Along-Strike Variation of Seismicity Near the Extinct Mid-Ocean Ridge Subducted Beneath the Manila Trench

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Abstract
The change in seismic activity is explored using data recorded by ocean-bottom seismometers (OBSs) and permanent seismic stations near the extinct Mid-Ocean ridge of the South China Sea (SCS) and the Manila trench. We apply the machine learning–based algorithm EQTransformer to the OBS dataset for seismic event detection and phase picking and then evaluate the precision and compare the time residuals between automatic and manual picks. We derive a catalog of earthquakes in the region and find bending-fault earthquakes in the outer rise at the northern of the Huangyan (Scarborough) Seamount chain, where no historical seismicity was reported in the routine catalog. Abundant outer-rise earthquakes occurred on both sides of the Huangyan (Scarborough) Seamounts chain, but the focal depths vary along the trench. The Wadati–Benioff zone of the eastward subducted SCS oceanic lithosphere can be clearly identified. The focal depths are down to ~100 km near Luzon island at ~16° N but deepen southward to a depth of ~180 km at ~14° N. Dips of the slab also steepen from north to south, indicating along-strike changes in the geometry of the Manila megathrust.

Introduction
Bending faults may occur in the outer rise of subduction zones when bending stresses exceed the yield strength of the incoming plate (Masson, 1991). They are common near a trench and can generate a number of bending-related earthquakes that occur within the outer-rise regions (Craig et al., 2014). Outer-rise earthquakes have become notable for many subduction zones because they can host intraplate earthquakes of great magnitudes, possibly inducing devastating tsunamis (Lay et al., 2010, 2011). Besides, deep outer-rise earthquakes have been regarded as an indicator of large water input via subduction zones, such as outer-rise events occurring at depths of ~35 km below the seafloor with normal-faulting focal mechanisms in central Mariana (Eimer et al., 2020) and a cluster of outer-rise events deeper than 50 km at southern Mariana (Chen et al., 2022). Therefore, understanding the distribution of the outer-rise seismicity and characterizing the nature of the outer rise of an active trench have become fundamental and necessary.

Although the outer-rise seismicity is an important feature in the trench-outter-rise system, there is little attention to the outer-rise earthquakes of the oceanic lithosphere of the South China Sea (SCS) in response to the loading along the Manila trench, partly due to the lack of near-field observational data. The Manila trench is the eastern boundary of the SCS (Fig. 1) and may be capable of generating megathrust earthquakes and devastating tsunamis (Yu et al., 2018; Li et al., 2022). According to the U.S. Geological Survey (USGS) catalog, interface and slab earthquakes are abundant. In contrast, the outer-rise earthquakes with magnitudes >3.6 are only recorded in the south of Huangyan (Scarborough) Seamount chain, but very few outer-rise earthquakes are reported in the north area of the seamount chain (Fig. 2). Outer-rise earthquakes occur on bending-related faults; therefore, such variations of outer-rise seismicity may indicate heterogeneous bending-related faults and strong variation in stresses of the subducting plate.

Both 2D (Zhang, Lin, et al., 2018) and 3D (Zhang, Sun, et al., 2018) numerical simulations of flexural bending have suggested variable elastic plate thickness along the trench. At the northernmost Manila, the elastic plate thickness of the crust is greater than that of the oceanic crust in south and central Manila because of the subduction zone transferred into the...
Taiwan collision zone (Zhang, Lin, et al., 2018; Zhang, Sun, et al., 2018; Zhang et al., 2022). On either side of Huangyan (Scarborough) Seamount chain in central Manila, however, the best-fitting bending parameters from numerical simulations are similar or slightly different, for example, elastic plate thickness of 16 and 15 km, vertical loading of 0.2 and 0.3 \text{10}^{12} \text{N·m}^{-1} south and north of the Huangyan (Scarborough) Seamount chain (Zhang, Lin, et al., 2018). The changeless simulation results across the chain seem inconsistent with the heterogeneous historical outer-rise seismicity. One possible reason is that outer-rise earthquakes could have been missed in the historical catalogs because of a lack of detection using near seismic networks.

