.1. Offshore extension of the PFZ

Based on the result of our MCS data, the offsets of strata allow us to identify the existence of thrust faults or normal faults in the forearc area of the Manila Trench (Fig. 3). Particularly, the thrust faults in the Vigan High area show a series of thrust faults, which indicates a compressive and a strike-slip fault regime. Gas-hydrate-related BSR (Bottom-Simulating Reflector) is distributed in the Manila forearc (Maglalang et al., 2023). However, we may observe the lateral stops of BSR distribution by the existence of faults, such as in MCS profiles ORV041-20, LGD2201-1 and ORV041-17 (Fig. 3). Overall, taking into account the morphological features of the seafloor, we can delineate four major fault zones trending

roughly from NW-SE to NNW-SSE in the offshore area of west Luzon (Figs. 2 and 3). For instance, the easternmost fault zone off west Luzon generally follows the eastern edge of Vigan High and the foot of the continental margin (Fig. 2). Since these fault zones off west Luzon generally have trends from NW-SE to NNW-SSE, they can be considered as the offshore extensions of the NW-SE trending PFZ in central Luzon. Together with the roughly N-S trending Abra River Fault in northwest Luzon, which is associated with the magnitude 7.0 left-lateral strike-slip Abra earthquake on July 22, 2022 (Perez et al., 2023; Tang et al., 2023), the PFZ in central Luzon may branch at $\sim 15.75^\circ\text{N}$ and $\sim 121.10^\circ\text{E}$ (Figs. 1 and 2). The three easternmost fault zones are distributed in the forearc area and exhibit strike-slip and thrust components (Figs. 2 and 3). Thus, the Vigan High displays an uplifted structure along two easternmost branch fault zones, forming a pop-up structure (Figs. 2 and 3). The transpressive mechanism in this area may be due to the fault zones being oriented obliquely to the convergence of the Philippine Sea Plate relative to the Eurasian Plate (Fig. 1). In contrast, the two westernmost fault zones have cut across the forearc basin and accretionary prism (Fig. 2). Because the westernmost branch fault zone is roughly in line with the NW-SE trending PFZ in central Luzon, it can be regarded as the principal fault zone of the PFZ (Figs. 2 and 4). Remarkably, the trend of the Manila Trench has counterclockwise changed $\sim 35^\circ$ from NE-SW to N-S from north to south at the northwest tip of the westernmost branch fault zone (Fig. 4a).

Contrary to the three easternmost fault zones, the westernmost branch fault zone (or the offshore portion of the principal PFZ) exhibits extensional structures, including the normal fault zone in MCS profile LGD2201-2 (Fig. 3). Because of the left-lateral motion of the principal PFZ, the Manila Trench and the Manila accretionary prism has been indented near 119.2°E and 17.5°N , where an earthquake of magnitude 7.5 occurred on Feb. 14, 1934 (Figs. 2 and 4).

A significant submarine canyon cutting across the Manila accretionary prism near 119.5°E and 17.4°N could be created due to the same mechanism (Fig. 2). The left-lateral offset of the Manila Trench may

