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A mega-splay fault system and tsunami hazard in the southern Ryukyu subduction zone

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ABSTRACT

In April 1771, a subduction earthquake generated a great tsunami that struck the south Ryukyu islands and killed ~12,000 people, whereas its mechanism is still enigmatic (Nakata and Kawana, 1995; Nakamura, 2006; Matsumoto et al., 2009). In this paper, we show its probable source on a mega-splay fault system existing along the southern Ryukyu forearc. Analyses of deep multi-channel seismic reflection profiles indicate that the mega-splay fault system is rising from the summit of a ~1 km high ridge situated at a ~5° landward dipping plate interface. An outer ridge marks the seafloor outcrop of the splay fault system and separates the landward inner wedge and the oceanward outer wedge. The inner wedge is uplifting and exhibits widespread normal faulting while the outer wedge shows folded structures. The mega-splay fault system is parallel to the Ryukyu Trench east of 125.5°E and is estimated to be ~450 km long. The origin of this south Ryukyu mega-splay fault system is ascribed to a resistant subduction of the elevated transverse ridges associated with the subducting portion of the trench-parallel Luzon–Okinawa Fracture Zone. In contrast, no similar splay fault is found west of 125.5°E where the oblique subduction has produced large shear zones along the south Ryukyu forearc. We infer that a thrust earthquake linked to the mega-splay fault system is responsible for the south Ryukyu tsunami. However, another possible scenario of generating a large tsunami affecting the south Ryukyu islands is that the subducted ridge in the western end of the mega-splay fault system nucleated a large earthquake and simultaneously triggered the ~100 km long E–W trending strike-slip fault west of 125.5°E and induced a southward-dipping tsunami-genic subsidence. In any case, after a quiescence of ~241 yr, a large earthquake and tsunami is anticipated in the south Ryukyu forearc in the near future.

1. Introduction

In subduction zones, convergent thrust faults usually occur in accretionary wedges and propagate trenchward in sequence. In contrast, several out-of-sequence thrust faults (splay faults) associated with great earthquakes are found in the Sunda (Sibuet et al., 2007), Nankai (Park et al., 2002; Moore et al., 2007), Ecuador–Colombia (Collot et al., 2004) and Alaska (Plafker, 1972) subduction zones. These splay faults, branching from plate interfaces with steep dipping angles near the seafloor, may generate devastating tsunamis in the nearby regions. This threat is emphasized by geodetic observation (Hsu et al., 2006) and theoretical modeling (Wang and Hu, 2006), which demonstrate that the splay fault and the plate interface beneath the inner wedge are co-seismically active, while the plate interface beneath the outer wedge slips post-seismically.

In the Ryukyu subduction zone, earthquakes of magnitude greater than 8 have not been recorded. However, in 1771 a devastating tsunami named Meiwa tsunami struck the south Ryukyu islands (Nakata and Kawana, 1995). The run-up exceeded 30 m and the main damage was reported on Ishigaki and Miyako Islands (Nakata and Kawana, 1995; Nakamura, 2006; Matsumoto et al., 2009). Reef boulders transported by the tsunami are distributed onshore along the southeast coast of Ishigaki Island (Goto et al., 2010), suggesting that the source of the Meiwa tsunami was located southeast of Ishigaki Island. Nakamura (2006) inferred that the 1771 tsunami was due to an earthquake near the Ryukyu Trench but no surface rupture was found yet. In fact, older reef boulders were found at even higher altitudes on Ishigaki Island, suggesting that great tsunamis larger than the Meiwa tsunami occurred intermittently in this area at an interval of several hundreds to one thousand years (Nakamura, 2006). In this study, we display four multichannel seismic reflection

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profiles across the south Ryukyu Trench to show the possible source of the earthquake related to the 1771 Meiwa tsunami and discuss the potential of a future large tsunami being generated in the southern Ryukyu subduction zone.

2. Tectonic background

Along the Ryukyu Trench, the Philippine Sea Plate (PSP) is subducting northwestward beneath the Eurasian Plate (EP) with a convergence rate of ~65 mm/yr near the south Ryukyu Trench (Seno et al., 1993) (Fig. 1). Near location J (~23.5°N and ~126°E) in Fig. 1, the Ryukyu Trench abruptly changes its orientation from ~N082° in the west to ~N052° in the east. In the east, the trench is relatively narrow and quasi-linear and the subduction direction is almost perpendicular to the trench orientation (Fig. 1). However, to the north of the Daito Ridge, the trench characteristic becomes unclear. The segment of the Ryukyu Trench between 126°E and 130°E almost coincides with the northeastward prolongation of the multi-stranded Luzon–Okinawa Fracture Zone (LOFZ), which is subducting northwestward beneath the Ryukyu forearc (Fig. 1). The subduction of the northeastern portion of the LOFZ has induced several NE–SW trending bathymetric undulation. From north to south, the orientation of the LOFZ has changed ~18° anticlockwise near the location J (Fig. 1). This change in orientation of the fracture zones could be linked to the change of seafloor spreading directions in the West Philippine Basin. This fact can be justified by examining the different orientations of the seafloor fabrics near the fracture zones: an orientation of ~N318° near 24.5°N and 128°E, but ~N300° near 21°N and 124.5°E (Fig. 1).