Improved near-field seismic observation allows us to explore the seismicity pattern near the extinct Mid-Ocean ridge (MOR)
subducted beneath the Manila trench. In this study, we build a catalog of local earthquakes using an ocean-bottom seismometer (OBS) array and adjacent land stations to improve constraints on the outer-rise seismicity and subducted slab in the SCS near the Manila subduction zone. We then examine what outer-rise seismicity can tell us about the deformation of the plate and depict the geometry of subducted slab by examining the cross sections of seismicity near the Manila trench and analyze the seismic activity for any indications of fragmentation of the subducted plate.

Tectonic Setting and Dataset

The oceanic lithosphere of the SCS is eastward subducted beneath the Manila trench. The SCS basin is the largest marginal basin in the northwest Pacific and is formed associated with several continental rifting and seafloor spreading (Briais et al., 1993; He et al., 2001; Chang et al., 2013; Li et al., 2014; Zhao et al., 2018). The seafloor spreading of the SCS oceanic basin is generally believed to start at ∼32 Ma and probably ceases at ∼16 Ma, during which multiple possible ridge jumps are discovered (Briais et al., 1993; Li et al., 2014; Guan et al., 2021). The axis of the final spreading center of the SCS is presented by the northeast–southwest-trending submarine Huangyan (Scarborough) Seamount chain (Fig. 1), which is suggested to be formed by magmas after the cessation of the seafloor spreading (after ∼16 Ma) (Chang et al., 2013). The Zhongnan fault zone is a major boundary for sub-basins within the SCS and is also characterized as a major boundary in magnetic anomalies (Li et al., 2008), but it is seismically less active.

The Manila trench rarely hosts earthquakes greater than a magnitude of 8. The maximum earthquake magnitude recorded in the Manila trench area has been $M_w$ 7.8 since 1560 (Yu et al., 2018). Four earthquakes larger than magnitude 7 have been recorded since 1934 (Figs. 1, 2a). The lack of great megathrust earthquakes is possibly related to the fault geometry heterogeneity caused by along-strike transitions in slab curvature (Yu et al., 2018). To the east of the Manila trench, Luzon island is characterized by a complex deformation pattern as shown by the diverse pattern of focal mechanism solutions (Fig. 2b).

Figure 2. Map of (a) the historical earthquakes from the USGS catalog during 1918–2021 and (b) the focal mechanisms from the Global Centroid Moment Tensor project data catalog. (c–e) The three black lines mark the locations of profiles. The other captions are the same as in Figure 1. The color version of this figure is available only in the electronic edition.
The data were collected from the passive-source OBS array (Liu et al., 2014, 2020) in the SCS basin from April 2012 to December 2012 (Fig. 1). The OBS experiment recovered 11 stations near the extinct MOR and Huangyan (Scarborough) Seamount chain, among which six OBSs had data for 7–8 months and two OBSs only recorded data during the first month due to various issues with the instrumentation. The others did not record any data because of the failure of their data logger. The timing of the OBS had been corrected using the time symmetric analysis based on ambient noise cross correlation (Le et al., 2018). Using the data set, Liu et al. (2020) investigated crustal thickness using the receiver function method, which showed the thickest oceanic crust near the Huangyan (Scarborough) Seamount chain. However, Hung et al. (2021) got different results using receiver functions that the oceanic crust abruptly thinned at sites close to the seamount chain. In addition to OBS data, we also collected data from two stations sitting on the Luzon island close to the Manila trench.

