Lin et al. Earth, Planets and Space 2014, 66:49
http://www.earth-planets-space.com/content/66/1/49

Earth, Planets and Space
a SpringerOpen Journal

FULL PAPER

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Could a Sumatra-like megathrust earthquake occur in the south Ryukyu subduction zone?

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Abstract

A comparison of the geological and geophysical environments between the Himalaya-Sumatra and Taiwan-Ryukyu collision-subduction systems revealed close tectonic similarities. Both regions are characterized by strongly oblique convergent processes and dominated by similar tectonic stress regimes. In the two areas, the intersections of the oceanic fracture zones with the subduction systems are characterized by trench-parallel high free-air gravity anomaly features in the fore-arcs and the epicenters of large earthquakes were located at the boundary between the positive and negative gravity anomalies. These event distributions and high-gravity anomalies indicate a strong coupling degree of the intersection area, which was probably induced by a strong resistance of the fracture features during the subduction. Moreover, the seismicity distribution in the Ryukyu area was very similar to the pre-seismic activity pattern of the 2004 Sumatra event. That is, thrust-type earthquakes with a trench-normal *P*-axis occurred frequently along the oceanward side of the mainshock, whereas only a few thrust earthquakes occurred along the continentward side. Therefore, the aseismic area located west of 128°E in the western Ryukyu subduction zone could have resulted from the strong plate locking effect beneath the high gravity anomaly zone. By analogy with the tectonic environment of the Sumatra subduction zone, the occurrence of a potential Sumatra-like earthquake in the south Ryukyu arc is highly likely and the rupture will mainly propagate continentward to fulfill the region of low seismicity (approximately 125° E to 129° E; 23° N to 26.5° N), which may generate a hazardous tsunami.

Background

The Mw 9.3 Sumatra-Andaman earthquake on December 26, 2004 was the second largest earthquake recorded during the last century. The earthquake triggered a significant uplift of the seafloor and induced a series of devastating tsunamis that attacked the coasts of most landmasses bordering the Indian Ocean. The tsunami run-up was up to 30 m high and over 230,000 people were killed in 14 countries (Paris et al. 2007). It is one of the deadliest natural disasters and is probably the most extensively analyzed earthquake-tsunami event in history. Since the occurrence of the Sumatra earthquake, the potential for the generation of tsunamis along subduction systems all around the world have been studied and several high risk areas have been identified (Cummins 2007; Gusiakov 2005; Liu et al. 2007).

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Methods

Empirical laws for the possible relation between the occurrences of large subduction zone earthquakes and the related tectonic parameters, such as the convergence rate, slab age, trench sediment thickness, bathymetric features, and plate motion, have been widely investigated (Kanamori, 1979; Pacheco et al., 1993; Peterson and Seno, 1984; Ruff and Kanamori 1983; Stein and Okal 2007; Uyeda and Kanamori 1979). A number of studies found that a faster convergence rate, older plate age, and higher upper plate absolute motion enhanced the triggering of the largest subduction zone events (Peterson and Seno 1984; Ruff and Kanamori 1983; Uyeda and Kanamori 1979), even though the validity of such correlations remains controversial (Pacheco et al. 1993). In less than one decade, several large subduction earthquakes occurred worldwide. Based on a more complex seismicity and subduction parameters catalog, Heuret et al. (2011) suggested that events with Mw ≥ 8.5 preferentially occurred in the vicinity of slab edges where the upper plate is continental and the back-arc strain neutral. Consequently, the occurrence of large subduction

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earthquakes seems to favor specific tectonic conditions and the comparison of the geodynamic environments of worldwide subduction zones with those of seismogenic areas where megathrust events occurred may help to identify high-risk potential zones. The Taiwan-Ryukyu margin, which is located at the westernmost corner of the western Philippine Sea plate, may present similarities with the Himalaya-Sumatra zone. In this study, we discuss the geophysical parameters, including plate tectonic framework, tectonic stress pattern, bathymetric characteristics, the spatial distributions of the oceanic fracture zones, and the gravity anomalies of these two subduction systems and suggest that a Sumatra-like earthquake may occur in the south Ryukyu fore-arc area.