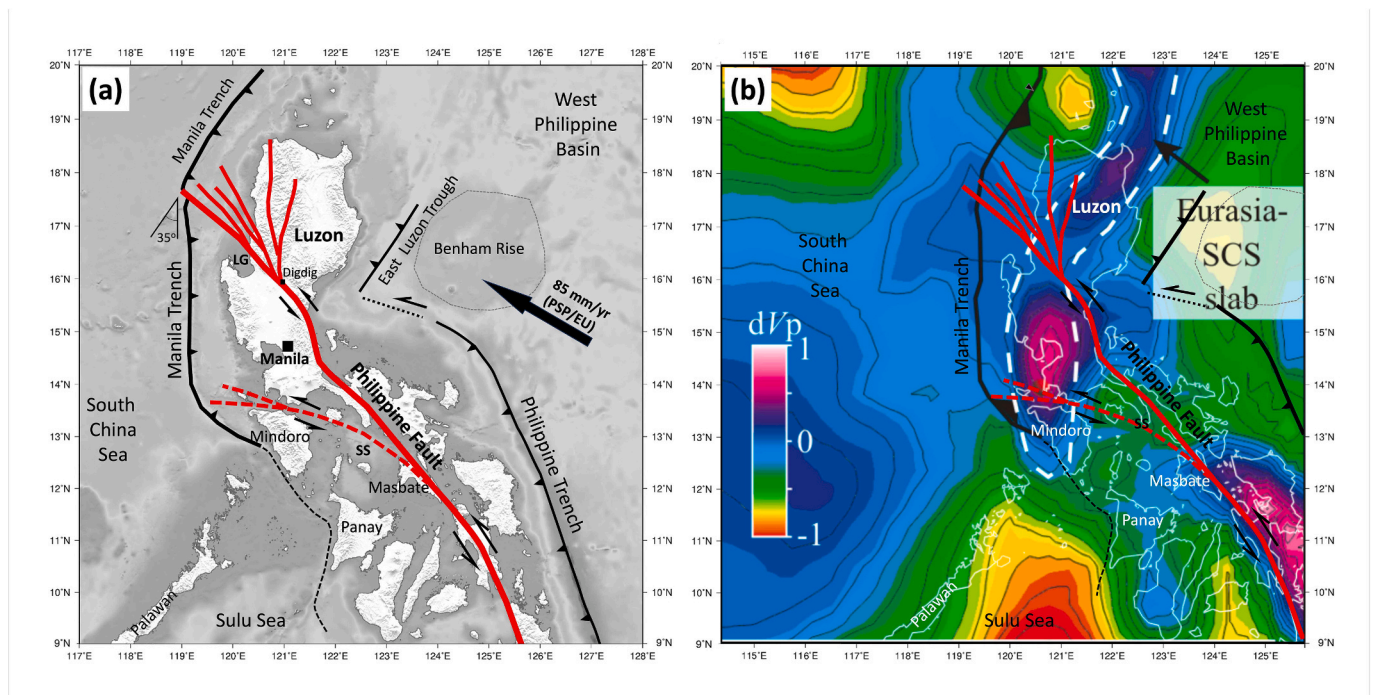


Fig. 4. (Left) The principal PFZ (marked by a heavy red color) extends offshore and divides the Manila Trench into NW-SE and N-S segments. There is a trend difference of 35° exists between the two segments. A new transform fault is inferred between two Manila Trench segments. (Right) A comparison of the Philippine Fault system with the Eurasia-SCS slab anomaly at 280 km horizontal section based on the tomographic result of Wu and Suppe (2018). Noted the Philippine Fault coincides with the segmentation of the Manila subducted slabs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

develop a new transform fault connecting the northern and southern Manila Trench segments (Fig. 4a).

3.2. Segmentation of the Manila subduction zone and a slab tearing

Tomographic images can reveal subducted slabs. Fig. 4b shows the distribution of the Manila subducted slab at a depth of 280 km beneath the Philippine Mobile Belt (Wu and Suppe, 2018); it exhibits a low-velocity zone separating two high-velocity subducted slabs near 121°E and 16°N. The separation trace coincides with the principal PFZ beneath central Luzon (Fig. 4). As mentioned previously, the principal NW-SE trending PFZ has extended offshore and divided the NE-SW trending segment from the N-S trending segment of the Manila Trench (Fig. 4). Similar to the trends of the two Manila Trench segments, the Manila subducted slab also shows the NE-SW trending portion in the north and the N-S trending portion in the south (Fig. 4b). It concurs that the tearing of the Manila subducting slab is along the NW-SE trending PFZ. Besides, the spatial distribution of hypocenters from the ISC-EHB earthquake catalog (Engdahl et al., 2020) agrees with the existence of slab tearing because the seismicity distribution indicates a gentle dipping angle of 42° for the Manila subducted slab to the north of the NW-SE trending PFZ but a steep dipping angle of 80° to the south (Fig. 5). The profiles AB

and CD in Fig. 5a are selected along the plate convergent direction so that a dipping angle of the subducted slab revealed by seismicity may be close to its actual dip (Fig. 5b). The Manila Trench and subducted slab have the same NE-SW trend in the north and the N-S trend in the south, suggesting that the Manila subduction zone has been segmented along the principal PFZ.

