The growth of forearc basins along the oblique western Sunda subduction zone and its implication to seismic hazards

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Abstract. The growth of forearc basins in an oblique subduction system has been proposed to have related to strike-slip faulting due to strain partitioning. We reviewed several models of the primary controls on the evolution of the forearc basin in the western Sunda subduction zone: formation of the sliver plate, the occurrence of continental backstop, development of strike-slip faults traversing the basins, flexure, and uplift of the forearc high. It appears that the major control of the subsidence of the basin is due to the uplift of forearc high. However, the present day morphology of the forearc high and forearc basin seems to have been largely controlled by the subduction of roughness morphology on the oceanic crust. The occurrence of subducting bathymetric highs on the oceanic crust is likely to have contributed on the spatial distribution of large earthquakes in the forearc region.

1. Introduction

In oblique subduction zones, strain partitioning occurs between the slip on the main subduction megathrust and the slip on a major strike-slip fault [1–3]. This type of strike-slip fault plays an important role in basin configuration and development [4–6]. Along the western Sunda oblique subduction, the arc-parallel motion is accommodated by the Sumatran Fault Zone (SFZ), which, together with the trench, bounded a sliver plate in between [1,2]. This hypothesis expanded by a suggestion that another major fault plays a role in the region that developed between the forearc basins and accretionary wedge complex, here referred to as the Mentawai Fault Zone (MFZ) and West Andaman Fault (WAF) [5,7,8]. Furthermore, there have been suggestions that a part of the strike-slip motion is accommodated within the forearc basins [4,8–10]. Several workers reconstructed the evolution of the Sumatran forearc basins in relation to major strike-slip faults [9–13]. However, recent studies on this region reveal the presence of landward-vergent fold-thrust faults separating forearc basin and accretionary wedge domain rather than strike-slip fault [14–17].

Furthermore, the Sunda subduction zone has been the site of several great earthquakes since the Sumatra 2004 earthquake and tsunami [18]. In the central part of this subduction system, the Mentawai segment is locked and likely to produce a large earthquake in the near future [18–20]. Here, we review several proposals of the primary controls on the evolution of the western Sunda forearc basin. We found that one of the major controls of the growth of the basin is uplift of the former forearc basin that now became a forearc high, hence the forearc basin is narrowing farther arcward. We also discuss the possible relationship between the subducting rough bathymetry on the oceanic crust to the spatial distribution of large earthquakes along this oblique subduction zone. Here, we review the available published geologic-geophysical data in the western Sunda forearc. Several onshore field works were highlighted in this paper.
Figure 1. Bathymetry showing several depressions along the western Sunda forearc basins and area of earthquake ruptures. WAF = West Andaman Fault, MF = Mentawai Fault, BF = Batee Fault, SF = Sumatra Fault, NSFB = North Sumatra Forearc Basin, CSFB = Central Sumatra Forearc Basin, SSFB = South Sumatra Forearc Basin, SBB = Sumatra Backarc Basins, SJFB = South Java Forearc Basin, NJBB = North Java Backarc. Rough oceanic plate occurred in the oceanic plate to the south of the equator, whereas to north seafloor of the oceanic plate appear to be smoother.

2. Geologic setting
The Indo-Australian plate subducts obliquely beneath the Sunda plate at a convergence rate of 43 to 60 mm/yr, resulting in strain partitioning between the trench-perpendicular slip along the megathrust and the trench-parallel slip along the Sumatra fault zone [1]. Several large earthquakes have been recorded along this oblique subduction system [18,22–25] that became the site for a northwest trending small forearc high islands. The western Sunda forearc high islands have developed as a part of the uplifted accretionary wedge complex in between the forearc basins and the Sunda trench [12,16,26–28]. These islands extend from Andaman-Nicobar islands in the north to Simeulue-Nias and Mentawai islands in the southeast (Figure 1). The origin of accretionary wedge complex along this margin is thought to have formed due to the accretion of Sunda trench sediments [9,12,26,27]. Structures developed in the forearc high, which represents the uplifted accretionary wedge complex, have been interpreted as either thrust faults and inverted normal faults [12,14,17,29,30]. Rocks exposed on the forearc high islands are of sedimentary origin, with basement rocks having a mixture of continental and oceanic origin [29–32].

In the southern part of the western Sunda arc, the forearc basins has been formed in a transtensional setting between two major strike-slip faults, the MFZ and SFZ [4,10,11,13,33]. The SFZ extends along the backbone of Sumatra Island [34–36]. This large strike-slip fault zone enters the Andaman Sea in
the northern part of the western Sunda arc [37,38] and merged with another major strike-slip fault, the WAF [39]. The forearc basin in Andaman appears to have been developed in between WAF and Eastern Margin Fault (EMF), which have also been interpreted as the strike-slip fault. In the southeastern end of this zone, the Semangko pull-apart basin developed in the Sunda Strait [40–44].