The LOFZ is also marked by the linear free-air gravity anomaly highs and lows (Fig. 2). The linear gravity highs may represent some transverse ridges formed due to tectonic transpression. Bathymetric and gravity highs also appear along the forearc off Miyako and Okinawa Islands (Figs. 1 and 2). The gravity high around 24°N and 126°E is particularly obvious and is close to the location J. In stark contrast, west of 125.5°E, there is no forearc gravity high but the forearc basins are well developed (Lallemand et al., 1999). Additionally, because the PSP/EP convergence direction is ~45° oblique to the trench, strain partition and trench-parallel right-lateral shear zones have developed in the

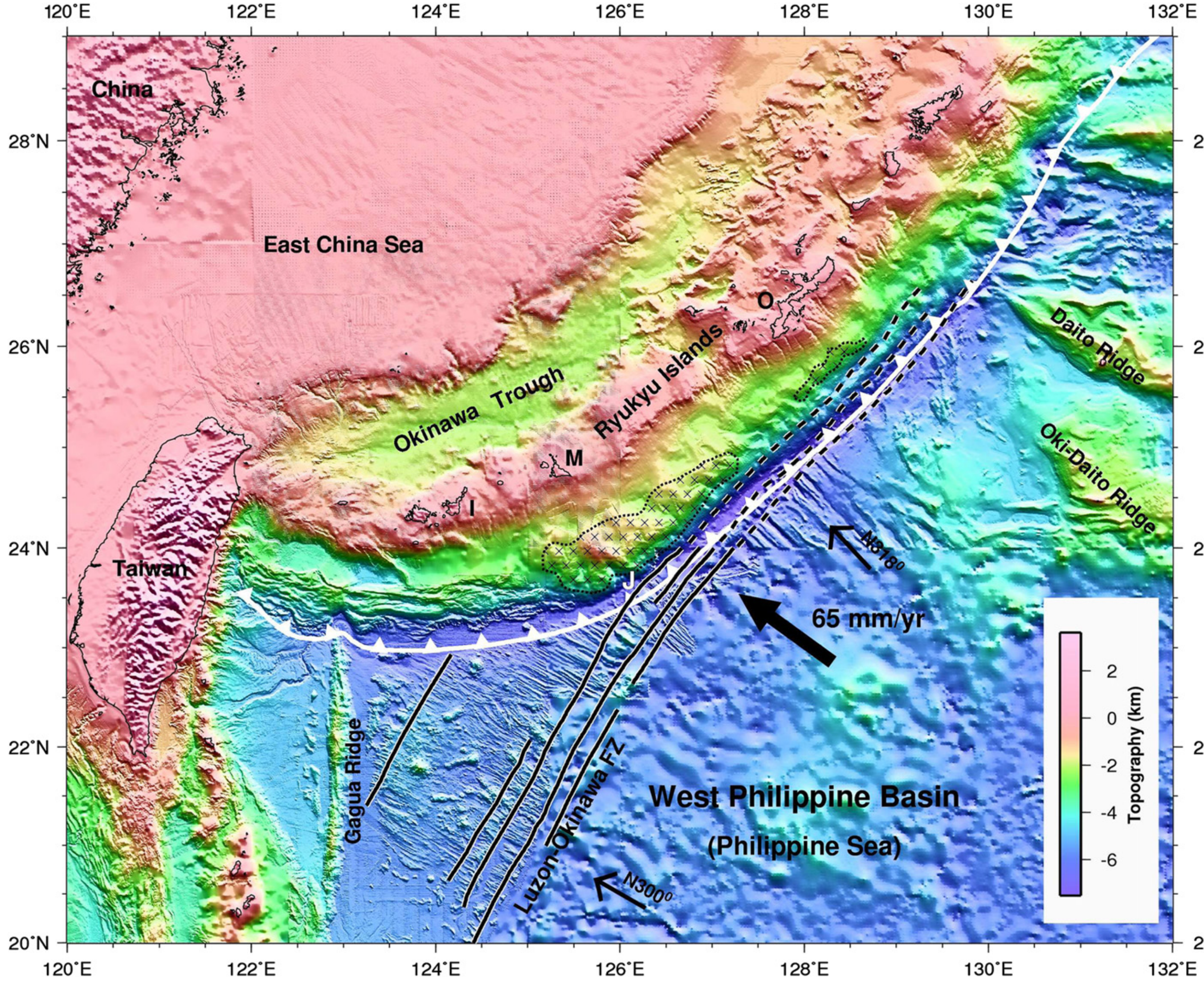

Fig. 1. Morphology of the study area. Black arrow indicates the convergent direction of the Philippine Sea Plate relative to the Eurasian Plate. Stippled areas indicate high gravity anomalies in the south Ryukyu forearc shown in Fig. 2. Note that the subduction is almost perpendicular to the Ryukyu Trench in the east of 125.5°E while the subduction is oblique in the west of 125.5°E. Note also that the orientation of the seafloor spreading fabrics near 24.5°N and 128°E is ~N318°, but it is ~N300° near 21°N and 124.5°E. FZ: Fracture zone; I: Ishigaki Island; M: Miyako Island; O: Okinawa Island.