The segmentation interpretation is also supported by recent local 3D P-wave and S-wave velocity models of the Luzon region, which show a crustal-scale slab tear characterized by low-velocity anomalies at a depth of 50 km and earthquakes with normal faulting mechanism along the PFZ between 16°N and 17°N (Nguyen et al., 2023). Bautista et al. (2001) also inferred a slab tear near 16°N based on hypocenter locations, and Fan et al. (2015) suggested a tear between 17°N and 17.5°N from tomographic images. Lu et al. (2025) calculated the flexural parameters of the subducting Eurasian Plate and also suggested a slab tear beneath central Luzon Island. However, all the previous authors linked the slab tear beneath Luzon Island to the subduction of a South China Sea fossil spreading ridge. On the contrary, our finding indicates that the Manila subducted slab tear generally follows the NW-SE trending PFZ and is associated with the segmentation of the Manila Trench (Fig. 4a and 6). The slab tearing beneath central Luzon may have been triggered by the collision near Mindoro Island between the Palawan

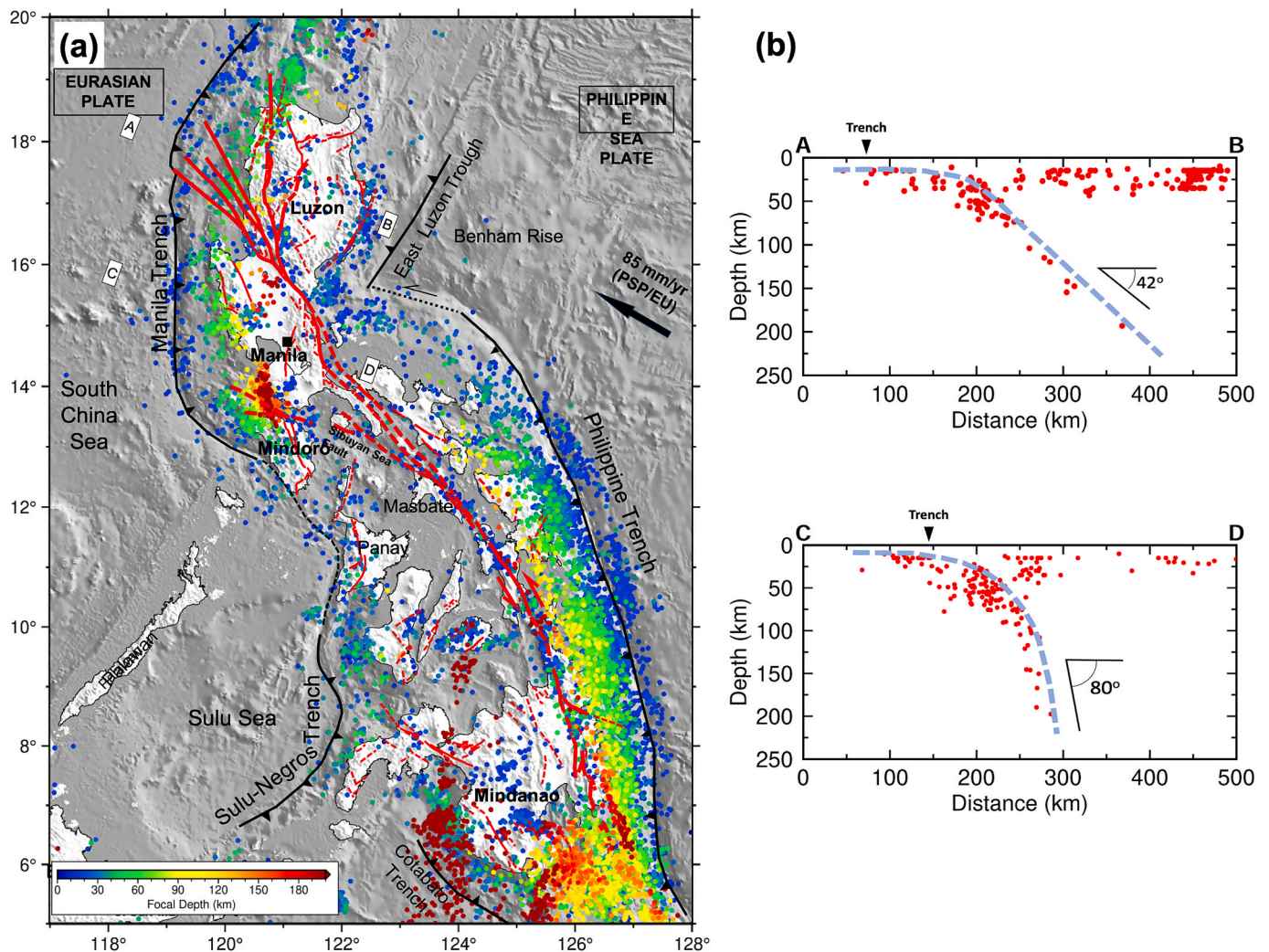


Fig. 5. Seismicity (red dots) from the latest ISC-EHB catalog (Engdahl et al., 2020) from 1964 to 2021 delineates the upper bound of the Manila subducted slab. (a) The map displays the distribution of epicenters and the location of two cross-sections, A-B and C-D, shown in (b). The arrow represents the relative plate motion direction predicted by the MOVEL model (DeMets et al., 2010). (b) Depth distribution of seismicity along the cross-sections, illustrating a sharp change in slab dip angle (approximately 40°) between the two profiles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

microcontinental block and the Philippine mobile belt (Rangin et al., 1985; Yumul et al., 2003). The collision between the Palawan microcontinental block and the Philippine mobile belt likely started in age between the late Early Miocene and early Middle Miocene (ca. 20–16 Ma) (Yumul et al., 2009). In consequence, the Philippine mobile belt has generally undergone a counterclockwise rotation relative to the Eurasian Plate (or Sunda Plate) with a rotation pole near south Palawan Island (Rangin et al., 1999) (Fig. 1). That is, the small circles of the rotation near the segmentation of the Manila Trench (119°E, 17.5°N) are roughly perpendicular to the fossil spreading ridges. This implies that the slab tear follows a fossil transform fault rather than a fossil spreading ridge (Fig. 4).

