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What conditions promote atypical subduction: Insights from the Mussau Trench, the Hjort Trench, and the Gagua Ridge

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ABSTRACT

Subduction zones act as interfaces for exchanging materials between the Earth's crust and mantle. The western Pacific plate region is evolving within a convergent tectonic environment. Old oceanic plates generally subduct beneath young oceanic plates, as exemplified by the Izu-Bonin-Mariana and Tonga-Kermadec subduction zones. However, in some subduction zones, such as the Mussau Trench, the Hjort Trench, and the Gagua Ridge, young and more buoyant oceanic plates have been recognized to subduct underneath older and denser plates. What conditions promote atypical subduction, however, remain elusive. In this study we take the Mussau Trench, the Hjort Trench, and the Gagua Ridge as examples to explore the possible underlying factors that control the formation of atypical subduction. By anatomizing the tectonic features of both the Mussau Trench and the Hjort Trench, we find that atypical subduction may be feasible mainly when the plate boundary is characterized by strike-slip-dominated transpression; that is, the strike-slip component overwhelms the compression component, which may argue against the atypical subduction occurring at the Gagua Ridge, at least at present. Moreover, in light of the evolution of both the Mussau Trench and the Hjort Trench, it is further suggested that subduction polarity reversal and a strike-slip border are the keys to atypical subduction.

1. Introduction

Subduction zones, the most extensive material recycling system on Earth, are characterized by complex tectonic activities. The main force driving plate motion has been primarily attributed to the negative buoyancy of subducting slabs in response to the mineral phase transitions. Therefore, subduction zones serve as an essential part of plate tectonics (Conrad and Lithgow-Bertelloni, 2002; Stern, 2002; Niu, 2013). It has been suggested that when the age difference between two adjacent plates is above 30 Ma, and the boundary between two plates is defined by either strike-slip faults or fracture zones, the older, thick and dense lithosphere is expected to sink underneath the younger, more buoyant lithosphere assisted by exerting extrusive stress on the system (Gurnis et al., 2004; Eakin et al., 2015; Zhang et al., 2021). In reality, however, subduction initiation is brutal (Mueller and Phillips, 1991; Toth and Gurnis, 1998). The controlling factors of subduction initiation and developing mature subduction have not been well understood, partly because the subsequent tectonic activities have modified most of the records of initiation dynamics, leading to a lack of direct topographic and structural observations (Collot et al., 1995; Eakin et al., 2015).

Stern (2004) has classified subduction initiation into two types, namely induced and spontaneous subduction, according to the force source of driving subduction initiation. Specifically, the convergence of two plates is needed to promote induced subduction. In contrast, spontaneous subduction occurs only when there is a significant lateral density contrast between different lithospheres and there is no previous plate relative motion (Stern and Gerya, 2017). Casey and Dewey (1984) proposed that the possible mechanisms for subduction initiation include two processes: (1) polarity reversal along the weak back-arc or island-arc interfaces and (2) plate boundary evolution related to plate boundary transform and accreting plate boundaries into subduction boundaries. It is widely realized that transform faults and fracture zones may represent the most possible subduction initiation sites due to their weak strength (Fitch, 1972; Mueller and Phillips, 1991; Toth and Gurnis, 1998). For instance, Boutelier and Beckett (2018) suggested that in the absence of a pre-existing inclined weak zone, the weak and younger plate may subduct beneath the older plate along a

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transform fault. A recent numerical modeling study on the polarity of subduction initiation along a transform fault under compression by Zhang et al. (2021) indicated that subduction polarity mainly depends on three factors, namely the age offset between the two adjacent plates, the strength of the transform fault and the plasticity of the plate.

Unlike the normal subduction of the older plate subducting beneath the younger one, some cases along the western Pacific plate boundaries show that the more youthful, lighter, and thinner oceanic lithosphere is subducting under the older, denser, and thicker oceanic lithosphere (Hegarty and Weissel, 1988; Meckel et al., 2005), which is recognized as atypical subduction. Atypical subduction is intriguing because it is not commonly seen in reality.

According to previous research, both the Mussau Trench and the Hjort Trench are in the initial stage of atypical subduction. The Gagua Ridge is inactive in terms of tectonic activity so it is recognized as an "aborted" atypical subduction zone (Eakin et al., 2015; Zhao et al., 2020). The focus of previous work in these regions is mainly on subduction initiation (Hegarty et al., 1983; Meckel et al., 2003; Eakin et al., 2015), and there is little research on the formation mechanisms of atypical subduction.

By analyzing atypical subduction in-depth, this paper aims to explore the underlying geologic conditions that lead to atypical subduction and discuss whether the Gagua Ridge is of atypical subduction or not.

2. Tectonic anatomy of three representative atypical subduction zones

In the section, the tectonic characteristics of three atypical subduction zones are identified by reprocessing and reinterpreting of the available seismic profiles, shedding light on the conditions that lead to the atypical subduction.

2.1. The Mussau Trench and its characteristics

The Mussau Trench, the result of the young Caroline plate subducting underneath the old Pacific plate at ~1 Ma ago (Fig. 1), together with the northern strike-slip nature of the Sorol Trough and NW-trending thrust fracture zone, contributes to forming the Caroline-Pacific plate boundary (Hegarty et al., 1983).

The Caroline plate is interpreted as a back-arc basin that started spreading in the Late Eocene and stopped in the Late Oligocene, with the spreading ridge axis in the NEE–SWW direction (Hill and Hegarty, 1987; Hegarty and Weissel, 1988). It is found that the age of the Caroline plate on the west of the Mussau Trench is Oligocene through analyzing the drilling core and geomagnetic data of stations DSDP 62 and 63 (Bracey, 1975), and the Pacific plate on the east of the Mussau Trench is Jurassic in age. The seismic reflection profiles between the East Caroline Basin and the Lyra Trough obtained by Hegarty et al. (1983) show substantial acoustic similarity, indicating that the crust on both sides of the Mussau Trench has a similar age. The sediment thickness and basement depth in the east of the Lyra Trough are significantly larger than those in the west, suggesting that the west of the Lyra Trough may be part of the Caroline spreading system in the Oligocene (Hegarty and Weissel, 1988).

It is found that the Mussau Trench is influenced by the relative motion of the Caroline plate on the west, the Pacific plate on the east and north, and the Australian plate to the south (Fig. 1). The northern part of the Mussau Trench is a heavily fractured landmass with the trench topography gradually diminishing, and the southern part is connected with the Manus Trench (Erlandson et al., 1976). Three seismic reflection profiles across the Mussau Trench (Fig. 2) show clearly that deformation intensity increases from profiles I to III. The depth of the trench is more significant than 6750 m with less sediment at the bottom, the eastern trench wall is steeper, the seismicity is inactive, and arc volcanic activity related to subduction is absent (Fig. 2). Hegarty et al. (1983) showed that about 10 km of Caroline crust had subducted beneath the Mussau Ridge based on a gravity model. The northern part of the Mussau Trench is recognized as an abnormal zone with severely damaged seabed topography (Weissel and Anderson, 1978; Hegarty et al., 1983; Hegarty and Weissel, 1988). Weissel and Anderson (1978) analyzed the data collected from profiles A to F (Fig. 3), proposing that the local topography within the deformation zone is particularly conspicuous in the first four profiles of Fig. 3, which is representative of the northeastward oceanic crust thrust belt. This thrust zone accommodates 2–5 km of crustal shortening (Hegarty and Weissel, 1988). The present-day Caroline-Pacific plate boundary is thought to be newly formed based on a series of observations, including (1) the small amount of crustal shortening, (2) low seismic activity in the Mussau Trench and northern thrust zone, and (3) the young topography of the Mussau Trench (Hegarty and Weissel, 1988). Weissel and Anderson (1978) constructed a simple elastic bending model of the Mussau Trench by constraining horizontal compression stress, and also proved that it is a recently formed subduction zone. The transition zone (3°–4°N) between the Mussau Trench and its northern subduction zone is the intersection of both the Kiilsgaard Trough and the Lyra Trough with the Caroline-Pacific plate boundary, representing a weakness zone with a sharp shift in structure formation and the direction of underthrusting (Weissel and Anderson, 1978). The east of the Mussau Trench is defined as the Lyra Trough, which has been considered as the Caroline-Pacific plate boundary during the spreading of the Caroline Basin (Hegarty et al., 1983; Hegarty and Weissel, 1988). When the basin spreading ceased, the relative motion along the Lyra Trough stopped.