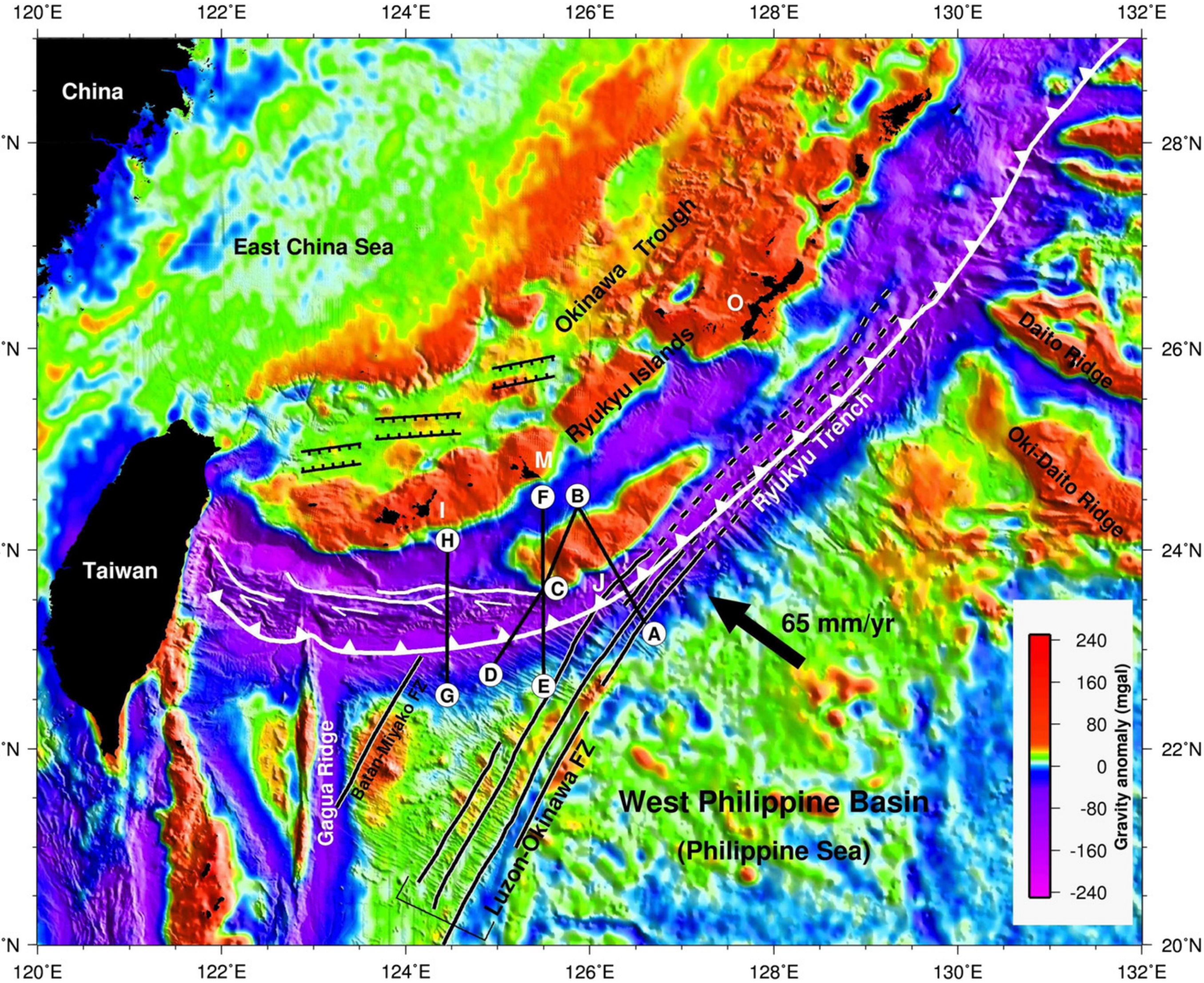

Fig. 2. Free-air gravity anomalies draped onto the bathymetry of the study area. White lines indicate the right-lateral shear zones in the southernmost Ryukyu forearc. Lines AB, BCD, EF and GH are the locations of seismic reflection profiles used in this study. FZ: Fracture zone; I: Ishigaki Island; M: Miyako Island; O: Okinawa Island.

accretionary wedge west of 125.5°E (Kao et al., 1998; Lallemand et al., 1999) (Fig. 2).

3. Seismic data processing and interpretation

During the TAIGER cruise in 2009, we have collected four 6-km-long multi-channel seismic (MCS) reflection profiles across the south Ryukyu Trench by using R/V *Marcus G. Langseth* with a 6600 c.i. air-gun source array (Fig. 2). The MCS profiles have been processed and a F–K migration was applied.

3.1. Mega-splay fault system

The easternmost MCS profile (Line AB in Fig. 2) shows a pronounced plate interface between the subducting PSP and the overriding EP, especially at the locations where the seismic phase shows an obvious negative-polarity reflection (Figs. 3 and A.1). The strong negative-polarity reflection indicates the existence of fluid in a high-porosity layer (Shipley et al., 1994). The clear stratification beneath the plate interface suggests that the relative plate motion has occurred along a sedimentary interface above the oceanic basement, where high-pressure fluid prevails (Fig. A.1) (e.g. Cloos and Shreve, 1988). The MCS profile AB also shows a ~30 km long thrust fault system that branches upward from the plate interface (red lines in Fig. 3). The thrust fault system cuts across sedimentary layers of the wedge and is an out-of-sequence thrust fault (splay fault) system. This splay fault system displays several branches, but as commonly observed in the Nankai Trough (Moore et al., 2007), none of them intersects with the seafloor. Negative-polarity seismic reflectors are also found in the splay fault system. Located at ~50 km landward from the trench axis and at a depth of ~6.5 s two-way-travel (TWT) time or ~11 km below the seafloor (Fig. A.2), the splay fault system rises from the summit of an elevated ridge on top of a ~5° landward dipping plate interface (Fig. A.2). Similar to the case in the Nankai Trough (Park et al., 2002; Moore et al., 2007), an outer ridge is observed near the updip end of the splay fault system (Fig. 3). Spatially, the outer ridge separates the inner wedge from the outer wedge. The inner wedge is intensively stretched as demonstrated by numerous normal faults in the top strata, whereas the outer wedge oppositely shows compressional folding features above the plate interface (Fig. 3).

Although there are several similarities between the south Ryukyu and the Nankai splay fault systems, there are some different features between these two systems. We use the outer