Focal mechanism solutions of strike-slip events from the global centroid moment tensor catalog (Dziewonski et al., 1981) from January 1976 to November 2024 support the surface traces of the Philippine fault system (Fig. 7a). It is noted that the PFZ has also branched near Masbate Island (Fig. 7a). One branch fault zone has developed along the Sibuyan Sea Fault and the Lubang Fault in NWW-SEE orientation (Fig. 7). This fault system and the PFZ to the south of Masbate Island are more consistent with a small circle of the rotation pole located at the NW Borneo Island (Fig. 7) (Hsu et al., 2025). Some large earthquakes have occurred along this branch fault zone (Fig. 7b). Fig. 7b shows the principal PFZ and its branch fault zones in red. They are prone to large earthquakes. However, the faults in dashed red lines require more data to realize their characteristics.

One question is why the slab tearing occurred beneath central Luzon. It is noted that the East Luzon Trough trends nearly parallel to the north segment of the Manila Trench and perpendicular to the PFZ (Fig. 4). Located oceanward of the East Luzon Trough, the plateau of Benham Rise is converging Luzon northwestward along the East Luzon Trough (Yeh et al., 2021) (Fig. 1). Both the collision of the Palawan microcontinental and the buoyant subduction of the Benham Rise might drive the tearing of the Manila subducted slab along the NE-SW trending Philippine Fault (Figs. 4 and 6).

A slab tearing could play a critical role in regional geodynamics and plate kinematics (e.g., Andrić-Tomašević et al., 2023; Jolivet et al., 2013; Li and Song, 2018; Wortel and Spakman, 2000), as it redistributes crustal stress (e.g., Wortel and Spakman, 2000) and triggers seismic activity (e.g., Gutscher et al., 2016; Kumar et al., 2016; Parera-Portell et al., 2023). The segmentation of the Manila subduction zone and the

slab tearing could significantly affect regional tectonics, earthquake scenarios, and tsunami simulations (e.g., Nguyen et al., 2014; Li et al., 2016; Sepúlveda et al., 2019).