Results

Similar geodynamic contexts for the Sumatra and Ryukyu subduction zones

Plate tectonic framework

In the Sumatra region, the Indo-Australian plate is subducting northwards beneath the Sunda plate at a rate of approximately 50 mm/yr (Briggs et al. 2006; Gahalaut and Gahalaut 2007; Paul et al. 2001), and it is colliding with the Eurasian continent to the west (Curray 2002; Paul et al. 2001). The age of the oceanic plate in the north Sumatra-Andaman area is about 60 to 80 Ma (Müller et al. 2008). The collision of the India plate with Asia results in the formation of the Himalaya Mountains and in the clockwise bending of the subduction front. From east to west along the Sunda and Andaman trenches, the plate convergence vector becomes oblique (Bock et al. 2003; Michel et al. 2001) (Figure 1a) and the slip is partitioned between the Sumatra trench and the right-lateral Sumatra fault system (Curray 1989; Fitch 1972; Genrich et al. 2000; McCaffrey 1991; McCaffrey et al. 2000; Prawirodirdjo et al. 1997). To the north, the Sumatra fault system is transformed into the spreading center of the Andaman Sea (Curray 1989).

Likewise, the Philippine Sea plate (PHS) subducts beneath the Eurasian plate (EU) along the Suruga-Nankai trough and Ryukyu trench at a rate of 80 to 85 mm/year in a 300 to 310° N direction (Yu et al. 1997) (Figure 1b). The age of the west Philippine basin is roughly 30 to 60 Ma (Hall et al. 1995), which is on the same order as that of the north Sumatra-Andaman area. The Luzon volcanic arc, which belongs to the PHS, collides westward with the EU margin and creates the Taiwan Mountains. Thus, the deformation of the Chinese passive margin by the Luzon arc indenter produced a clockwise bend of the southern Ryukyu arc (Letouzey and Kimura 1985; Sibuet et al. 1987), and the subduction of the PHS, which occurs at an oblique angle of about 40° E of Taiwan (Lallemand et al. 1999). Similar to the Sumatra fault system, the median tectonic line (MTL) is a right-lateral shear fault (Kimura 1996), which follows the onland arc volcanoes and is prolonged southwestward by the Okinawa trough back-arc basin.

Tectonic stress pattern

The stress orientations retrieved from the World Stress Map (WSM) (http://dc-app3-14.gfz-potsdam.de/) (Heidbach et al. 2010) as well as the *P*- and *T*-axes distribution calculated from focal mechanisms extracted from the Global centroid-moment-tensor (CMT) catalog during the period between 1976 and December 25, 2004 for the Sumatra area and between 1976 and the end of 2011 for the Ryukyu area are shown in Figure 1c,d, respectively. On the basis of the stress regime and epicenter distribution, the focal mechanisms of the Sumatra and Ryukyu subduction zones were further divided into groups in terms of *P*- and *T*-axes orientations. Groups 1 and 2 represent the thrust and extensional events that occurred along the subduction zone (yellow contour in Figure 1c,d); group 3 illustrates the earthquakes located along the collisional front (yellow dashed contour in Figure 1c,d); and group 4 depicts the events occurring within the oceanic plate (yellow dotted contour in Figure 1c,d). The spatial pattern of the stress regime along the Himalaya-Sumatra collision-subduction zone is in good agreement with that along the Taiwan-Ryukyu collision-subduction zone. Specifically, thrust events with a *P*-axis perpendicular to the trend of the arcs dominate in the subduction areas (group 1 in Figure 1c,d), whereas those with a *P*-axis sub-parallel to the relative plate motion vector occur around the colliding areas (group 3 in Figure 1c,d). Almost all the extensional earthquakes with a trench-parallel *P*-axis occur in the seaward portion of the collision-subduction system, east of approximately 100° E for the Sumatra subduction system and east of approximately 126° E for the Ryukyu subduction system (red bars in Figure 1c,d). These extensional events are characterized by a vertical *P*-axis and a scattered *T*-axis distribution probably resulting from changes in the trench geometry (group 2 in Figure 1c,d) (Engdahl et al. 2007; Tanaka et al. 2006). Besides, it is noticeable that for the strike slip and thrust earthquakes occurring in the oceanic domain of the subducting plate, their *T*-axis shows a trench perpendicular direction whereas the *P*-axis is proximately sub-parallel to the relative plate motion (group 4 in Figure 1c,d). Such a stress pattern shows that large portions of the Indo-Australian and PHS are widely affected by the NW-SE compressive deformation due to the collision processes in spite of their large distance from the orogenic belts (Chamot-Rooke et al. 1993; Lin et al. 2013).