In conclusion, based on the in-depth analysis of the tectonic setting of the Mussau Trench, we speculate that the Caroline-Pacific plate boundary was the Lyra Trough, formed in response to the spreading of the Caroline Basin. With the cessation of the Caroline Basin spreading, the movement along the Lyra Trough stopped (Hilde et al., 1977; Hegarty et al., 1983; Hegarty and Weissel, 1988; Altis, 1999). The Lyra Trough and the part on the east of the Mussau Trench are presumed to be captured by the Pacific plate and become a part of the Pacific plate, inheriting the motion and mechanical properties of the Pacific plate, i.e., the affiliation to the Pacific plate formed a firm plate boundary. At ~1 Ma, thanks to the absence of a weak zone at the plate boundary (i.e., the Lyra Trough), concurrently assisted by the continuous NW-oriented motion of the Pacific plate, the Caroline plate along an internal transform fault started to subduct underneath the Pacific plate, leading to atypical subduction in the Mussau Trench. In contrast, due to the lack of strike-slip motion north of 3°N, the compression between the Pacific plate and the Caroline plate leads to the Pacific plate subducting underneath the Caroline plate. This evolutionary process thus formed several types of plate boundaries, varying from atypical subduction (the Mussau Trench) to normal subduction (the NW-oriented thrust zone) to strike-slip (the Sorol Trough).

2.2. The Hjort Trench and its characteristics

The Hjort Trench, located in the southernmost part of the Macquarie Ridge Complex (MRC) (Fig. 4a), is the product of the Australian plate subducting underneath the Pacific plate that commenced at ~11 Ma ago (Ruff et al., 1989; Meckel et al., 2003; Meckel et al., 2005). The MRC is the active submarine portion of the Australia-Pacific plate boundary to the south of New Zealand, extending to the Macquarie Triple Junction (MTJ) (Collot et al.,