4. Conclusions

Using high-resolution multichannel seismic (MCS) profiles and bathymetry data, we have identified four strike-slip fault zones trending roughly from NW-SE to NNW-SSE off west Luzon. These fault zones are the branches of the northwestward prolongation of the NW-SE trending PFZ in central Luzon. Together with the branch fault zones inland Luzon Island, such as the Abra River Fault, the quasi-linear PFZ terminates in central Luzon and continues by several branch fault zones northward and northwestward. The principal NW-SE trending PFZ extends offshore and connects the Manila Trench at $\sim 17.5^\circ\text{N}$ and $\sim 119^\circ\text{E}$, segmenting the Manila Trench into the NE-SW trending and the N-S trending segments. The trend of the Manila Trench was rotated $\sim 35^\circ$ counterclockwise from \sim NE-SW to \sim N-S at the segmentation point. A slab tear beneath central Luzon is associated with the lithospheric faulting along the NW-SE trending PFZ. The tearing of the Manila subducted slab beneath central Luzon is possibly due to the collision of the Palawan microcontinent against the Philippine mobile belt and the buoyant subduction of the Benham Rise. The branch fault zones of the PFZ off west Luzon have caused a transpressive regime in the Manila forearc region and formed the Vigan High uplifted structure. The complete configuration of the Manila subduction zone and Philippine Fault system allows us to understand better the crustal deformation throughout the Philippine archipelago and to assess potentially catastrophic earthquakes or tsunamis more accurately.

CRediT authorship contribution statement

Shu-Kun Hsu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Wen-Nan Wu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation. **Lien-Kai Lin:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis. **Shiou-Ya Wang:** Writing – review & editing, Validation, Investigation, Formal analysis. **Yi-Ching**

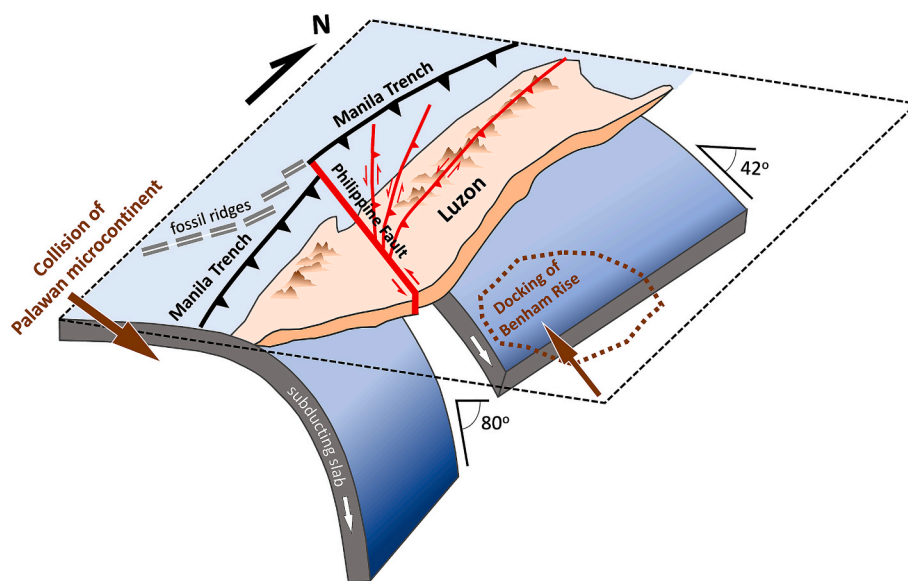


Fig. 6. A schematic model shows that the principal NW-SE trending PFZ has segmented the northern and southern Manila subduction zones with two different slab dipping angles. The faulting along the principal PFZ is probably due to the collision of the Palawan microcontinental block and the docking of the buoyant Benham Rise.