Detecting Phases by Machine Learning Algorithms

We then employed the machine learning (ML)–based algorithms, PhaseNet (Zhu and Beroza, 2019) and EQTransformer (Mousavi et al., 2020), on the OBS array for earthquake phase detection. These two widely used ML models creatively convert the phase picking into phase probability distributions based on a convolutional neural network. The three-component waveform was 1 Hz high-pass filtered. Seismograms with a sampling rate of 100 Hz and 30 s time segments, with 50% overlap between consecutive segments, were provided as the input. For the EQTransformer, a threshold of 0.1 for P and S phases was typically used for land stations. Whereas a higher threshold got fewer detections, a lower threshold gave more detections but could damage precision. In the study, considering lower signal-to-noise ratios (SNRs) of OBS data compared with land-station data, we tested thresholds lower than 0.1 (e.g., 0.04, 0.06, and 0.08). To balance the aims of getting more phases and avoiding false detections, we finally retained picks above the probability threshold of 0.06 for P and S phases. For the PhaseNet, P- and S-wave arrivals were predicted by PhaseNet with probability thresholds of 0.3.

In total, 161,375 P- and 88,571 S-wave arrivals were predicted by PhaseNet, and 9244 P- and 10,961 S-wave arrivals were predicted by EQTransformer. The daily number of predicted phases on each station is shown in Figure 3. For PhaseNet, picks of several stations abruptly increased during the days with air gun sources released (Fig. 3). Unfortunately, the probability of air gun impulses predicted by PhaseNet is higher than the threshold of 0.3, resulting in a large number of false positives of the air gun signals (Fig. 4). In comparison, the daily number of predicted phases by EQTransformer reduces several to tens of times, but the EQTransformer is less affected by the air gun signals (Fig. 3).

Well-trained ML-based automatic phase pickers have been widely used on land-based seismic stations, which show high accuracy for picking P and S waves on various instruments, including a short period and broadband, high gain and low gain accelerometer and seismometer (e.g., Park et al., 2020; Tan et al., 2021; Wong et al., 2021; Zhou et al., 2021; Jiang et al., 2022; Zhu et al., 2022) and OBS data (Chen et al., 2022; Gong et al., 2022). However, their application of identifying seismic phases from OBS data is quite limited, so the performance of the OBS dataset is not clear. Therefore, we examined the precision of the two algorithms in processing OBS data. Because of lacking predetermined events data with manual labeled P- and S-wave arrivals in this region, deriving the recall rate is impossible for this study. Instead, only precision was introduced to evaluate the performance. On days without air guns, we randomly chose 100 predicted picks from each algorithm and manually inspected the detections. We repeated the process three times and took the average value as the precision. The precision is defined as \( \text{Precision} = \frac{TP}{TP + FP} \), in which TP are the number of true and false positives, respectively.

Generally, the precision of the EQTransformer is higher than PhaseNet on the OBS stations (Table 1), but both are lower than the precision of land stations.

To assess the uncertainty of the automatic picker, we compared their predicted phases with manually labeled P- and S-wave arrivals (Fig. 5). We manually picked P and S phases for the relocated events from the catalog in the later section as the benchmarks and compared these picks with the EQTransformer automatic picks. Figure 5 shows the distribution of time residuals between the automated and human-labeled P and S picks. The residual distributions of both P and S phase picks are distinctly narrow and have no obvious biases. The average residuals are –0.07 s and 0.25 s for P and S waves with a standard deviation of 1.33 s and 2.83 s, respectively. The standard deviation of residuals is about one order of magnitude larger than the travel-time residuals from land stations (Zhou et al., 2021).

Phase Association and Location of Earthquakes

Although the PhaseNet predicted many more potential picks than EQTransformer, the false positives predicted by EQTransformer are much fewer than PhaseNet according to our visual inspection. The larger number of predicted false positives by PhaseNet would disturb the association results, leading to false associations of events. Therefore, we adopted P- and S-phase arrivals by EQTransformer in the following association and relocation of events.