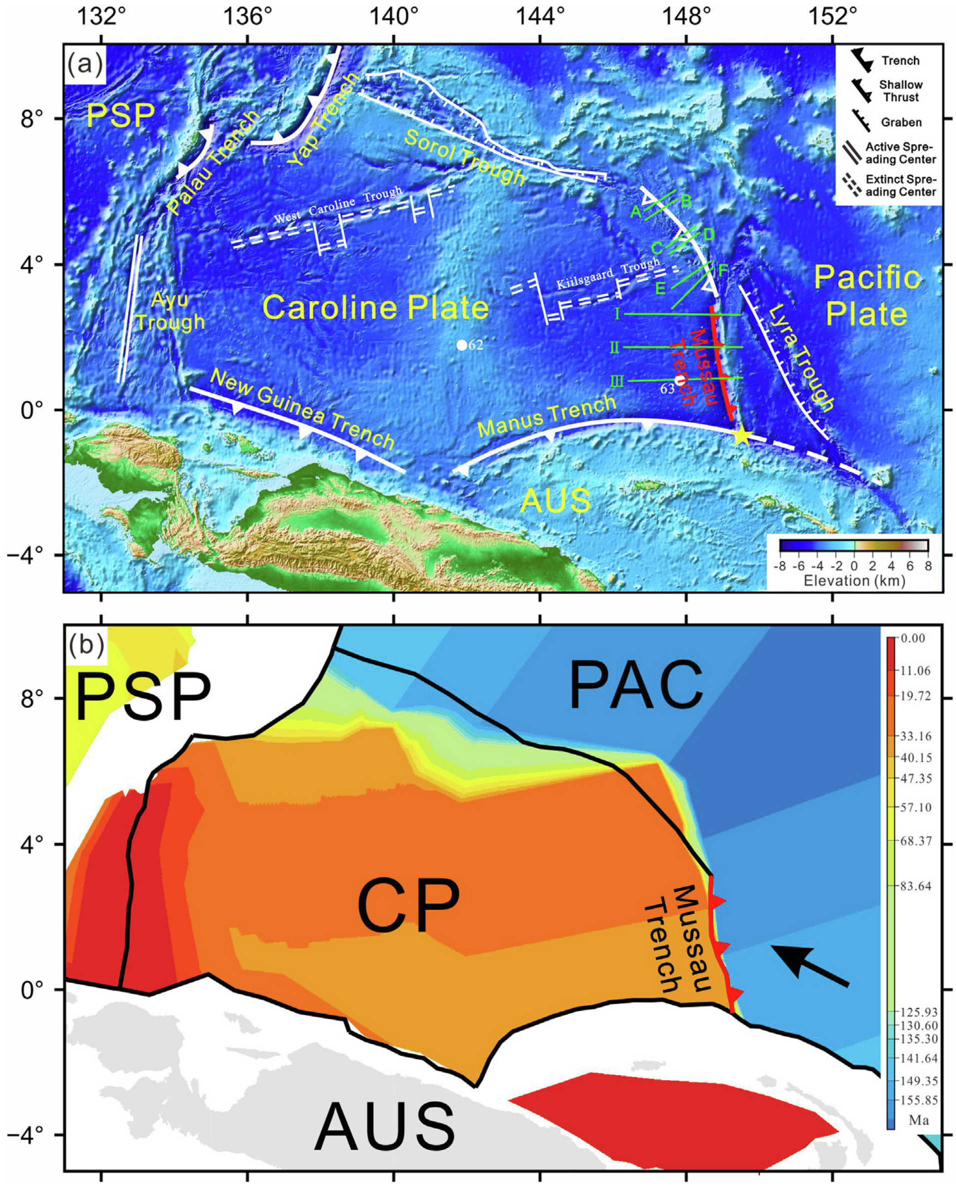

Fig. 1. Bathymetry (a) and oceanic crust age map (b) overlapped with central tectonic units in the Caroline area. (a) The seismic lines (I to III in Fig. 2 and A to F in Fig. 3) are shown in green by Weissel and Anderson (1978), and the yellow star marks the triple junction of the Caroline-Pacific-Australia plates. DSDP sites (labeled as 62 and 63) are indicated with solid circles; the dashed lines represent the locations of the extinct spreading ridges (Hegarty and Weissel, 1988). (b) The black lines indicate the plate boundary, and the arrow shows the direction of the Pacific plate motion from Li et al. (2019). PSP: Philippine Sea plate; AUS: Australian plate; CP: Caroline plate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1995; Meckel et al., 2003). The Hjort Trench is found to be of westward indentation, separating the oceanic crust formed by the Southeast Indian Ridge on the south (SEIR crust) from the one created by the extinct spreading center of the Australia-Pacific plate on the north (MRC crust) (Fig. 4b) (Meckel et al., 2003). The eastern part of the trench is the Hjort Ridge, with a joined valley at its crest, which continues the paired ridge system identified in the northern Macquarie region (Massell et al., 2000; Choi et al., 2017). In the west of the trench, the magnetic anomaly bands are identified as C4–C6, and the crustal age is less than 25 Ma. The eastern age is uncertain, but the calibrated magnetic anomaly bands (C12 and C13) indicate that the age of the crust in the east must be around 30 Ma (Falconer, 1972; Meckel et al., 2003). Seismic activities are thought to be limited only to the vicinity of the Hjort Trench and the Hjort Ridge, characterized by shallow seismicity (<20 km) (Ruff et al., 1989; Meckel et al., 2003). Few earthquakes are located in the east of the trench, and there is no prominent Wadati-Benioff Zone, suggesting a subduction initiation phase. More importantly, the focal mechanisms are characterized by both thrust and dextral strike-slip types, indicating that the boundary is under the stress condition of transpression (Fig. 4b). It is clear from the three transects across the Hjort Trench (Fig. 5) that the SEIR crust subducts underneath the MRC crust. In contrast, the segment of the low-gravity anomaly occurring in the Macquarie transect, opposite the Hjort Trench, possibly represents a change in subduction polarity. This scenario may directly reflect a process of the MRC crust subducting underneath the SEIR crust (Meckel et al., 2003).

We speculate on the formation of the Hjort Trench based on the evolution of the Australia-Pacific plate boundary south of New Zealand. At about 45 Ma, the intra-ocean rifting formed the Macquarie Spreading Center (MSC), which defined a new Australia-Pacific plate boundary (Sutherland, 1995; Cande and Stock, 2004;

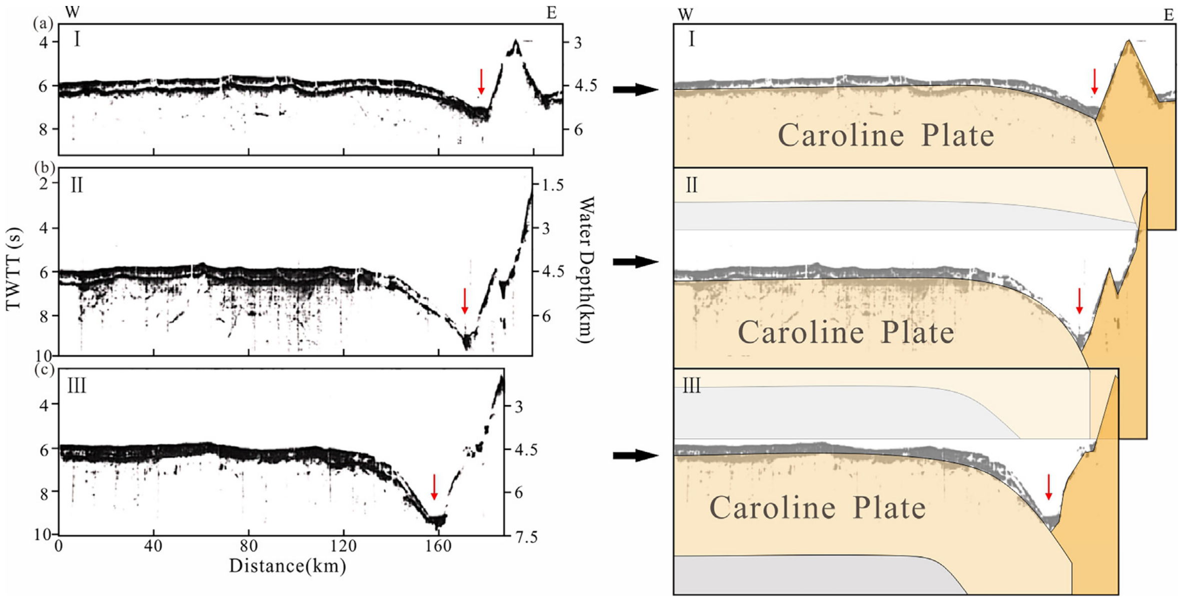

Fig. 2. Three seismic reflection profiles across the Mussau Trench (left column) and the corresponding structural interpretations (right column). The locations of the survey lines (I, II and III) are shown in Fig. 1. The arrows indicate the location of the Mussau Trench. TWTT means two-way travel time. Adapted from Weissel and Anderson, 1978

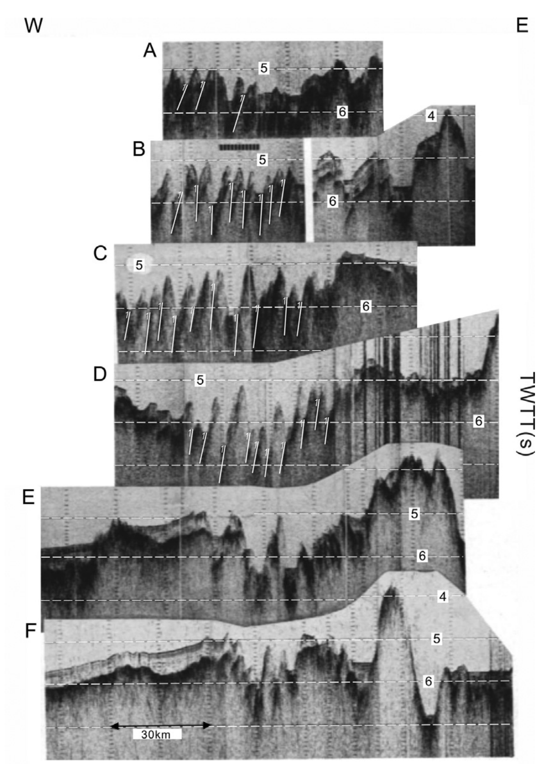

Fig. 3. Seismic reflection profiles across the overthrusting segment of the Caroline-Pacific plate boundary, north of the Mussau Trench. The locations of the survey lines are shown in Fig. 1. The white lines represent thrust faults. Water depth is given in the unit of seconds corresponding to the two-way travel time (TWTT), as indicated by the yellow dashed lines (1 s ≈ 750 m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) Adapted from Weissel and Anderson, 1978

Shuck et al., 2021). From ~30 Ma, the Euler pole of the Australia-Pacific plate boundary migrated southward relative to the Pacific plate, resulting in gradual inclination of the seabed expansion along the MSC. The strike-slip component in the plate boundary was gradually increasing. Until 20 Ma, the plate boundary evolved into an entire strike-slip border (Collot et al., 1995; Cande and Stock, 2004; Gurins et al., 2019). Therefore, the series of evolution processes led to a transpression stress regime in the south of the Australia-Pacific plate boundary, assisted by continuous compression exerted by the Pacific plate movement, promoting the development of subduction at the Hjort Trench. As a result, the relative motion of the Australia-Pacific plate boundary evolving from spreading to strike-slip also resulted in the plate boundary transitioning from atypical subduction (the Hjort Trench) to possible normal subduction (the southern end of the Macquarie region) to strike-slip (the Macquarie and McDougall regions) and normal ocean-continent subduction (the Puysegur Trench).