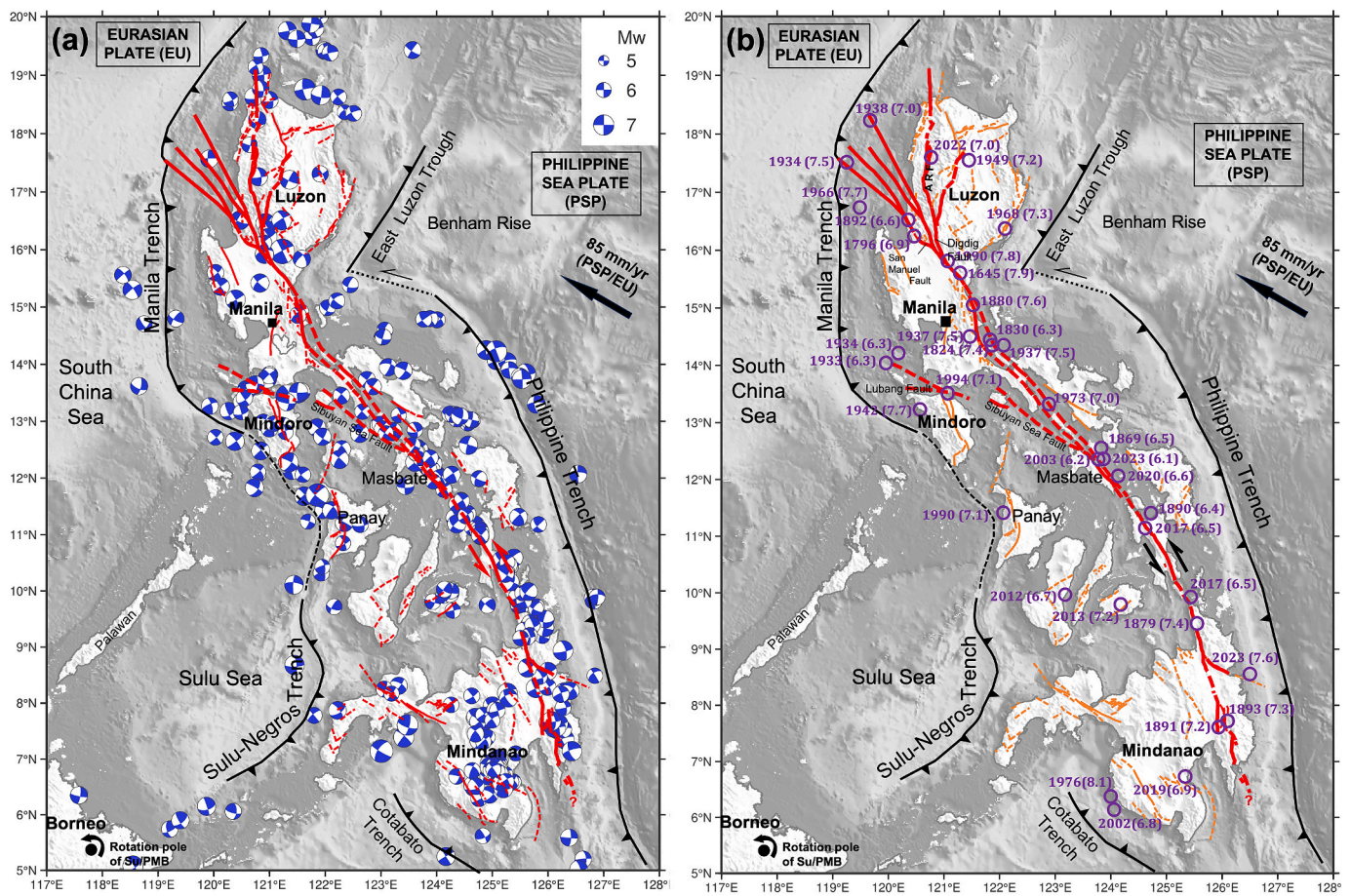


Fig. 7. (a) The distribution of updated active faults (in red) in the Philippines. The PFZ and its branch fault zones are indicated in heavy red lines. Strike-slip focal mechanism solutions for shallow events (≤ 35 km) between January 1976 and November 2024 from global centroid moment tensor solutions (Dziewonski et al., 1981) are plotted for reference. The PFZ is generally consistent with strike-slip earthquakes. (b) The distribution of the PFZ and its branch fault zones (in red). Historical large earthquakes usually occurred along the PFZ and its branch fault zones. Su/PMB: rotation of Sunda Plate (Su) relative to the Philippine mobile belt (PMB) (Hsu et al., 2025). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Yeh: Writing – review & editing, Validation, Methodology, Investigation. **Leo T. Armada:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis. **Carla B. Dimalanta:** Writing – review & editing, Visualization, Validation, Investigation. **Kuan-Ting Chen:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Yun-Jie Tsai:** Writing – review & editing, Visualization, Methodology. **Ching-Hui Tsai:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The Generic Mapping Tools (Wessel et al., 2019) are used in plotting. This study was funded by the National Science and Technology Council (NSTC), Taiwan, and the Department of Science and Technology (DOST), the Philippines. We appreciate the fruitful discussion with Prof. Serge Lallemand, Dr. Ya-Ju Hsu, and Dr. Jean-Claude Sibuet. We are grateful to the crew of R/V Legend and people from TORI and UP Dili-man, who helped gather the marine geophysical data.

Data availability

The data that has been used is confidential.

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