In total, EQTransformer yielded 9244 P and 10,961 S picks on the SCS OBS dataset. We associated the phase picks with individual events using the Rapid Earthquake Association and Location package (Zhang et al., 2019). Only events with at least five phases, including at least 1 P phase and 1 S phase, were retained. The events were preliminarily located at the grid...
Figure 3. The daily number of predicted $P$ and $S$ phases on each station by (a,c,e,g,i,k,m) PhaseNet and (b,d,f,h,j,l,n) EQTransformer. The vertical light green bars mark the days with air guns released. The color version of this figure is available only in the electronic edition.
with the maximum number of seismic picks or the grid with the smallest travel-time residual if multiple grids have the same number of picks. A total of 240 events were associated and preliminarily located in this step, after visually inspection and discarding false detection events. To estimate the apparent $V_P$ and $V_S$, we fitted the distribution of the $P$- and $S$-wave travel times versus hypocentral distances after the association. The results indicate an apparent $V_P$ of 6.41 km/s and $V_S$ of 3.44 km/s, leading to the best-fitted $V_P/V_S$ ratio of 1.86 (Fig. 6).

We then located the associated events with at least one $P$ pick and one $S$ pick and five total picks with the HYPOINVERSE algorithm (Klein, 2002) using a 1D velocity model derived from a regional 2D $P$-velocity model (Zhao et al., 2018). We obtained the locations of 205 events using the HYPOINVERSE algorithm. We then used the double-difference method (Waldhauser and Ellsworth, 2000) to relocate the events. We measured the differential travel time using both existing $P$ and $S$ picks and waveform cross correlation. A total of 3609 $P$ phase and 2654 $S$ phase differential times were measured from existing picks, but only 134 $P$ phase and 170 $S$ phase differential times were calculated from waveform cross correlation. The number of cross-correlation differential times is quite limited because of the low waveform similarity due to the poor quality of the OBS data. During the hypoDD relocation, a minimum of five differential travel times was required to relocate each event pair within a maximum distance range of 400 km. We relocated 27 events using hypoDD, with the other 178 events remaining in their HYPOINVERSE locations.

The final catalog contains 205 events, which were all visually inspected by plotting their waveforms aligned with epicentral distance. Example waveforms of two relocated earthquakes are shown in Figure 7. Generally, the relocated events were spread across the trench, which is $\sim$10 times more than the catalog of the USGS. Within the SCS basin, several earthquakes occurred during the period, including the one near the intersection of the Zhongnan fault zone and the extinct fossil ridge (event 1 in Figs. 7, 8a), indicating intraplate deformation does occur within the SCS basin. Importantly, abundant outer-rise earthquakes occurred both in the north and south of the Huangyan (Scarborough) Seamount chain. Clusters of shallow seismicity were observed in the outer-rise region at the south of the Huangyan (Scarborough) Seamount chain (near BB’ in Fig. 8), with focal depths of most earthquakes shallower than 10 km. In comparison, the most of outer-rise earthquakes in the north of Huangyan (Scarborough) Seamount chain were within the upper $\sim$30 km (near AA’ in Fig. 8).

For the subduction-related earthquakes, most of the earthquakes were shallower than 100 km, and no trace of seismicity deeper than 150 km could be observed along the northern segment of the Manila trench (north of $15^\circ$ N). In contrast, the area along the southern segment is characterized by relatively deep seismicity, with a maximum depth of 180 km.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Estimated Precision of EQTransformer and PhaseNet on Each Ocean-Bottom Seismometer (OBS) Station</th>
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<tbody>
<tr>
<td>Station</td>
<td>HY02</td>
</tr>
<tr>
<td>EQTransformer</td>
<td>0.65</td>
</tr>
<tr>
<td>PhaseNet</td>
<td>0.41</td>
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near $\sim 14^\circ$ N (Fig. 8). The dip angles of the slab steepen southward from $\sim 30^\circ$ (Fig. 8c) to $48^\circ$ (Fig. 8e) to $57^\circ$ (Fig. 8e). In addition, a noticeable gap in seismicity that trends in a north-easterly direction is observed, which extends from a deeper part of the slab up to the surface at the trench line at $14^\circ$–$14.5^\circ$ N.