2.3. The Gagua Ridge and its characteristics

The Gagua Ridge, located to the southeast of Taiwan, is an N–S-trending aseismic ridge (Schnurle et al., 1998a; Sibuet et al., 1998). It extends from the northeastern North Luzon Arc to the Ryukyu Trench, characterized by approximately 300 km in length, 20–30 km in width, and 2–4 km in height (Deschamps et al., 1998; Eakin et al., 2015) (Fig. 6). To the north of 23° N, the Gagua Ridge subducting beneath the Ryukyu edge has been evidenced by several observations, including the maximum depth (6000 m) and low-gravity anomaly (−120 mGal) of the crest of the Gagua Ridge, a significant depression at the base of the Ryukyu accretionary wedge, and the partial uplift and deformation of the Nanao forearc basin (Deschamps et al., 1998; Schnurle et al., 1998a; Sibuet et al., 1998). The Gagua Ridge is a narrow linear elevation associated with early subduction that separates the Huatung Basin in the west from the West Philippine Basin in the east (Li et al., 2007; Eakin et al., 2015). The West Philippine Basin has experienced back-arc spreading and intraplate magmatism and developed several Late Mesozoic arc terranes (Yan et al., 2022). Hilde and Lee (1984) showed that the West Philippine Basin was formed through two stages (60–45 Ma and 45–35 Ma) of spreading of the Central Basin Spreading Center (CBSC), while the Huatung Basin was formed in the second stage of CBSC with magnetic anomaly bands of C16–C19. Although E–W trending magnetic anomaly bands in the Huatung Basin have been identified, only four magnetic anomaly bands are insufficient to determine a reliable age (Deschamps et al.,

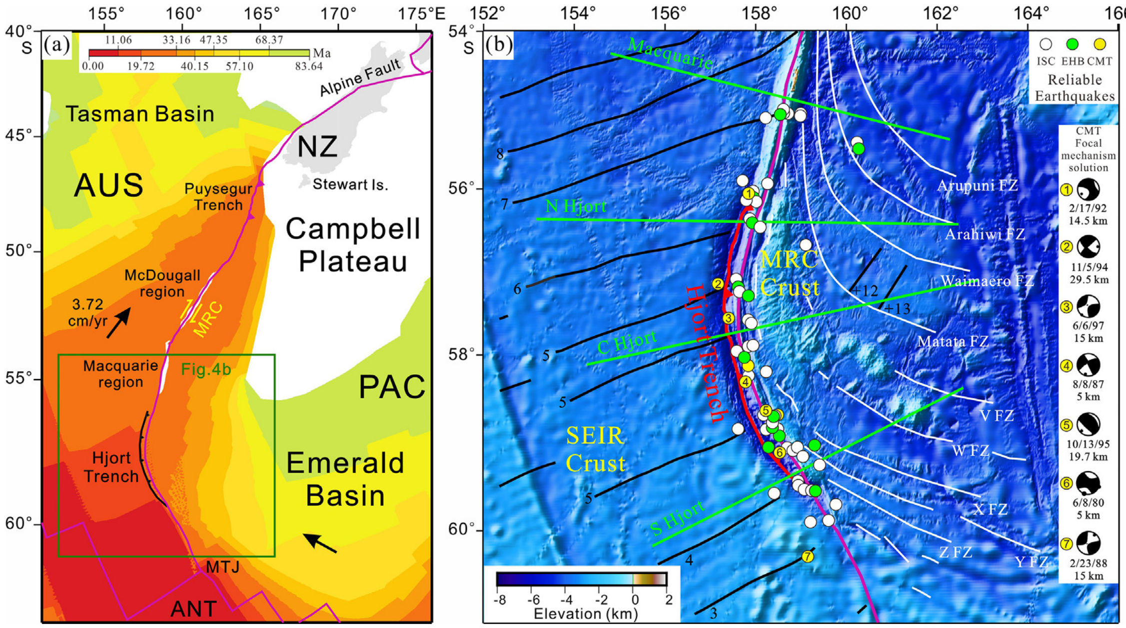

Fig. 4. (a) Tectonic setting and Oceanic crust age map of the Hjort Trench; (b) Bathymetry map of the Hjort Trench. The area indicated with the green square (a) is zoomed in at the right panel (b). The green lines (b) are four gravity survey lines (Macquarie, N Hjort, C Hjort and S Hjort), the red line is the Hjort Trench, the purple line is the plate boundary, the white lines are fracture zones, and the black lines are magnetic anomalies from Weissel et al. (1977). The white, green and yellow circles represent the earthquake locations of better-determined events from the International Seismological Centre Catalog (ISC), Relocations (EHB; Engdahl et al., 1998), and Harvard Centroid Moment Tensor Catalog (CMT) (Adapted from Meckel et al., 2003), respectively. CMT catalog includes both thrust and strike-slip events as indicated with beachballs. Black arrows show the directions of plate motion. Australian plate velocity (relative to Pacific plate fixed) from MARVEL (DeMets et al., 2010). AUS: Australian plate; PAC: Pacific plate; ANT: Antarctic plate; NZ: New Zealand; MTJ: Macquarie Triple Junction; FZ: Fracture Zone; MRC: Macquarie Ridge Complex; SEIR: Southeast Indian Ridge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2000). The Huatung Basin is later identified as a Cretaceous ocean basin by analyzing the gabbro samples collected by trawling at RD19 and RD20 stations in the basement of the Huatung Basin (Fig. 6), together with $^{40}Ar/^{39}Ar$ dating of 131–119 Ma and 130 Ma (Deschamps et al., 2000; Zhao et al., 2020). Qian et al. (2021) also confirmed a Cretaceous age for the Huatung Basin based on the Gagua Ridge lava eruption age and the youngest zircon age.

The origin of the Gagua Ridge is still controversial. Deschamps et al. (1998) suggested that the Gagua Ridge is an intra-oceanic fracture zone uplifted during the Middle Eocene by compression along a north-south fault zone which was formed during the second spreading of the West Philippine Basin. Some studies suggested that the Huatung Basin is a plate separated from the Philippine Sea plate by the Gagua Ridge, accommodating the NW-oriented shear movement of the Philippine Sea plate (Sibuet and Hsu, 1997; Sibuet et al., 2002). Eakin et al. (2015) established four wide-angle OBS velocity structure models across the Gagua Ridge (Fig. 7), showing the negative gravity anomaly, and crustal thickening asymmetry. Westward subduction of the West Philippine Basin oceanic crust underneath the Huatung Basin was suggested mainly based on the apparent deepening of the oceanic crust of the West Philippine Basin near the east of the Gagua Ridge (Li et al., 2007; Eakin et al., 2015). There are other different views. Specifically, Qian et al. (2021) found that the Gagua Ridge zircons are most likely to be affiliated to the Cathaysian block by constraining the zircon ages in the Gagua Ridge lavas, suggesting that the Gagua Ridge broke away from the Eurasian margin with the opening and spreading of the Huatung Basin. Zhang et al. (2020) found a suit of N–S oriented, eastward dipping normal faults on the east side of Gagua. The branch of the fault zone with these faults inclining 60°–70°are distributed in an echelon pattern, suggesting that the Gagua Ridge may undergo a strike-slip tectonic evolution (Zhang et al., 2020; Zhang et al., 2022).

In summary, the genesis of the Gagua Ridge is still under debate. This study aims to verify its atypical subduction as described in section 3.2, but not to discuss its tectonic affiliation.

3. Results and discussion

3.1. The tectonic conditions of atypical subduction

For normal subduction, it is generally accepted that the negative buoyancy of the old oceanic lithosphere provides a sufficient driving force of subduction (Vlaar and Wortel, 1976; Korenaga, 2013). However, atypical subductions at the Mussau Trench and the Hjort Trench are referred to as the subduction of the young oceanic lithosphere to the old. Therefore, negative buoyancy is seemingly not decisive in plate subduction, especially at the initial stage of subduction. A recent numerical simulation suggested that atypical subduction may occur when the ocean age difference is slight (∼30–50 Ma) along the desired boundary (Zhang et al., 2021), indicating that the age gap being favorable for atypical subduction between two plates cannot be too large.