Bathymetric characteristics, oceanic fracture zones, and gravity anomalies

The large-scale features of the oceanic plate observed in the Indo-Australia plate are the Ninety East ridge and

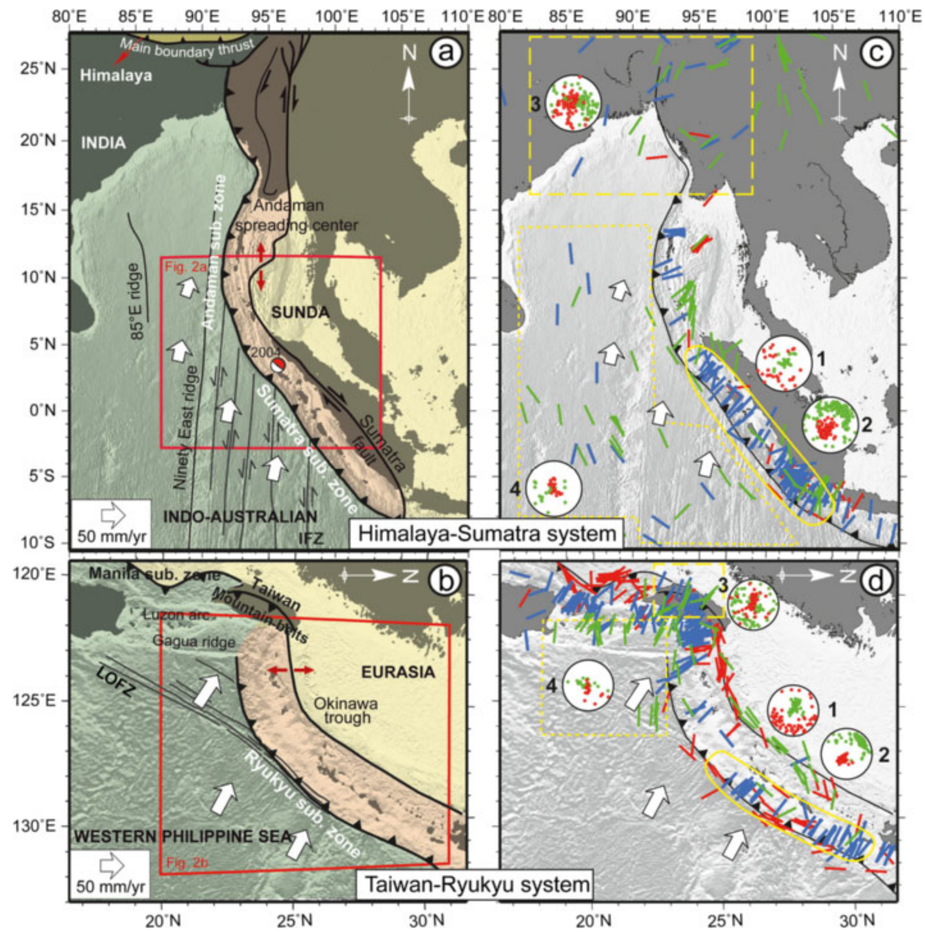

Figure 1 Tectonic context. Of the **(a)** Himalaya-Sumatra and **(b)** Taiwan-Ryukyu collision subduction systems. The red beach ball shows the location and focal mechanism of the Mw 9.3 Sumatra-Andaman earthquake on December 26, 2004. The red rectangle shows the position of Figure 2. LOFZ, Luzon-Okinawa fracture zone; IFZ, Investigator fracture zone. **(c, d)** The color bars show the stress orientations obtained from different fault types, which were retrieved from the World Stress Map (WSM) (http://dc-app3-14.gfz-potsdam.de/) (Heidbach et al. 2010). Red indicates normal faulting, green indicates strike slip, and blue indicates thrust faulting. Numbered circles show the orientations of the *P*-axis (red dot) and *T*-axis (green dot) in an equal-area projection of the lower hemispheres of the focal spheres from the global centroid-moment-tensor (CMT) catalog from 1976 to December 26, 2004 for the Sumatra subduction system and from 1976 to December 31, 2011 along the Ryukyu subduction system. The patterns for groups 1 and 2 were calculated from the thrust and normal faulting earthquakes along the subduction zone shown by the yellow contour, respectively. Group 3 used the events in the collision zones (yellow dashed contour), and group 4 used the events in the oceanic domain of the subducting plate (yellow dotted contour). Relative plate motions, shown by the white arrows, are based on the MORVEL model from the plate motion calculator (http://www.unavco.org/community_science/science-support/crustal_motion/dxdt/model.html) (DeMets et al. 2010).