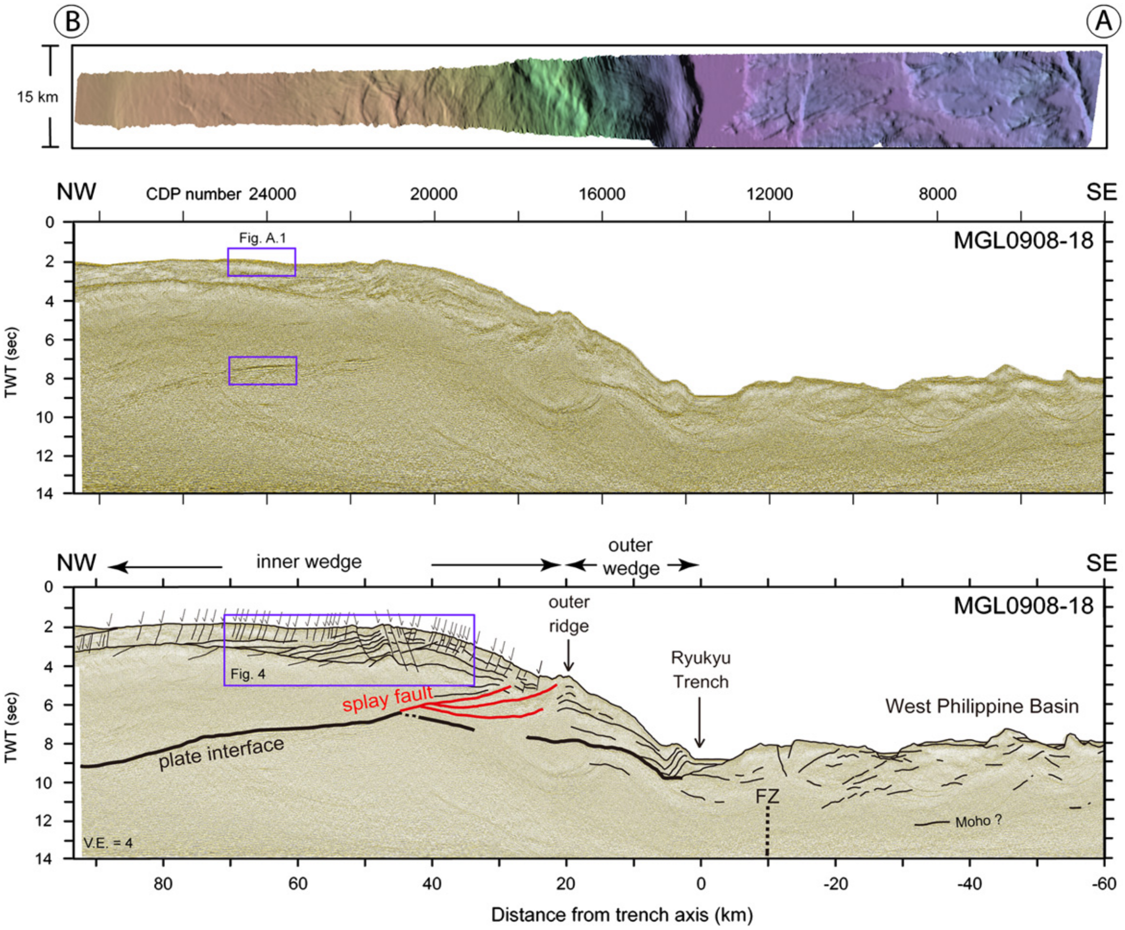

Fig. 3. Multi-beam bathymetric image and seismic reflection along profile AB (upper two panels, respectively). The seismic interpretations are shown in the lower panel. Red lines indicate the splay fault system. Blue boxes indicate portions of close-ups shown in Fig. 4 and Fig. A.1. FZ: Fracture zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ridges of the two systems as a fixed reference point even though the outer ridge in the southern Ryukyu subduction zone is ~1.5 km deeper than in the Nankai subduction zone. In that case, we can observe that the highest inner wedge is ~2 km higher and the trench is ~1 km lower in the southern Ryukyu subduction zone (Fig. A.2). Moreover, the horizontal position of the south Ryukyu Trench is ~10 km closer to the outer ridge. In other words, the plate coupling is much stronger in the southern Ryukyu subduction zone; thus, its overriding plate is seriously bent and dragged deeper along the plate interface. It implies that earthquake and tsunami hazard is much more imperative and vital in the southern Ryukyu subduction zone than in the Nankai subduction zone. However, a décollement is not observed beneath the outer wedge in the profile AB.

3.2. Deformation of the inner wedge and the outer wedge

As shown in Fig. 4, sedimentary layers L3 and L2 in the inner wedge display onlaps over the unconformity Ua between 54 and 66 km landward from the trench axis. Ua is tilted ~2.5° landward. Between 52 and 67 km, the tilted layers L7–L4 are roughly parallel to Ua but display onlaps over the unconformity Ub (Fig. 4), which means that Ub was rotated ~2.5° anticlockwise after the deposition of layer L4. Beneath Ub, the sedimentary layers are tilted ~4.5° landward, suggesting that prior to the deposition of layer L7, the inner wedge was rotated ~2° anticlockwise. The landward tilting of the strata implies that there were episodic uplifts on the seaward edge of the basin. Thus, there were at least two major tectonic events as indicated by Ua and Ub unconformities or two major slip events along the mega-splay fault, which uplifted the south Ryukyu forearc inner wedge. It indicates also that the megathrust splay faults are breaking backward (away from the trench) in an out-of-sequence thrust mode. In comparison with the interpretation of seismic stratigraphy by Park et al. (1998), the tectonic event of Ua possibly occurred in Pliocene. Currently, there are numerous small and active landward-dipping normal faults that widely spread in the top layer of the inner wedge (Figs. 3 and 4). It implies that the inner wedge is gradually bent. However, there are four larger seaward-dipping normal faults in the inner wedge and they even cut across unconformity Ub and the acoustic basement (Figs. 3 and 4). It indicates that a subducted ridge or seamount has passed beneath the inner wedge, which caused the conspicuous seaward subsidence.

The normal faults in the inner wedge reflect a decreasing stress of the splay fault system in current inter-seismic period. Because the uplifted center of the inner wedge is situated above a relatively high ridge of the subducted plate interface (Fig. 3), the subducted elevated relief could be the source of the strong plate coupling that causes the warping and tensile deformation of the inner wedge as well as the development of the splay fault system. On the other hand, the compressive features in the outer wedge could be generated during each post-seismic slipping along the plate interface beneath the outer wedge (Hsu et al., 2006). In