The landward margin of western Sunda accretionary wedge have been interpreted as a major strike-slip fault zone based on observation of seismic reflection data [4,7,8]. However, earlier observations on this fault zone on land and offshore suggested either the presence of flexure or inverted normal faults along the margin of the forearc high island [29,30,45,46]. Based on observation of high-resolution seismic reflection data, the arcward boundary of Sumatra accretionary wedge is occupied by landward-vergent backthrusts [14,15,17] that continued at depth to a trenchward dipping backstop [17,47]. The continuation of the backthrusts farther northwest has been observed in Nias Basin and farther north in the Andaman area [15,16,38,46,48].

3. Observations on the forearc dynamics

3.1. The Sumatra sliver plate

The early proposal of strain partitioning in Sumatra has been suggested by the development of a sliver plate between the arc and the trench that bounded by the SFZ and the deformation front of the Sunda megathrust in the trench [1,2]. The hypothesis then expanded by the suggestion that another major fault occurred in between the forearc basins and accretionary wedge [7,8]. In the northern end of MFZ, the fault is attenuated and seems to connect to the SFZ by the Batee Fault (BF). This pattern can be explained by a simple model with two sliver plates: the Mentawai and Aceh sliver plates, on the top of which the forearc basin has developed [7]. However, there was a disagreement on the suggestion of the transverse movement along the MFZ, because the GPS network crosses the northern third of the Mentawai showed no indications of any large transverse movement [49,50]. Furthermore, slip vectors of moderate earthquakes along the Sumatran subduction zone are nearly perpendicular to the strike of the plate boundary [3].

If the vectors of the slip directions observed by McCaffrey represent long-term slip trajectories along the megathrust, then subduction itself is only slightly oblique, and most of the dextral component of plate motion should have been accommodated elsewhere [35]. We also do not find any moderate to large earthquakes with strike-slip fault motion along the trenchward boundary of the Sumatran sliver-plates. The trench-parallel component of strain in this oblique subduction system is possibly distributed as transpressional folding and thrusting in the accretionary wedge, as indicated by the strike of fold-thrust belt in the trenchward part of the Sumatran accretionary wedge formed at a low angle to the direction of the trench [14,51]. Furthermore, the trench-parallel component of strain partitioning in the oblique western Sunda subduction zone may have been largely taken up by networks of strike-slip faulting that deformed the accretionary wedge as shown in Nias Island [46], which is also observed in other forearc high islands along the Sumatran forearc [52–54].

3.2. The western Sunda continental backstop

The lack of seismicity with the strike-slip mechanism in the boundary of the sliver plate could be due to the occurrence of a trenchward dipping continental backstop as imaged in many seismic refraction models along the margin [47,55–57]. All of these models show no indication of any large vertical structures that may accommodate transverse motion in between the forearc basins and accretionary wedge complex. However, a major strike-slip fault in a relatively north–south direction occurred in the forearc of Andaman here referred to as the West Andaman Fault [39] or the Andaman Nicobar Fault (ANF) [38]. Furthermore, this strike-slip fault appears to have extended farther south, crossing the accretionary wedge as shown in the bathymetry.

The continental backstop became the place where the landward-vergence backthrusts developed and bounded the accretionary wedge as shown by recently acquired seismic reflection data set along the Andaman and Sumatran forearc [14,16,17,48,58–60]. The trenchward-dipping backstop facilitates
a wide seismogenic zone in the plate interface, in between the toe of the backstop and the deepest part of the continental crust [61,62]. Hence it was suggested that the upper-plate controls the spatial distribution of megathrust earthquake in the Sunda margin [63].

3.3. Strike-slip fault zones

In the Simeulue basin, northern Sumatra strike-slip faults were initiated during the end of Late Miocene-Pliocene [64]. The opening of the basins is interpreted as the result of a limited E-W extension linked to the incipient play of the Sumatra and Mentawai fault during the growth of the Miocene forearc basin. In Pliocene-Quaternary times, the fore-arc basin is segmented into several sub-basins (Aceh, Simeulue, and Nias basins) by compressional zones or by strike-slip faults [65] (Figure 2). Farther south, the Nias basin is bordered by a large offset of the vertical fault of the Batee Fault [7]. The Paleogene forearc basin depocenters appear to have related to transtensional movements between major strike-slip faults [11,33]. Near the southern termination of the SFZ, transtensional pull-apart basin formed in the Sunda Strait [41–43,66].

The proposal of sliver-plates in between the Sumatran arc and accretionary wedge-trench gap was expanded by a hypothesis that a large-scale strike-slip duplex formed in the Sumatran forearc basins [4]. Based on observation of seismic reflection, swath bathymetry, and high-resolution sub-bottom profiler data, they recognized a set of wrench faults obliquely connecting the SFZ and MFZ. These wrench faults separate at least four horses of a regional strike-slip duplex, where each horse comprises an individual forearc basin with differed subsidence and depositional history started since Mid/Late Miocene. The strike-slip duplexes propagated northward along the Sumatran margin over 2000 km until Early Pliocene. The domains, where major strike-slip zones formed, are along the volcanic arc for the Sumatran Fault Zone and the boundary between the forearc high and forearc basins for the MF and WAF. The connecting splay faults, referred as Siberut and Batee faults, are located at the edges of the Batu and Banyak Island groups. Splay faults divide strike-slip horses that comprise single forearc basins: the Bengkulu, Nias, Simeulue and Aceh basins [4].