**Discussion**

**Performance of ML algorithms on OBS dataset**

ML algorithms significantly improve the performance of automated tasks in seismology, which have been widely used in land-based seismic stations and have shown remarkable accuracy and processing speed for seismic signals (Perol et al., 2018; Ross et al., 2018). However, the application of PhaseNet and EQTransformer on OBS is quite limited. One recent study shows that their precision and recall rate are relatively lower using the OBS data in southern Mariana (Chen et al., 2022). The SNR of OBS data is always low because of a variety of factors, such as poor coupling conditions, tilt noise caused by seafloor currents, compliance noise produced by pressure variations induced by ocean gravity waves, and other uncorrelated noises (Webb, 1998; Crawford and Webb, 2000).

The precision of the PhaseNet and EQTransformer automatic pickers may not be satisfactory when applied to OBS data, although both of them exhibit excellent performance on land stations. The precision, recall, and F1 score of the PhaseNet and EQTransformer are 0.96, 0.96, and 0.99, respectively (Zhu and Beroza, 2019; Mousavi et al., 2020). However, the precision of EQTransformer ranges from 0.65 to 0.85 on OBS stations, and the precision of PhaseNet is even lower, ranging from 0.41 to 0.54. In particular, the PhaseNet model falsely detects the impulsive signals generated by air gun sources. If including the mass of false picks of air gun signals, the precision of PhaseNet will be further reduced.

Potential bias of estimated precision is possible in this study because the number of picks used for estimating the precision is quite limited. The low precision mainly results from the generally low SNR or unusual OBS signals because of various factors. For example, tilting caused by seafloor currents affects amplitudes of three components, which may lead to pseudomorphic radiation patterns different from normal earthquakes. Some unexpected problems of polarity or horizontal orientations may also disturb OBS seismograms (Zhu et al., 2020). Besides, this can be attributed to the fact that no OBS data were used in the training, so the false detection rate was high when...
processing OBS data. Because of limited OBS data and labeled seismic signals from OBS recordings, a well-trained ML model suitable for OBS data is lacking by far. The catalog for the region could be further trained for an improved ML model for active subduction zones.

**Implications for the regional tectonic features**

The seismicity can illuminate the presence of active faults and can serve as proxies that denote changes in slab geometry and potential slab tears, although this might not be representative of long-term seismic activity in this region.

**Figure 6.** Distribution of the travel times of seismic phases associated by the Rapid Earthquake Association and Location package (REAL) method and the fitting of $V_P/V_S$. (a) Travel times of seismic phases associated and located using the REAL method. The purple (cyan) dots signify the relationship between the travel time of the seismic phase of the $P$ wave ($S$ wave) and the hypocentral distance. The slopes of black lines indicate the best-fitted $V_P$ (6.41 km/s) and $V_S$ (3.44 km/s). (b) Fitted $V_P/V_S$ ratio of 1.86 based on the travel times. The color version of this figure is available only in the electronic edition.

**Figure 7.** Waveforms of two relocated events: (a) event 1 near Zhongnan Fault zone and (b) event 2 at east of the trench, for which locations are marked as stars in Figure 8a. The red and green bars represent $P$ and $S$ picks by EQTransformer. The color version of this figure is available only in the electronic edition.
**Outer-rise seismicity.** The outer-rise seismicity provides a useful constraint on the plate bending. Abundant earthquakes have been found in the outer-rise region in various subduction zones (e.g., Zhu et al., 2019; Chen et al., 2022; Guo et al., 2022). A notable difference is the existence of bending fault earthquakes at the northern of Huangyan (Scarborough) Seamount chain, where is lacking seismicity in the historical USGS and Global Centroid Moment Tensor recordings. The outer-rise seismicity in the northern of Huangyan (Scarborough) Seamount chain is deeper than the south. The variation in outer-rise seismicity may be the proxy of active bending faulting, indicating intertrench changes in bending stresses (Zhou et al., 2015; Zhang, Sun, et al., 2018). Compared with other subduction zones, the depths of most outer-rise earthquakes in Manila are shallower than that.