the Investigator Fracture Zone (IFZ) (98° E) (Larson et al. 1978) (Figure 1a). In between these features, a set of roughly N-S sub-parallel fracture zones were identified from bathymetric, gravity, magnetic, and seismic data (Barckhausen 2006; Delescluse and Chamot-Rooke 2007; Deplus et al. 1998; Lin et al. 2009; Sibuet et al. 2007) (Figures 1a and 2a). Similarly, several major NE-SW-oriented fracture zones have been defined using bathymetric and magnetic data in the western PHS (e.g. Deschamps and Lallemand 2002; Hsu et al. 2013). Among them, the Luzon-Okinawa fracture zone (LOFZ) is the largest of these features (Figure 1b and 2c) (Hsu et al. 2013). Based on seismic profile interpretations and seismicity distribution, all these fracture zones subduct below the EU, which leads to kinks in the trend of the deformation front (Deplus et al. 1998; Hsu et al. 2013; Kopp and Kukowski 2003; Lange et al. 2010), and this is thought to influence the rupture behavior of major earthquakes (Abercrombie and Ekström 2001; Bilek et al. 2003).

In both subduction systems, the free-air gravity anomaly generally displays positive values for the oceanic plates and portions of fore-arcs (Figure 2b,d). In the Ryukyu subduction zone, the entire fore-arc has a low anomaly value expect in the area where the LOFZ intersects the Ryukyu trench (approximately 125° E to 129° E; 23° N to 26.5° N) (Figure 2d). Similarly, in the Sumatra

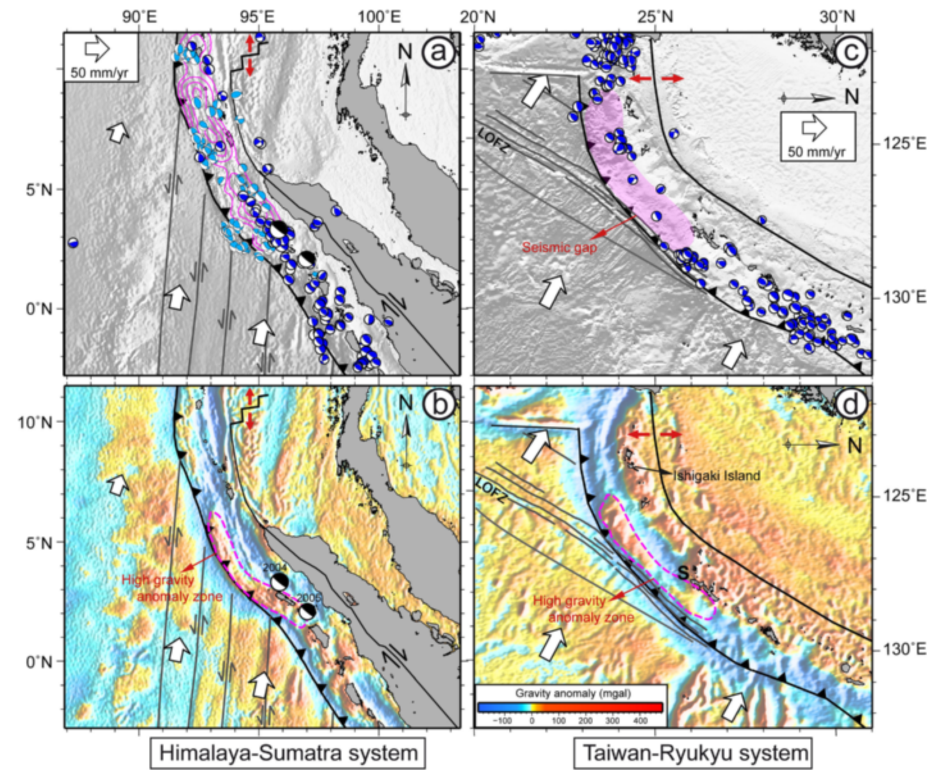

Figure 2 Focal mechanisms of the thrust-type earthquakes extracted from the Global CMT catalog. (a) Along the Sumatra subduction system from 1976 to 25 December 2004 and **(c)** along the Ryukyu subduction system from 1976 to December 31, 2011 are shown. Deep blue beach balls show focal mechanisms. Co-seismic slip contours every 5 m of the 2004 great Sumatra earthquake shown in pink in (a) are from Chlieh et al. (2007). Pink light areas show the aseismic zones. **(b, d)** The free-air gravity anomaly. Purple dashed contours show the high free-air gravity anomalies in the fore-arc areas. The letter 'S' shows the possible mainshock area if a Sumatra-like earthquake were to occur in the Ryukyu fore-arc. The black focal mechanisms in (a) and (b) show the positions of the 2004 and 2005 mainshocks.