3.4. Flexure, inverted normal faults and backthrusts

Flexures have been observed in one of the forearc high islands that continue at depth as high-angle reverse fault [30,45] (Figure 2). These reverse faults might be the structures that previously interpreted as inverted normal faults [46]. However, recently acquired seismic reflection data set show that this inverted faults are actually landward-vergent backthrusts developed in the landward margin of the accretionary wedge [48]. Field observation suggested that strike-slip motion is of limited importance along the 600 km long MFZ that crossing the island of Nias [46].

The growth of the accretionary wedge that bounded the trenchward margin of the Sumatran accretionary wedge is maintained by the development of frontal thrusts and backthrusts in the trenchward- and arcward-part of the accretionary wedge, respectively. Similar patterns of the growth of the accretionary wedge were also observed farther north in the Andaman forearc [16,67] suggesting that the doubly-vergent accretionary wedge is not uncommon to have developed in an oblique subduction system, contrary to the previous suggestions that in such setting major strike-slip faults should have formed in the landward margin of accretionary wedge [4,5,26].

Furthermore, the forearc backthrust is also suggested to have ruptured simultaneously with the Sunda megathrust in 2004 [14,58]. Most of the sudden uplift recorded by corals over the past 7 centuries exhibit landward tilting and are thus consistent with a slip on the Sunda megathrust [68]. However, one large uplift event, around 1685 has ambiguous indication of tilting, hence it might have resulted from a slip on the backthrust [25]. Furthermore, the relocation of the 1976 M7 earthquake and its aftershock in the north Sumatran forearc indicates that they were ruptured on a backthrust system [69,70].

3.5. Uplift of the former forearc basins

In the north Sumatran forearc, a stack of strata on top of the top of accretionary wedge is observed along the area where the forearc high is formed [21]. These strata are highly folded and faulted,
suggesting compressional tectonics occurred in this area. The reflectivity of these strata resembles the reflectivity of the Neogene sediments observed in the forearc basin. This similarity suggest that the sediments on the forearc high might have been formed in a former forearc basin environment, but have since been deformed and uplifted [21]. The former Sumatran forearc basin might have been located in the area of the present-day forearc high that now has shifted arcward. Similar observation have been documented in the central and southern Sumatran forearc, where the older forearc basin strata were uplifted and formed as a structural high in the present-day forearc high [17,46].

Fig. 2. Uplift mechanisms for the Sumatran forearc high. A) Strike-slip fault [7]. B) Inversion-controlled uplift [46]. C) Flexure and reverse fault [39]. D) Uplift of the Paleogene accretionary wedge [12]. E) doubly-vergent thrusts in the core of accretionary wedge [59].

4. Discussion and conclusions
The growth of the forearc basins have been proposed to have largely influence by the sliver-plates in the between the arc and accretionary wedge, major strike-slip faults parallel or crossing the basins [4–11]. However, we do not observed any moderate-major earthquakes with strike-slip motions within this area. This observation suggests that the major strike-slip faults do not exist or the strike-slip motions have been largely accommodated by networks of strike-slip faults deforming the accretionary wedge. Moreover, the growth of the basin appears to have been controlled by the development of the accretionary wedge, which part of this wedge has been uplifted and formed the forearc high [14,17,21,60,71]. In the forearc high, older forearc basin strata occurred on top of the accretionary wedge sediments, suggesting the uplift of the former forearc basin [17,21,46]. Hence, the former forearc basin was developed farther trenchward as compared to the present-day forearc depocenters.

In the arcward margin of the Sunda accretionary wedge, backthrusting appears to have played a major role on the accretionary wedge mechanics and forming the forearc high [14,16,17,21,57,60]. However, if the backthrust itself governed the uplift of the forearc high, then we expect to have a chain of continuous forearc high islands along the western Sunda forearc. Therefore, it seems that something else played in controlling the development of forearc high islands. Interestingly, the forearc high islands occur in the prolongation of ridges on the subducting oceanic plate. The rough bathymetry on the subducting oceanic plate related to fracture zones like the Investigator and Wharton ridges appear to have significant influence on the forearc configuration [72,73]. This relationship has been demonstrated for the spatial distribution of earthquakes and their rupture area [74,75]. Furthermore, a close relationship between the subducting high bathymetric features on the oceanic plate with shallow seafloor in the forearc basin and boundary of earthquake rupture has been observed [76]. Further detail
investigation is needed to clarify the relationship between the evolution of the forearc basin, subducting rough oceanic plate and earthquake rupture zone in this oblique subduction system.

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