**Figure 8.** The distribution of relocated earthquakes from our final catalog. (a) Map view of the relocated events. The dots represent located earthquakes colored by depth. The three black lines mark the location of cross sections. The other captions are same as Figure 1. (b) The depth distribution of earthquakes along the longitude direction. The cyan dashed line marks the position of a potential slab tear. (c–e) Cross-section views of the relocated events from our final catalog. The inset panels zoom in the cross sections of outer-rise earthquakes with the error ellipses indicating the location uncertainties given by HYPOINVERSE algorithm. The color version of this figure is available only in the electronic edition.
near the Mariana trench (>40 km) (Chen et al., 2022) and offshore southern Taiwan (44–50 km) (Tan, 2020). The results are consistent with the numerical models that the plate age can be a dominant factor in controlling the bending shape for relatively young subducting plates, for example, the Manila (16–36 Ma) and the old subducting plates, for example, the Mariana (140–160 Ma) (Zhang, Lin, et al., 2018).

The bending faults may serve as pathways for seawater to enter the slab’s interior, facilitating the formation of hydration minerals and leading to a pervasively serpentinized region (Shillington et al., 2015; Fujie et al., 2016; Zhu et al., 2021). The region has a slightly higher apparent $V_P/V_S$ of 1.86 than the average regular oceanic crust composition (Christensen, 2004), which may indicate the presence of serpentine. Anomalously high $V_P/V_S$ ratio close to 2.0 is also observed at the south of the ridge using receiver functions (Hung et al., 2021). Serpentinites have also been widely observed at slow and ultraslow spreading ridges where offset normal faults and detachment faults commonly form (Sauter et al., 2013; Guillot et al., 2015). The bending faults near the trench and faults related to the extinct fossil ridges may both contribute to forming hydrated minerals.

**Slab tear.** The Wadati–Benioff zone seismicity is ambiguous near the extinct MOR based on the historical catalog (Fig. 2c), partly because of the lack of near-field observational data, also ascribed to the complexity of the tectonic environment of the region. By analyzing historical seismic catalogs in the region, the segmentation of Wadati–Benioff zone seismicity has been hypothesized to be related to the subduction of the extinct MOR at 16–17° N, in which a slab window is proposed along the Manila trench (Bautista et al., 2001). The seismological tomographic results also show along-strike variational slab images, suggesting a slab tear along the ridge beneath Luzon Island (Fan et al., 2014).

The results clearly trace the Wadati–Benioff zone seismicity near the extinct MOR, which improves constraints on the subducted slab. Combined with historical seismicity, the observed change in dip from shallow to steep southward along the trench may indicate a slab tear at the south of ~18° N, which is spatially correlated with the subduction of the extinct MOR. Slab tearing may affect mantle processes and the long-term geodynamic evolution of continents, which may be responsible for the abrupt termination of the eastern chain of volcanoes south of 18° N on Luzon Island (Yang et al., 1996). The subducted ridge may serve as the weakest zone where slab tear could be localized (Bautista et al., 2001). Subducted oceanic ridges inducing slab tears are also observed in the Nazca slab beneath the South American subduction zone, which is characterized by lateral variations in slab dip angle (Scire et al., 2015; Lynner et al., 2017).

In addition to the potential slab tear related to the extinct MOR near 17° N, it is also likely a slab tear between 14 and 14.5° N, in which a seismic gap trending in a northeasterly direction. From this point southward, the segment of the Manila trench bends sharply to the east-southeast. Besides, the seismicity of the southern segment is distinctly deeper than the segment north of 15° N. The earthquakes are down to a depth of ~180 km in this study, and deep historical seismicity extends up to a depth of ~240 km. A slab tear can occur because of along-strike changes in slab geometry, which may be associated with the sharp bending of the slab caused by the collision of a microcontinental plate with the islands (Bautista et al., 2001). The slab tear may result in the seismic gap between 14 and 14.5° N.