subduction system, a high gravity anomaly zone exists behind the trench (approximately 93° E to 97° E and 2.5° N to 6° N), where series of fracture zones intersect the Sumatra trench (Figure 2b). The size of the two positive free-air gravity anomalies is similar (about 450 km long).

Discussion

The role played by the oceanic fracture zones and their orientation

Müller and Landgrebe (2012) have proposed that the fracture zones are characterized by continuous, uplifted ridges, which could be at the origin of strong, persistent coupling at the plate interface. Therefore, the occurrence of large subduction earthquakes (magnitude >8) is strongly biased towards regions at the intersections of oceanic fracture and subduction zones. This observation is supported by the occurrences of the 2004 Sumatra and 2005 Nias earthquakes, which were both located in areas where the IFZ subridges enter the Sumatra trench (Figure 2a,b). As shown by Figures 1 and 2 and in the previous section, the presence of fracture zones is apparent on both the Indo-Australian and PHS subducting plates. When entering in the subduction system, these fracture zones generally change the trench morphology, which is suggestive of a high resistance of the fracture zone against the subduction (Hsu et al. 2013; Lin et al. 2009). In addition, a trench-parallel high gravity anomaly zones are located at the intersection of the oceanic fracture ridges and the subduction zone, on the landward side of the trench wall for both subduction systems. These gravity anomaly high patterns could be the result of the presence of oceanic fracture zone material stuck beneath the accretionary wedge area (Hsu et al. 2013; Lin et al. 2009), which also suggests that the high resistance of fracture zones could cause a strong coupling environment (Hsu 2001) and block the subduction system. It is worthnoting that epicenters of the 2004 Sumatra and 2005 Nias earthquakes were located on the eastern border of the trench-parallel high anomaly zone at the boundary between the positive and negative gravity anomalies (Figure 2b). Consequently, if this epicenter location of the Sumatra earthquakes is transferred to the Ryukyu subduction system, a possible location for a Sumatra-like earthquake in the Ryukyu area would be in area S (Figure 2d), at the junction of positive and negative gravity anomalies along the boundary of the trench-parallel high anomaly. In addition, the size of the positive free-air gravity anomaly in the both areas is similar (about 450 km long). We therefore infer that the magnitude of a potential earthquake occurring in the Ryukyu fore-arc area could be as large as the 2004 Sumatra earthquake under the premise that the whole potential source area would rupture simultaneously.

Otherwise, the angle between fracture zone directions and the plate motion are different for the two subduction zones and amount to about 120° and 0° for the Ryukyu and Sunda subduction zones, respectively (Figures 1 and 2). Based on the distribution of the principle stress axes, the occurrence of earthquakes seems to be mostly controlled by the regional stress regime, i.e., the relative plate motion and the slab-pull mechanism that are caused by the plate collision and subduction processes (Chamot-Rooke et al. 1993; Lin et al. 2013; Yue et al. 2012). It means that even the presence of fracture zones in a subduction system could result in slab coupling in the fore-arc area; their orientation seems to have a relatively small influence on the tectonic stress regime, which greatly affects the seismogenic characteristics of a subduction system. In addition, Müller and Landgrebe (2012) show that the dimension of topographic highs of the oceanic subducting plate is the main factor controlling the megathrust seismogenic potential of a subduction system. What this means is that the fracture zones characterized by laterally continuous ridges and high degrees of structural integrity could cause a strong coupling effect; small volcanic chains present a relatively fragile internal structure, which results in a weak coupling. However, the impact induced by the fracture zone orientation appears to have been neglected. Therefore, we suggest that the difference of fracture zone directions with respect to the two subduction systems may not influence the subduction processes as well as change the seismogenic characteristics.