It is found that both the Mussau Trench and the Hjort Trench are formed in similar geological settings and conditions; that is, both experience intense compression but with significant strike-slip activity, leading to strike-slip-dominated transpression, and thereby promoting the atypical subduction. Specifically, atypical subduction is formed at the Mussau Trench assisted by the oblique compressional stress in response to the Pacific plate northwestward moving toward the Caroline Basin. By contrast, at the Hjort Trench, the strike-slip motion, attributed to the southward migration of the Euler pole of the Australia-Pacific plate boundary and accompanied by an NW-directed compression occurs to the strike-slip border, leading to strike-slip-dominated transpression, and thereby promoting atypical subduction.

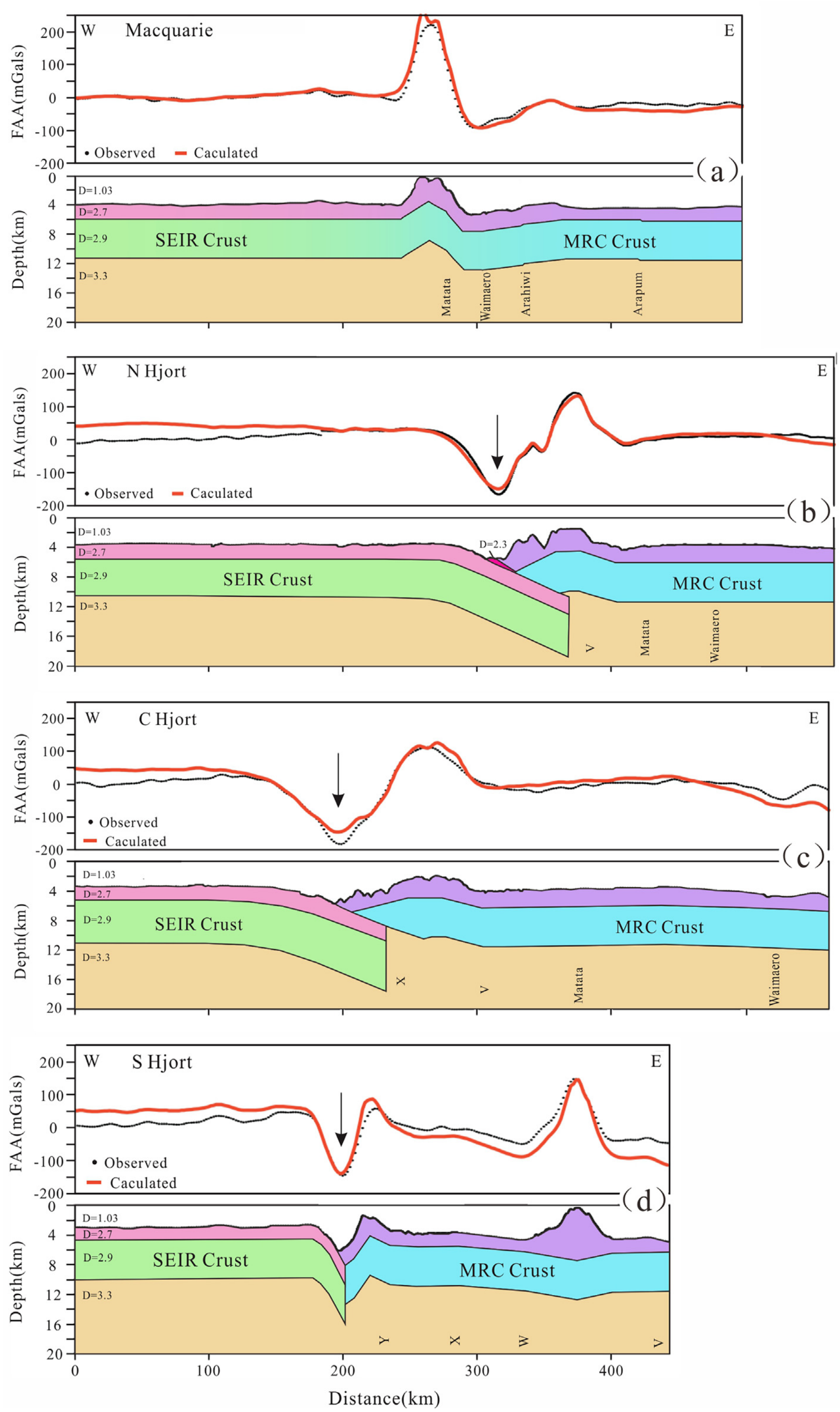

Fig. 5. Gravity transects and density structures beneath four profiles (a-d) across the Hjort and Macquarie regions. In each profile, the upper panel shows the comparison between the observed and modeled gravity, and the lower panel shows the interpreted structures. The MRC crust appears to be more prone to underthrusting than the SEIR crust (a). The three transects across the Hjort Trench (b), (c), and (d) show the limited underthrusting of the SEIR crust. Arrows indicate the location of the Hjort Trench. The gravity models include four layers: water (1.03 g/cm^3); upper crust (2.7 g/cm^3); lower crust (2.9 g/cm^3); and mantle (3.3 g/cm^3). Limited sediment accumulations (N Hjort transect) have a density of 2.7 g/cm^3. Adapted from Meckel et al., 2003

To sum up, a transpression environment is most favorable for forming atypical subduction, particularly when the plate boundary is dominated by strike-slip movement and squeezed by the old plate moving towards the younger plate.

3.2. The Gagua Ridge may not be of atypical subduction

Although the Gagua Ridge was recognized as an atypical subduction setting, it is not evident that a strike-slip movement across