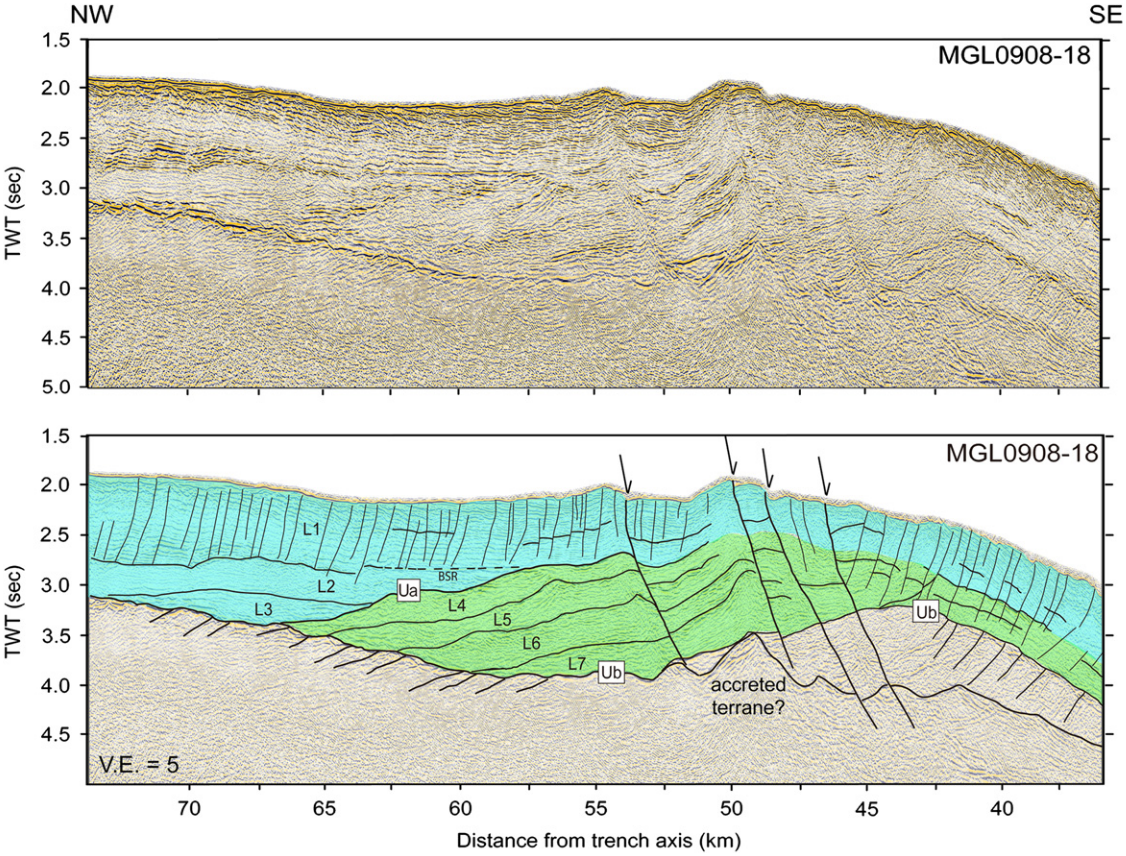

Fig. 4. Close-up of a portion of the extensional inner wedge, indicated by a blue rectangle in the lower panel of Fig. 3. Note that the warping inner wedge contains two major unconformities (Ua and Ub) and four major normal faults dipping seawards. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

response to megathrust earthquake cycles, the inter-seismic convex bending and normal faulting are also observed in the forearc in northern Chile (Shirzaei et al., 2012).

3.3. *Forearc strike-slip fault and décollement west of 125.5°E*

In contrast to the profile AB, the MCS profile GH crosses a strike-slip fault system along the southern end of the Ryukyu forearc (Lallemand et al., 1999) (Fig. 2). There is no clear distinction between the inner wedge and the outer wedge, but some in-sequence thrusts are observed along profile GH (Fig. 5). Besides, a décollement is observed beneath the accretionary prism and a forearc basin is well developed (Fig. 5). However, the forearc basin is separated from the rest of the accretionary prism by a major E–W trending left-lateral strike-slip fault (Figs. 2 and 5). The formation of the normal faults in this forearc basin could be due to a fast retreat of the subducted PSP or a strong decoupling between PSP and EU in this area (Hsu, 2001). In contrast, the normal faults in the inner wedge of profile AB is mainly due to a convex bending caused by the subduction of a locally elevated ridge and a strong coupling in the plate interface.

Between profiles AB and GH, the profiles BCD and EF are located in a transitional setting (Figs. 6 and 7). The splay faults rising from the subducted plate interface and the normal faulting in the inner wedge can also be observed in profiles BCD and EF. A décollement beneath the outer wedge is also observed in profile BCD and profile EF (Figs. 6 and 7). The overall structures of these two MCS profiles are quite similar to the mega-splay fault system in the Nankai Trough (Park et al., 2002).

4. Discussion

The outer ridge characterizes the updip end of the splay fault system. In terms of morphology, it may continue along the forearc from 125.5°E to 129.5°E (Fig. 1). In the north, the elongated distribution of the inner wedge spatially coincides with a free-air gravity anomaly high (Figs. 2 and 8), which is probably related to the doming of the inner wedge. Taking into account the high gravity anomaly distributed along the forearc off Miyako and Okinawa Islands, the splay fault system along the south Ryukyu forearc can extend up to ~450 km long, until the northwestern end of the Daito ridge (Fig. 2). Further north, the tectonic stress regime is different (Wu et al., 2010). Considering such a large scale, the splay fault system beneath the south Ryukyu forearc is regarded as a mega-splay fault system. Accordingly, we may ascribe the 1771 Meiwa tsunami and prehistoric larger tsunamis hitting the southern Ryukyu islands to great earthquakes that occurred intermittently along this south Ryukyu mega-splay fault system.

As shown in Fig. 1, several topographic features such as the Gagua Ridge or Daito Ridge are subducting or will subduct beneath the Ryukyu forearc. Such subducted oceanic plateaus, seamounts or ridges would increase the seismic coupling and recurrence intervals of great earthquakes (Scholz and Small, 1997). Although Mochizuki et al. (2008) suggested that interplate coupling over seamounts was weak because of the repeating earthquakes of magnitude M~7 in the Japan Trench, there was a 2011 Tohoku earthquake of M9 at almost the same seamount subducted interface (e.g. Lay et al., 2011). In the southern Ryukyu subduction zone, the undulated geometry of the oceanic basement