Pre-seismic distribution of earthquakes

In Figure 2a,b, the distribution of earthquakes along the Sumatra and Ryukyu subduction is extracted from the Global CMT catalog. Before the 2004 Sumatra earthquake, the thrust earthquakes with a trench-normal *P*-axis extended over the fore-arc area to the southeast of the 2004 mainshock source area (deep blue beach balls in Figure 2a). In contrast, only a few earthquakes were observed in the fore-arc region to the north, which implies that the slab interface north of the mainshock area has been locked and seismic strain has accumulated (Engdahl et al. 2007). During the occurrence of the 2004 mainshock, the accumulated seismic strain was released and the rupture propagated northward (pink contours in Figure 2a) (Chlieh et al. 2007) inducing a huge number of thrust-type events along the trench.

Along the Ryukyu subduction zone, thrust events with a trench-normal *P*-axis are numerous in the vicinity of the trench and fore-arc region, east of the high free-air gravity anomalies (approximately east of 128° E) (Figure 2c,d). However, the seismicity disappears west of this boundary. This spatial distribution of seismic activity is in accord with the pre-seismic pattern of the 2004 Sumatra earthquake (Figure 2a): the thrust earthquakes with a trench-normal *P*-axis occurred frequently on the oceanward side of the mainshock area, whereas few thrust-type earthquakes occurred in the cotinentward side. The area located west of 128° E with a low seismicity distribution could be locked between the interface of the PHS and EU along the high free-air gravity anomaly zone and may correspond to a potential rupture area (pink light area in Figure 2c). Therefore, if a Sumatra-like earthquake occurs in the vicinity of 128° E (area S), as was mentioned in the previous section, we would expect to see a westward rupture propagation (pink light area in Figure 2c) and the occurrence of thrust-type earthquakes along the present-day aseismic zone in the area west of 128° E.

Tsunamogenic potential

In April 1771, a subduction earthquake generated a very large tsunami that struck the south Ryukyu Islands and killed approximately 12,000 people (Ando et al. 2009; Matsumoto et al. 2009; Nakamura 2006, 2009). Reef boulders of building size were transported by the tsunami to beaches along the east and southeast coasts of Ishigaki Island (Goto et al. 2010), which suggests that the source of the tsunami was located east and southeast of Ishigaki Island (Figure 2d). As discussed in the previous section, if a Sumatra-like earthquake occurs along the Ryukyu subduction zone in the vicinity of 128° E (area S), there will be a westward propagation of the rupture. This westward rupture movement could be a possible tsunami source similar to the 2004 Sumatra earthquake. Moreover, based on seismic profile interpretations, Hsu et al. (2013) demonstrated the presence of a splay fault system within the trench-parallel high gravity anomaly area of the Ryukyu subduction zone, where a highly resistant subduction due to the integration of significantly developed fracture zones or strong plate coupling is expected (Ando et al. 2009). Similar splay faults have been reported along the Sumatra subduction zone (Sibuet et al. 2007). They branch at the plate interface, present steep dipping angles near the seafloor, and may have generated the devastating tsunamis. As a result, if a Sumatra-like earthquake occurs in the south Ryukyu fore-arc area, this may also trigger a tsunami similar to that during the 2004 Sumatra earthquake and induce serious damage.

Large historical interplate earthquakes along the subduction system

Although the tectonic similarity between the Sumatra and Ryukyu subduction systems was denoted, these regions have differences as regards to the occurrence of large historical interplate earthquakes, according to previous studies. Magnitude 8 to 9 class interplate earthquakes occurred frequently in the region of the Sumatra trench, such as the 1797 earthquake (Mw 8.7 to 8.9), the 1833 earthquake (Mw 8.8 to 9.2), and the 1861 earthquake (Mw 8.5). In contrast, the risk of great earthquakes and tsunamis was assumed to be low in the Ryukyu trench because the interplate coupling appeared to be weak and great interplate earthquakes (Mw >8.0) had not been recorded historically for about 300 years. However, Nakamura (2013) revealed that the 1771 Yaeyama earthquake (Mw 8.5 from the tsunami height distribution) in the south Ryukyu subduction zone and the 1911 Kikaijima earthquake (Mw 8.0) in the north-central Ryukyu subduction zone were interplate earthquakes. In addition, two historical tsunamis occurred in 1768 and 1791 on Okinawa Island, and it has been suggested that these were induced by two Mw 8 interplate earthquakes that occurred around the Ryukyu trench on the basis of the source fault model for these two tsunami events (Nakamura 2013). Consequently, the lack of large historic earthquakes along the Ryukyu subduction zone may be due to incomplete records in old documents. Meanwhile, a much higher concentration of oceanic fracture zones can be observed in the Indo-Australian plate than in the PHS. As the subduction of fracture zones can cause larger earthquakes (Müller and Landgrebe 2012), this suggests that there may be a higher possibility for the occurrence of large earthquakes along the Sumatra subduction area.