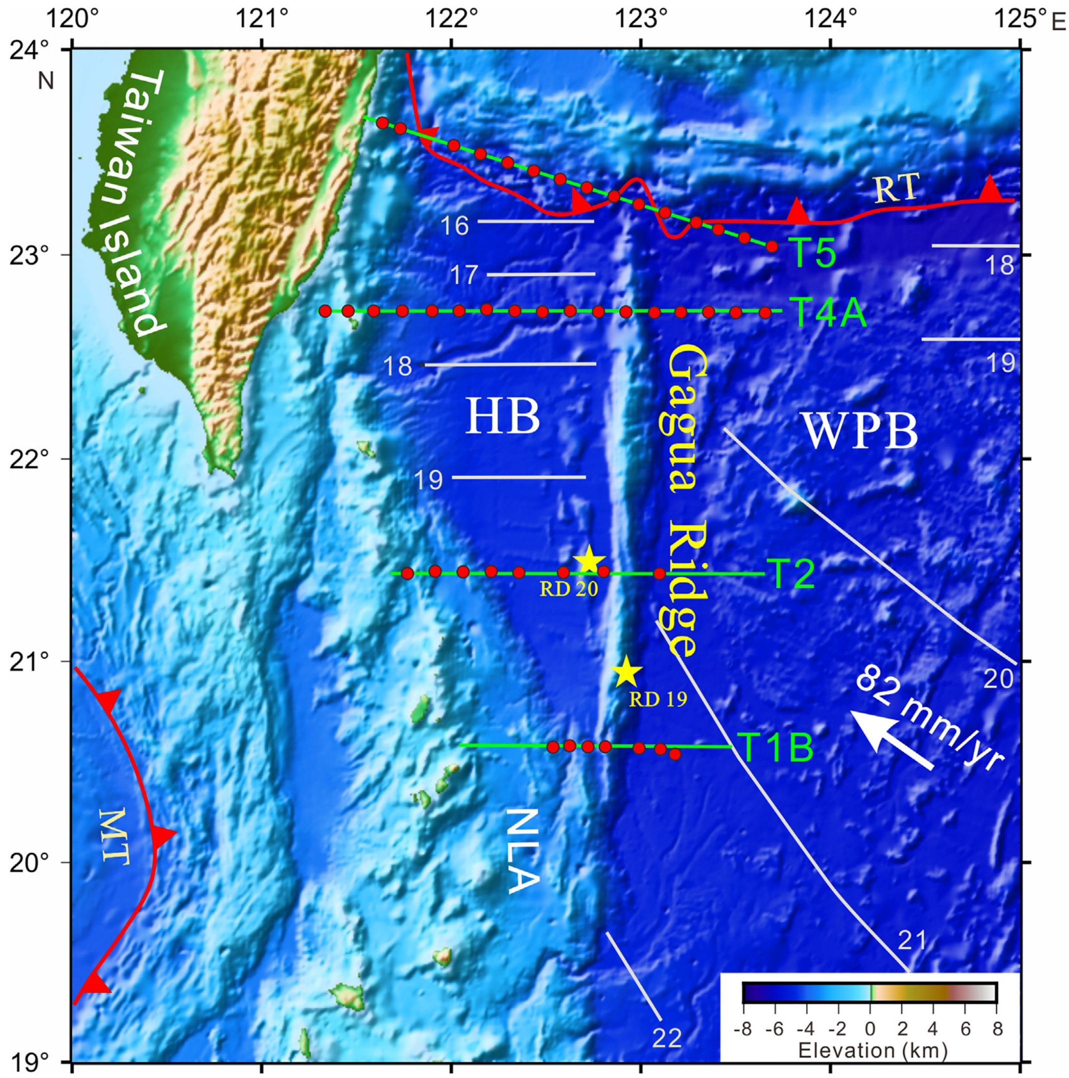

Fig. 6. Bathymetry map of the Gagua Ridge area. The green lines represent wide-angle transects (T5, T4A, T2 and T1B) with OBS stations (red circles). The gray lines are magnetic anomalies from Hilde and Lee (1984). The white arrow shows the direction and velocity of the Philippine Sea plate movement from Sibuet et al. (2021). The yellow stars are the RD19 and RD20 sample sites, where the position of RD19 is revised according to the ship tracks and water depth (https://www.ngdc.noaa.gov/trackline/request/?surveyIds=V3609#). HB: Huatung Basin; WPB: West Philippine Basin; NLA: North Luzon Arc; MT: Manila Trench; RT: Ryukyu Trench. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Gagua Ridge is active due to a lack of GPS observations of crustal movement. Based on the tectonic setting of atypical subduction formation as we proposed above, compression alone without strike-slip movement is insufficient to start atypical subduction. In addition, the young West Philippine Basin seems to move in the NW direction toward the Huatung Basin, leading to compression between them, contrary to our proposal that the old plate is extruding into the young plate, which further suggests that the Gagua Ridge may not be of atypical subduction.

The velocity model of the T1B line across the Gagua Ridge has been inverted using the first-arrival time (Eakin et al., 2015; Fig. 7). Still, the structural interface of each layer at depth was missing. To improve our understanding of the deep structure, which is crucial to reveal how the Huatung Basin is contacting the West Philippine Basin, a new velocity model was obtained using both the first-arrival and second-arrival reflections by our group (Pang et al., 2019; Fig. 8). Compared with previous studies, the advantages of the new work are as follows: (1) Topographic correction and basement correction of the seismic profile was carried out, which is necessary to ensure accurate identification of the refraction and reflection waves since the topography of the T1B line fluctuates significantly from west to east (Fig. 8b); (2) The seismic reflection from the Moho interface, PmP, determined by using the multiple-wave identification technique, was incorporated into the construction of the velocity model, which improves the reliability of the model because the crustal refractions have been interfered by the structure of the Gagua Ridge; (3) The finalized velocity model was further confirmed by the acoustic forward modeling. Therefore, the reconstructed velocity model of the T1B line is more realistic and reliable, providing more in-depth information of the tectonic activity in and around the Gagua Ridge.

From the constructed velocity structure across the Gagua Ridge (Fig. 8c), it can be seen that the basement relief and the depth of the Moho are highly variable. The crustal thickness below the Gagua Ridge is ~15 km. More importantly, the velocity structure on both sides of the Gagua Ridge is almost identical, with similar gravity isostatic root features, showing no structural features of subduction. Therefore, we conclude that the Gagua Ridge is not at the phase of subduction, at least at present, although the two plates across the ridge are of distinct ages.