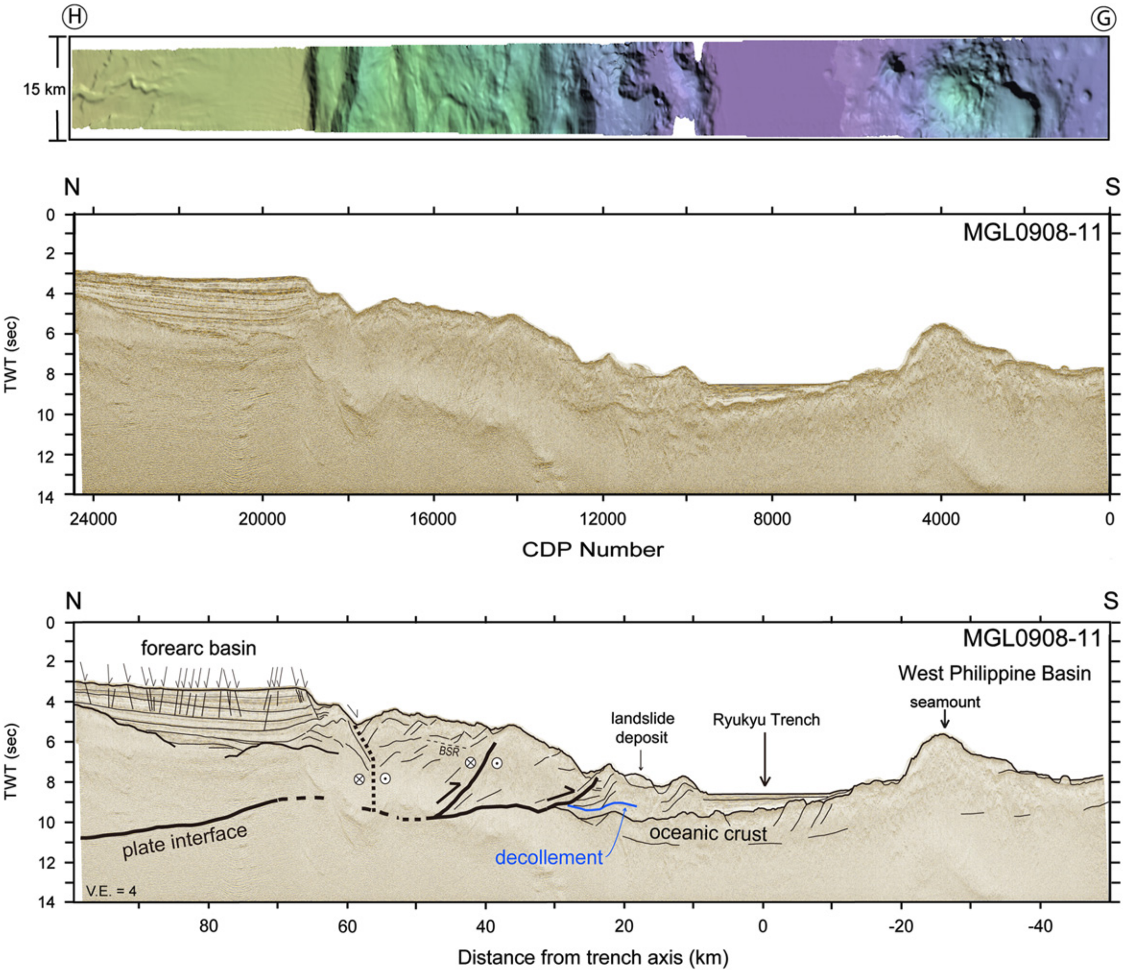

Fig. 5. Seismic reflection profile GH (middle panel) with seismic interpretation in the lower panel and multi-beam bathymetric image in the upper panel. Note that a major subsidence exists at the top of the strike-slip fault located at ~60 km landward from the trench (see map view in Fig. 2).

across the LOFZ provides the current roughness of the subducted plate interface. As revealed by the high gravity anomalies, the transverse ridges of the fracture zones in the West Philippine Basin can be recognized (Fig. 2). When the transverse ridges approach the Ryukyu Trench and subduct beneath the forearc, the undulated basement can cause the development of the splay faults. Because the transverse ridges or fracture zones along the trench are almost orthogonal to the subduction direction, a highly resistant subduction or a strong plate coupling is expected (Ando et al., 2009). It may explain why currently there are less subduction earthquakes of magnitude greater than 6 around the free-air gravity anomaly high areas of the south Ryukyu forearc (Fig. A.3).

How to relax the strong coupling and generate a mega-thrust earthquake along such a seismogenic zone is not clear. In any case, the high-pressure fluid, attested by the presence of the strong negative-polarity seismic reflection along the plate interface beneath the inner wedge, can effectively reduce the friction or seismic coupling along the plate interface (Hubbert and Rubey, 1959). A wide distribution of high-pressure fluid along the smooth plate interface landward of the outer ridge thus can release the lock of the seismogenic zone. As evidenced in Fig. 4, the inner wedge was episodically uplifted and two major unconformities were created. Furthermore, the steep angle of splay faults near the seafloor is effective in generating tsunamis. It indicates that the 1771 Meiwa tsunami and its associated earthquake are very probably ascribed to the mega-splay fault system in the southern Ryukyu subduction zone.

Another alternative source of generating large tsunamis affecting the south Ryukyu islands lies in the ~100 km long E–W trending strike-slip fault located at ~60 km landward from the trench in profile GH (Figs. 2 and 5). This strike-slip fault not only has a right-lateral motion component but also consists of a significant vertical offset of several hundred meters (Fig. 5). If the subducted ridge in the western end of the mega-splay fault system relaxes the plate interface coupling and causes a large earthquake, the strike-slip fault system may be simultaneously triggered; a large amount of subsidence or landslide can also be generated due to the sudden subduction of the elevated ridge. The current vertical offset at the top of the strike-slip fault could be accumulated due to several times of subsidence. In this scenario, this linear source of tsunami has a similar orientation and size as proposed by Nakamura (2009). Nevertheless, Nakamura (2009) suggested a thrust earthquake source along the plate interface near the Ryukyu Trench, while we suggest the tsunami-genic source lies in the ~15° trenchward-dipping scarp along the ~100 km long strike-slip fault. In view of the seafloor morphology, it seems that only this strike-slip fault system has such a large-scale offset that favors a large tsunami genesis (Fig. 2).