Comparison with other studies

The tectonic similarity between the Sumatra and Ryukyu subduction systems has been already raised by Hsu and Sibuet (2005), and they suggested that there was a potential megathrust earthquake in the Nankai area. Based on more detailed analyses, we found a closer tectonic similarity between the southwestern Ryukyu and Sumatra subduction zoned: the area S in Figure 2d appears to be a possible location for a Sumatra-like earthquake along the Ryukyu subduction zone. Based on a geodetic analysis, Hsu et al. (2012) suggested that the plate interface of the southernmost Ryukyu subduction zone is fully locked and a potential large earthquake (Mw 7.5 to 8.7) and tsunami might occur in the region. However, if the most southwestern end of the Ryukyu subduction zone was totally locked, the overriding EU plate should be closely contacted with the subducting PHS and largely affected by a compressional stress regime. With this hypothesis, it is difficult to explain the continued opening of the Okinawa trough and the southern migration of the Ryukyu arc already evidenced by geological, geodetic, and seismic data (Sibuet and Hsu 1997; Sibuet et al. 2007). Therefore, we propose that the strong coupling area is located at the intersection of the oceanic fracture ridges and the subduction zone, which block the western movement of the subducting plate resulting in low seismic activity in the southernmost Ryukyu subduction zone (approximately 125° E to 129° E; 23° N to 26.5° N).

Conclusions

In this study, we evaluated the seismic risk along the Ryukyu subduction zone by examining the similarity in tectonic environments between the Himalaya-Sumatra and Taiwan-Ryukyu collision-subduction systems. We found that both of the two systems share the four following common geodynamic contexts. (1) The Indo-Australian plate is subducting beneath the Sunda plate and the Indian portion of the plate collides with the Eurasian continent resulting in the formation of the Himalaya Mountains. Similarly, the Philippine Sea plate subducts beneath the EU and the Luzon volcanic arc creating the Taiwan orogen. (2) Owing to the collisional process, the subduction fronts started to bend clockwise resulting in an oblique subduction and associated partitioning. (3) Oceanic fracture zones with high topographic features exist on both subducting oceanic plates. The intersections of such fracture zones with the subduction systems are associated with trench-parallel gravity highs where the foci of large earthquakes, such as the 2004 Sumatra and the 2005 Nias earthquakes, are located. The locations of these mainshocks may be related to the strong plate coupling resulting from the high resistance of the fracture zones. (4) The spatial distribution of the earthquakes along the Ryukyu arc-trench system is very similar to the pre-seismic activity pattern of the 2004 Sumatra earthquake: the thrust earthquakes with a trench-normal *P*-axis occur frequently in the oceanward side of the mainshock area, whereas few thrust-type earthquakes occur in the continentward side.

From the similarities in geodynamic contexts between the Sumatra and Ryukyu subduction zones, we suggest that a potential Sumatra-like earthquake may occur along the border of the high gravity anomaly zone located in the fore-arc area of the Ryukyu subduction zone and the present low seismicity area in its western part should correspond to the possible co-seismic rupture area. Such a potential earthquake could generate a risky tsunami that would threaten many countries in Eastern Asia.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions
All authors have been involved in drafting the manuscript or revising it critically for important intellectual content. JYL has made substantial contributions to conception of data. All authors read and approved the final manuscript.

Acknowledgements
We thank two anonymous reviewers for their careful reviews which help a lot to improve this manuscript. Figures were prepared with the Generic Mapping Tool (GMT) software (Wessel and Smith 1998). This research was supported by the Taiwan Earthquake Research Center (TEC) and funded through Ministry of Science and Technology (MOST) with grant numbers MOST-103-3113-M-008-001 and NSC-102-2116-M-008-024. The TEC contribution number for this article is 00104.

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Received: 19 November 2013 Accepted: 26 May 2014
Published: 9 June 2014

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doi:10.1186/1880-5981-66-49
Cite this article as: Lin *et al.*: Could a Sumatra-like megathrust earthquake occur in the south Ryukyu subduction zone? *Earth, Planets and Space* 2014 **66**:49.

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