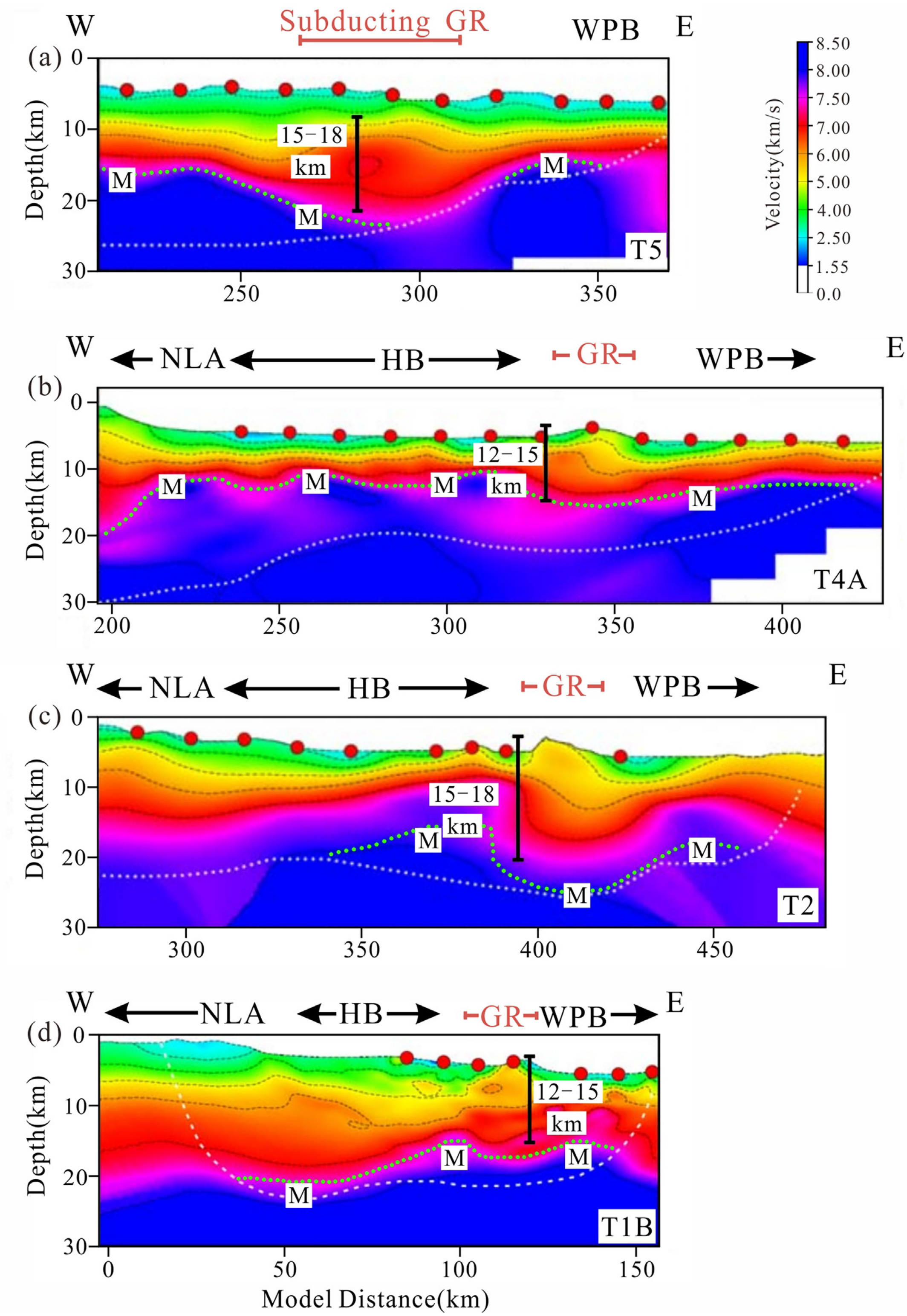

Fig. 7. First-arrival tomographic models along the seismic transects of T5, T4A, T2, and T1B across the Gagua Ridge. The locations of the survey lines are shown in Fig. 6. The red circles are the positions of OBSs. The white dashed line marks the bottom limit of the final model resolution. The green dashed line and M in the models mark the approximate location of the Moho interface (Adapted from Eakin et al., 2015). HB: Huatung Basin; GR: Gagua Ridge; NLA: North Luzon Arc; WPB: West Philippine Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We further speculate why no subduction took place at the Gagua Ridge. Both the West Philippine Basin and the Huatung Basin move in the NNW direction and subduct under the Ryukyu Trench in response to the Pacific plate moving toward the Eurasian plate in the NNW direction. The internal deformation led to the uplift of the Gagua Ridge rather than subduction due to the strong rigidity of the Huatung Basin. The lack of strike-slip movement also prevented the West Philippine Basin from subducting beneath the

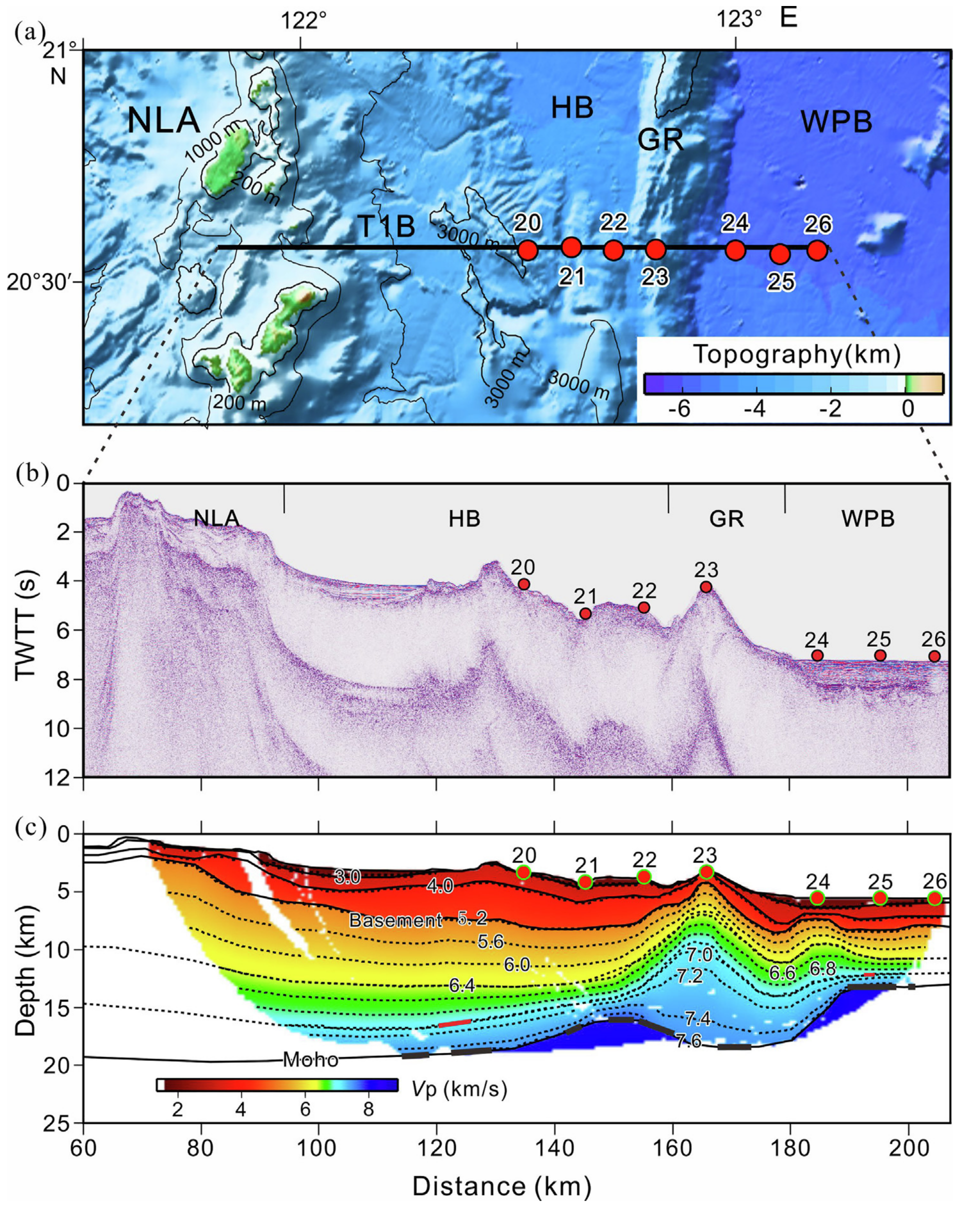

Fig. 8. (a) Location of the T1B line across the Gagua Ridge on a bathymetric map with major tectonic features and OBS stations; (b) Multi-channel seismic profile of T1B; (c) The velocity model of T1B. The black line in (a) represents the multiple-channel seismic line. Red circles represent OBS locations. TWTT means two-way travel time. The red and black thick lines in (c) indicate the identified high-velocity layer and Moho interface (Adapted from Pang et al., 2019). NLT: North Luzon Trough; NLA: North Luzon Arc; HB: Huatung Basin; GR: Gagua Ridge; WPB: West Philippine Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Huatung Basin. The structure of the Huatung Basin is thus controlled by compression-related uplift only. As the Manila subduction started, it accommodated most of the deformation that occurred at the Gagua Ridge. As a result, the subduction at the Gagua Ridge becomes less likely unless the strike-slip movement across it accelerates.

3.3. Possible evolution models of atypical subduction

Tectonic analysis of both the Mussau Trench and the Hjort Trench and their surrounding tectonic settings shows that these two atypical subductions are small in scale, located at the south of the Caroline-Pacific plate boundary and the south of the Australia-Pacific plate boundary in southern New Zealand, respectively. It becomes clear that subduction polarity reversal and strike-slip border in the north occur in both settings. Therefore, atypical subduction may be relatively small in scale and usually is feasible for a plate boundary with subduction polarity reversal and strike-slip boundary.