5. Conclusion

The tectonic features of the south Ryukyu forearc can be distinguished into two regimes. To the east of 125.5°E, the PSP

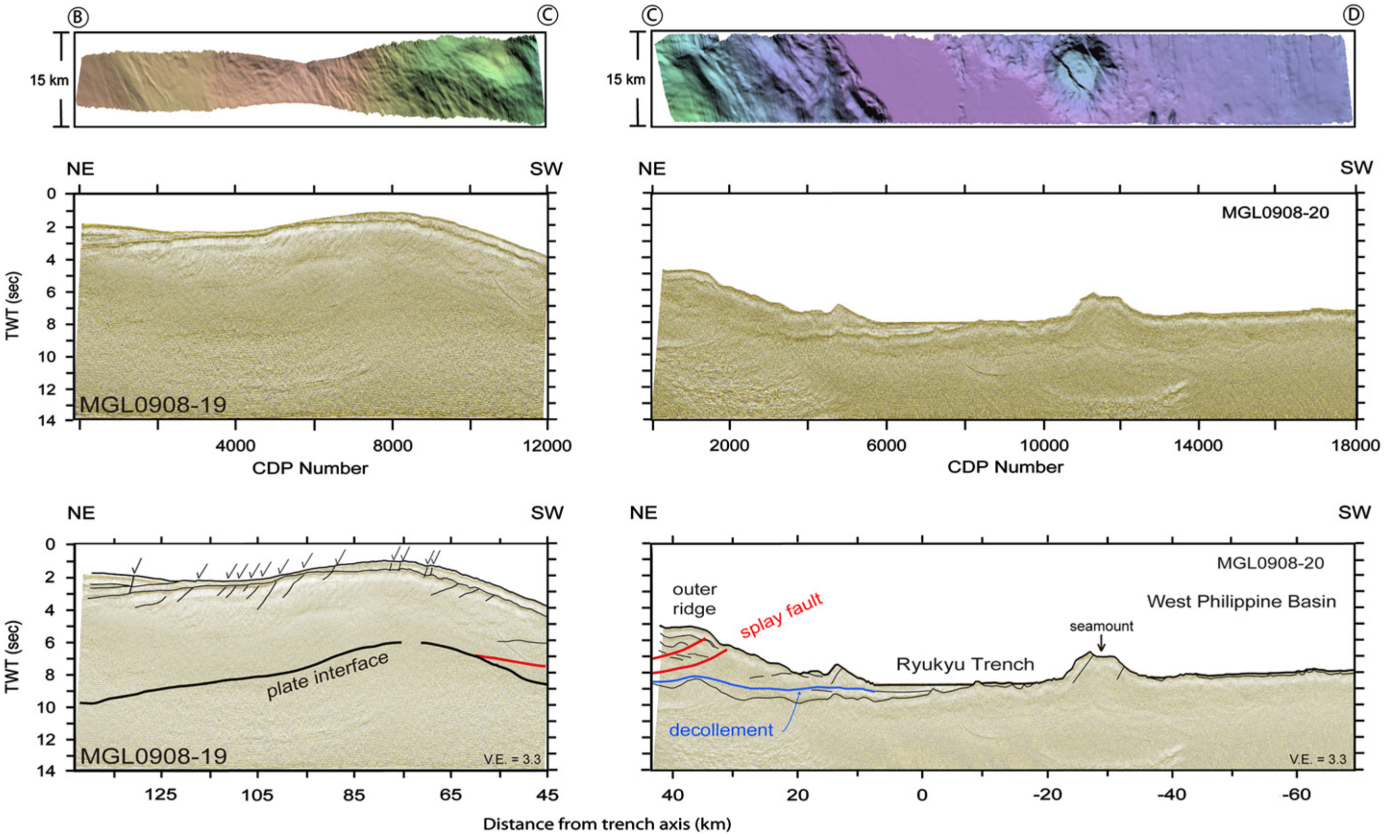

Fig. 6. Seismic reflection profile BCD (middle panel) with seismic interpretation in the lower panel and multi-beam bathymetric image in the upper panel.

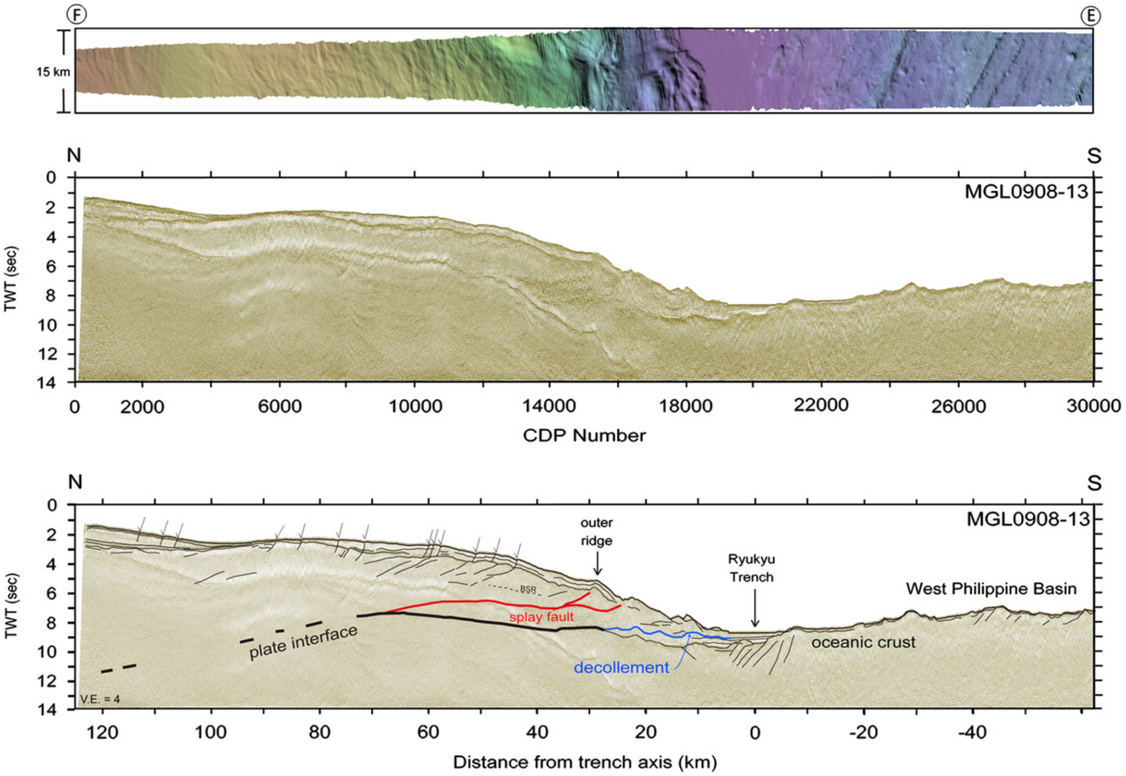

Fig. 7. Seismic reflection profile EF (middle panel) with seismic interpretation in the lower panel and multi-beam bathymetric image in the upper panel.