The variation in slab geometry and the subducted seamounts may affect the megathrust earthquake rupture and earthquake potential along the Manila trench. The geometrical segmentation of the slab can host ruptures on either segments but likely inhibits rupture of the entire fault to generate earthquakes with magnitudes greater than $M_w$ 8.5. (Yu et al., 2018). Indeed, it has been suggested that fault geometry can be the first-order factor controlling earthquake rupture behaviors by increasing shear strength heterogeneity (e.g., King, 1986; Bletary et al., 2016), in addition to heterogeneous stress and frictional properties (e.g., Yang et al., 2019, 2022; Yao and Yang, 2022). In addition, the Huangyan (Scarborough) Seamount chain could act as a barrier in stopping megathrust ruptures. Previous studies have discussed the barrier effects of subducted seamounts on coseismic ruptures (e.g., Yang et al., 2012, 2013). Subducted seamounts could stop coseismic ruptures by various mechanisms, such as increasing frictional resistance (Kodaira et al., 2000), increasing normal stress on the thrust interface (Scholz and Small, 1997), or reducing elastic strain accumulation due to low effective normal stress of fluid-rich sediments near seamounts (Mochizuki et al., 2008).

**Summary**

We apply the ML-based algorithms, EQTransformer and PhaseNet, to the OBS dataset in the SCS for detecting seismic events and picking phases. We evaluate the precision of the two algorithms and analyze the picking uncertainties by comparing the time residuals. The PhaseNet has low precision compared with EQTransformer on OBS data and is significantly disturbed by impulsive air gun signals.

Based on the detected seismic phases by EQTransformer, we relocate the detected events and derive a catalog of earthquakes for the duration of the temporary OBS deployment. The final catalog contains 205 located earthquakes in the region, which is ~10 times the USGS catalog. Most of the relocated earthquakes are near the Manila trench, but a few occur within the SCS basin. In the outer-rise region, tens of bending-fault earthquakes occur at the northern of the Huangyan (Scarborough) Seamount chain, where there is no seismicity in the historical recordings. The variation in outer-rise seismicity may be the proxy of active bending faulting, indicating intermittence changes in bending stresses. For
slab-related earthquakes, most of them are shallower than 100 km north of 15° N. The focal depths of slab-related earthquakes gradually deepen to ~200 km southward along the trench, indicating slab tears related to the extinct MOR or sharp bending of the slab.

**Data and Resources**

The ocean-bottom seismometer data for earthquakes used in this study can access by connecting with the corresponding authors. We collected seismograms of the two Global Seismographic Network stations via the Incorporated Research Institutions for Seismology. The historical earthquake catalog was searched using https://earthquake.usgs.gov/earthquakes/search. The Global Centroid Moment Tensor Project database was searched using www.globalcmt.org/CMTsearch.html. All websites were last accessed in July 2022.

**Declaration of Competing Interests**

The authors acknowledge that there are no conflicts of interest recorded.

**Acknowledgments**

This work is supported by National Natural Science Foundation of China (Grant Numbers 92158205, 92058209, and 91958211), an award from the Center for Ocean Research in Hong Kong and Macau (a joint research center for ocean research between Qingdao Pilot National Laboratory for Marine Science and Technology and The Hong Kong University of Science and Technology), Hong Kong Research Grant Council grants (Grant Number 14304820), Gaohua Zhu’s stand-up fund, Shenzhen Science and Technology Program (Grant Numbers KQTD201701111725321 and JCYJ20180504170422082), and a Youth Innovation Promotion Association Chinese Academy of Sciences Grant (Grant Number 2016189). The authors thank Qingsheng Guan from the Second Institute of Oceanography, Ministry of Natural Resources, for sharing the updated position of extinct fossil ridges. The authors thank the two reviewers and editor for insightful suggestions.

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