Comparison between the Hjort Trench and the Mussau Trench indicates that the former coincides with the extinct spreading center, and the latter is nearly perpendicular to the direction of the extinct spreading ridge. In view of this, we propose two possible and more specific geological evolution models of atypical subduction according to the characteristics of their geological settings (Fig. 9). The first scenario occurs when the plate boundary is approximately parallel to or coincident with the extinct spreading ridge affiliated with the young plate. It is assumed that the old oceanic plate moves northwestward toward the young plate, and the young plate begins to spread in the east-west direction (Fig. 9a). As the Euler pole of the plate boundary migrates southward, the plate boundary becomes increasingly curved, resulting

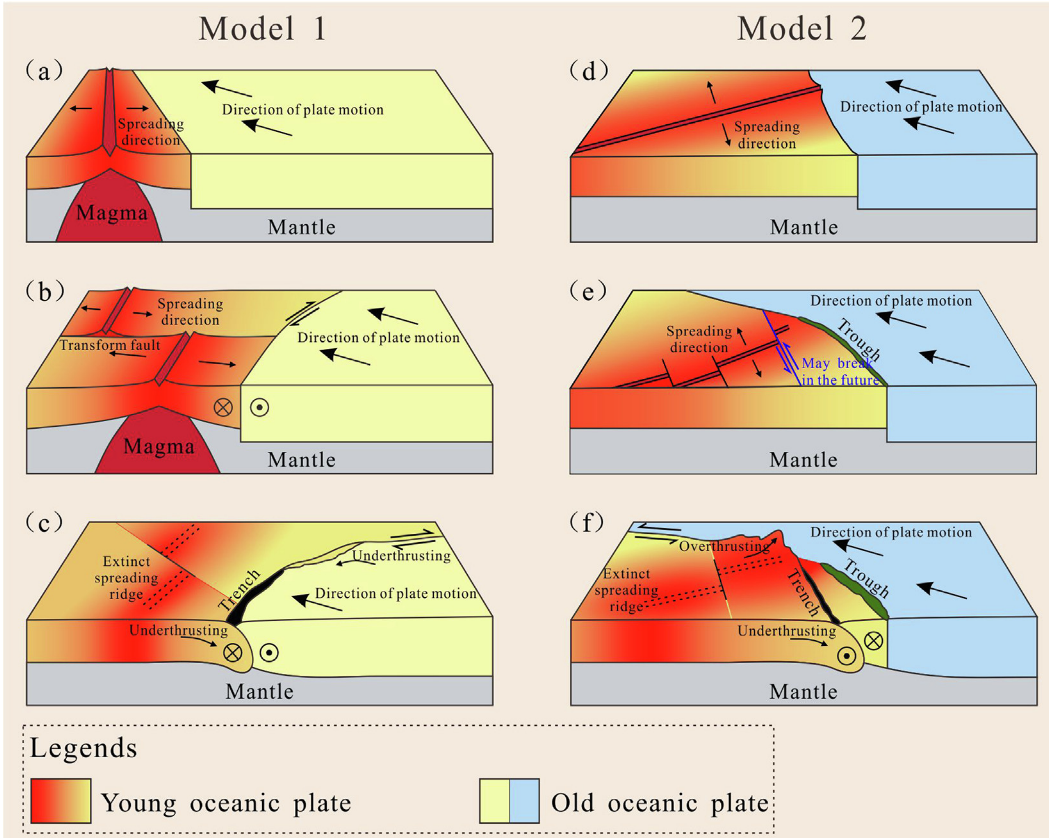

Fig. 9. Schematic diagrams of the geological evolutionary model for atypical subductions. Model 1(left column) shows the atypical subduction evolution processes when the plate boundary is parallel to the extinct spreading ridge. (a) The young plate begins to spread in the W–E direction, and the older plate moves along the NW toward the younger plate. (b) As the Euler pole of the plate boundary migrates southward, the motion at the border becomes progressively more strike-slip. (c) With the relative motion of the old and new plates, the transpression stress increases south of the plate boundary, leading to the young plate subducting underneath the old plate. Model 2 (right column) shows the atypical subduction evolution processes when the plate boundary is perpendicular to the extinct spreading ridge. (d) The young plate begins to spread in an NW–SE direction accompanied by clockwise rotation, and the old plate moves in the NW direction toward the young plate. (e) During the early stages of relative motion of the two plates, a trough serves as a plate boundary. (f) The mid-ocean ridge stops spreading, and subduction of the young plate underneath the old plate occurs along another transform fault, forming a new plate boundary. The red–yellow–blue colors indicate the increasing plate age. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in a strike-slip movement, and the continuous movement of the old plate leads to the transpressional stress in the south of the border (Fig. 9b). Under this transpressional condition, the newly formed, and thereby thermal and deformable plate will begin to subduct, leading to atypical subduction (Fig. 9c).

The second scenario occurs when the plate boundary is approximately perpendicular to the extinct spreading ridge affiliated with the young plate. It is assumed that the old oceanic plate moves northwestward toward the young plate, and the young plate starts to spread in an NW direction, accompanied by a slow clockwise rotation (Fig. 9d). In the early stage of the relative motion of the two plates, the plate boundary is bounded by a trough (Fig. 9e). As the young plate continuously rotates, the plate boundary gradually bends. The extrusion of the old plate into the young plate results in the transpression stress in the south of the border, which eventually leads to the young plate subducting to the old plate along another transform fault within it, forming atypical subduction (Fig. 9f).

4. Conclusions and prospect

In light of the tectonic features of three trenches, namely the Mussau Trench, the Hjort Trench, and the Gagua Ridge, we suggest that atypical subduction may form mainly when the plate boundary is of strike-slip-dominated transpression, particularly favored by the older plate moving toward the younger one. Such a model conflicts with the Gagua Ridge being of atypical subduction, as evidenced by the new velocity structure of the T1B survey line across the Gagua Ridge, which shows no structure at depth associated with subduction (Fig. 8). Two more specific geologic evolution models (Fig. 9) are proposed for atypical subduction by introducing a transpressional stress regime in some parts along their boundary. It is further suggested that the following two specific situations are favorable for starting new atypical subduction: 1) When the plate boundary is parallel to or coincident with an extinct spreading ridge affiliated with the young oceanic basin, the newly formed, and thereby thermal and deformable plate is more prone to subduct under the transpression environment; 2) When the plate boundary is nearly perpendicular to an extinct spreading ridge of the young oceanic basin, during the young basin spreading, a trough acts as the plate boundary. With the increasing transpressional stress, atypical subduction along another transform fault inside the young basin will be formed anticipatively. More importantly, it is also suggested that atypical subduction is usually small in scale and forms along a plate boundary with subduction polarity reversal and strike-slip movement.

The Mussau Trench was formed at ~1 Ma and the Hjort Trench at ~11 Ma, with no other new subduction zones surrounding them, which makes us wonder whether atypical subduction at both the Mussau Trench and the Hjort Trench can evolve into selfsustaining subduction or not. To answer this question, we should first constrain the crustal age at the east side of the Mussau Trench because it is still controversial. Further investigations are accordingly needed to improve understanding of the nature of the Mussau Trench and the initial conditions of atypical subduction. In addition, whether the Gagua Ridge will evolve into atypical subduction or not needs to be studied through numerical simulations in the future.

CRediT authorship contribution statement

Xingyue Wang: Conceptualization, Investigation, Writing – original draft. **Lingmin Cao:** Conceptualization, Writing – review & editing. **Minghui Zhao:** Supervision, Writing – review & editing. **Jinhui Cheng:** Writing – review & editing. **Xiaobo He:** Writing – review & editing.

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.

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