is almost perpendicularly subducting beneath the Ryukyu Arc, while to the west of 125.5°E the plate subduction is oblique to the Ryukyu Trench. In consequence, to the west of 125.5°E strain partitioning and trench-parallel strike-slip faults can be observed. In contrast, the mega-splay fault system has developed well to the east of 125.5°E. Its formation is attributed to the resistant

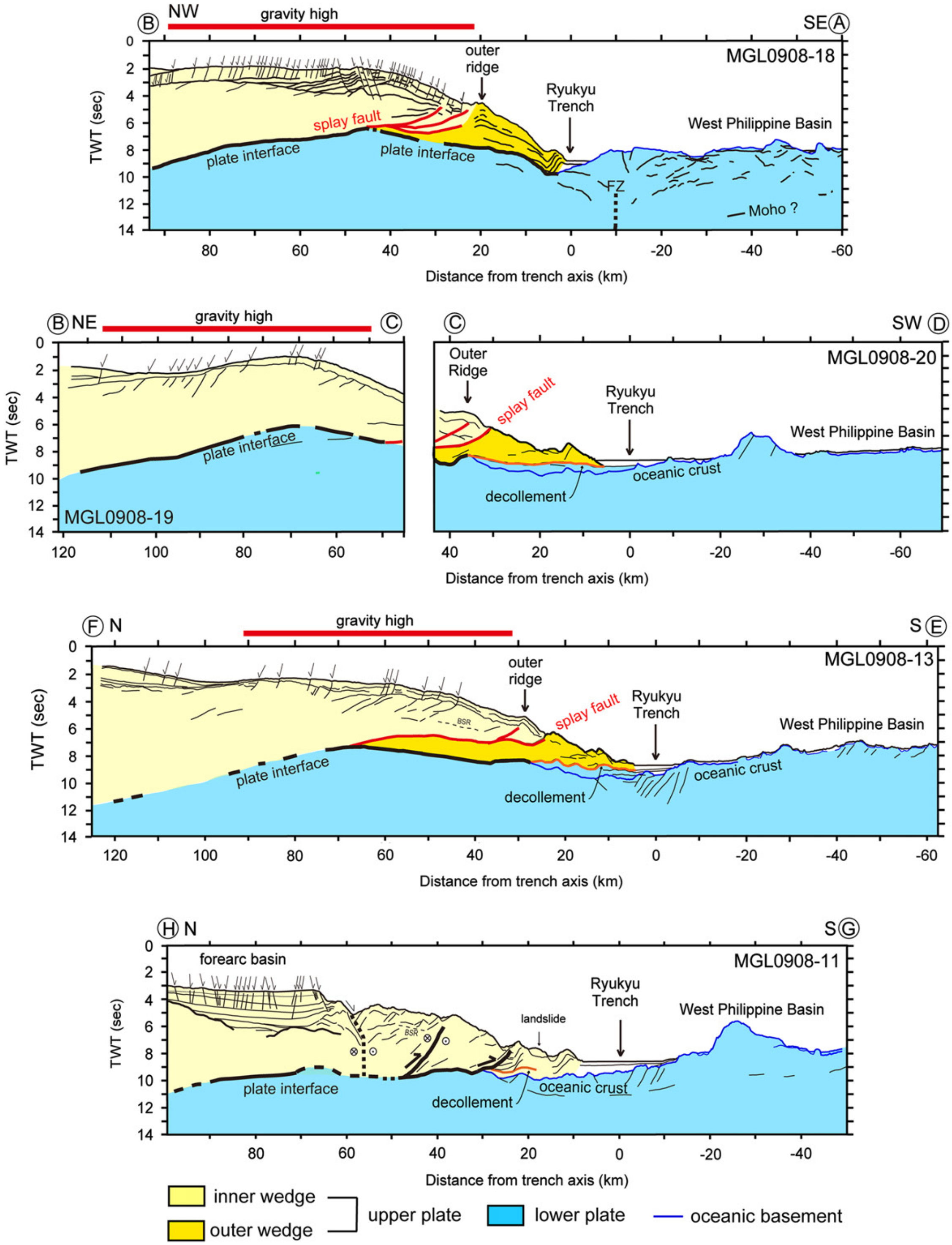

Fig. 8. A series of the seismic interpretations across the south Ryukyu Trench and forearc area. It is noted that the development of the splay fault system is associated with an elevated subducted ridge and a free-air gravity high.

subduction of the elevated ridges associated with the multi-stranded Luzon–Okinawa fracture zone whose orientation is almost parallel to the Ryukyu Trench.

Geometrically, the quasi-linear Ryukyu Trench, the subducted fracture zones and the gravity anomaly highs east of 125.5°E marks the spatial distribution of the mega-splay fault system along the south Ryukyu forearc. This system is not segmented until the Daito Ridge and is about 450 km long. Accordingly, historical megathrust earthquakes and tsunamis that occurred due to the activities of this splay fault system are not surprising. Currently, the plate coupling in the southern Ryukyu subduction zone is very strong; thus, extensional features are present throughout the inner wedge and the outer wedge is deeply dragged or rotated clockwise with a pivot at the outer ridge. High pore-pressure fluids also clearly exist along the plate interface of the seismogenic zone, which could effectively reduce seismic coupling and induce a megathrust earthquake. After a quiescence of ~241 yr, a potential great earthquake of magnitude ~8.5 can be expected in the south Ryukyu forearc in the near future. A devastating tsunami linked to the mega-splay fault system could again heavily strike the coastal regions of the Ryukyu islands, Taiwan, China, Korea, Japan and the Philippines. An integrated marine program for prevention observations or an early warning system for great earthquakes and tsunamis seems necessary in East Asia.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.epsl.2012.11.053.

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