A Complex Structure in the northwestern of Sumatra Fore-arc

W S Priyanto¹, H Permana¹, D Arisa¹, A Aulia¹, M M Mukti¹, L Handayani¹ and A Farisan¹

¹Research Center for Geotechnology, Indonesian Institute of Sciences (LIPI), Bandung, Indonesia

*Corresponding author: wisn003@lipi.go.id

Abstract. The Sumatran offshore region is known as an active seismogenic zone. Consequently, there were many records of great events that caused a big catastrophe, such as the 2004 Sumatra-Andaman earthquake. In order to investigate the geometry and nature of the earthquake ruptures and structures, we utilize the bathymetry and Multi-Channel Seismic (MCS) profiles from the SO-198 research project in 2008 (R/V Sonne) and KH-10-5 research project in 2010 (R/V Hakuho-Maru). We find that the area along the Sunda Trench to the fore-arc high in the northwestern Sumatra are characterized by parallel anticlinal ridges with distinctive vergence regimes. These vergence regimes classified as seaward, mix and landward vergence system. Our data interpretation recognized structures such as Main thrust, Lower thrust, Middle thrust, Upper thrust, piggy-back basin and West Andaman Fault within this region. Our conclusion suggest that the anticlinal seaward and landward vergence are considered as the product of recent deformation rupture. The co-seismic slip from the past earthquake ruptures tends that it was occurred from the deeper part in the entire northwestern of Sumatra fore-arc.

1. Introduction

The Sumatra subduction is the oblique subduction or under-thrusting of Indo-Australian Plate beneath Eurasia Plate in Sumatra [1]–[4]. The slip rate of the subduction within this area is decreasing from 60 mm/yr. to 50 mm/yr. in the West Sumatra [5]. The age of the oceanic crust in the offshore northwestern Sumatra region varies from 40 to 60 Ma [6], [7]. The Sumatra subduction zone is also known by great earthquakes such as the December 26th, 2004 (Mw~9.3), March 28th, 2005 (Mw~8.7) and April 11th, 2012 (Mw~8.6 and 8.2) [8]–[13] (Fig.1). The seismic activities occurred in the Sumatra Island relate to the Great Sumatran Fault (GSF), which accommodate the dextral strike-slip motion [14], [15]. The catastrophe of the Aceh tsunami in 2004 is the result of a rupture of the seafloor. Several study suggested that the rupture occurred beneath the accretionary prism rather than the fore-arc basin [9], [10], [16]. Another suggestion is that during the 2004 tsunami, the upper thrust in the fore-arc high was displaced, and second tsunami occurred due to in the middle thrust [17], [18]. The third study hypothesized that the huge tsunami was generated due to the co-seismic motion along the entire fore-arc high [19], [20]. Moreover, several researches was reported the involvement of Sumatra fore-arc structures and anticlinal piggyback basin in the northwestern of Sumatra [19]–[22].

The northwestern of Sumatra fore-arc is well known by mega-earthquake and potential of tsunamigenic hazard in the record history. Our study objectives to understand the structures and the associates which control the rupture propagation within this area. We presented high-resolution multichannel-seismic profiles and complemented with bathymetry data across the northwestern
Sumatra fore-arc basin to the trench of the subduction zone. The data provide information of the subduction zone, Sunda Trench, fore-arc high, and fore-arc basin. In this paper we demonstrate the correlation between seaward and landward vergence, the thickness of the oceanic crust and discuss the implication and rupture processes in this region.

![Figure 1](image1.png)

**Figure 1.** Bathymetry map and location of survey area (Source: BATNAS, Hakuho-Maru Bathymetry Data, The 2004-2020 with Mw>7 from Global CMT data).

2. Data and Method
We used multi-channel seismic profile data of, Sumut07 from the SO-198 research project and Line05 from the Hakuho-Maru research project (Fig. 3). The SO-198 project used 12-G-guns 5240 cu, and a 2.4 km streamer with 192 channels on board R/V Sonne in 2008. The data has been processed, including bandpass filtering, amplitude recovery, deconvolution, normal move-out, and performed 2-D Kirchhoff pre-stack time migration (detailed processing in [20], [23], [24]). The KH-10-5 research was conducted in 2010 with GI gun of 150 cu and a 1.2 km streamer with 48 channels, 25 m group spacing on board R/V Hakuho-Maru. The data has been processed, including bandpass filtering, gain recovering, deconvolution, velocity analyses, Normal move-out, then post-stack time migration [22]. Moreover, we utilized the bathymetry data from the KH-10-5 research, which has a 5 m grid resolution and from BATNAS with a resolution of 30-s.

We used these processed seismic profiles and bathymetry to investigate the northwest Sumatra fore-arc. Interpretation was focused in the selection area, including the Sunda Trench, trench slope, fore-arch high, and Aceh Basin. A combination of these interpretation analyses allowed us to extend our interpretation in correlating faults that exhibit the seafloor ruptures and subsurface structures.

3. Result and Discussion
The bathymetry data showed us the Sunda trench, fore-arc high, and Aceh Basin (Fig. 2). The previous research suggested that the northwestern Sumatra fore-arc region characterized by upper
thrust, middle thrust, lower thrust and main structures [22]. Moreover, those thrusts tend to be parallel, which indicates that the motion of the plate within this area.

![Bathymetry map and location of survey area](source)

Figure 2. Bathymetry map and location of survey area (Source: BATNAS, Hakuho-Maru Bathymetry Data). PBB = Piggy-back basin, MT = Main Thrust, LT = Lower Thrust, MDT = Middle Thrust, UT = Upper Thrust.

We analyses bathymetry data in order to presume the fold vergence by comparing each slope lineament. Then, we validate the fold’s vergence with our seismic profiles (Fig. 3). An additional information that our Sumut07 profile is nearly parallel to the Line05 with distance range ~46 km to the southeast (Fig. 2). This may allow us to know the consistency of the interior structure between this areas. Our seismic profile (Fig. 4) shows that the northwestern Sumatra fore-arc is characterized by landward vergence, mixed vergence, and seaward vergence thrust, with the landward vergence is dominant. Seismic profile Sumut07 shows that the accretionary prism at ~4.5 km water depth with oceanic crust thickness ~4km, and West Andaman Fault (WAF) adjacent to Aceh Basin [20], [23]–[25].

The seawater depth is in an average range of 2.2 seconds (two ways travel-time) or equal to 1.65 km. The depth, in the trench is 6 second (TWT) or 4.5 km, and in Aceh Basin is ~2.7 km. The accretionary prism along the Sumut07 profile is ~165 km and ~185 km from the trench [24]. The seaward vergence is characterized by WAF at CDP ~5500. The fold of seaward vergence is up to 88.8 km. A mixed vergence region is nearly 24 km wide. Meanwhile, the landward vergence is more than 92.5 km in this profile. In the seismic profile Line05, the landward vergence fold is started from CDP ~20800 (Fig. 4). The fold of landward vergence is up to 57 km. A mixed vergence region is nearly 19 km. Meanwhile, the seaward is more than 45 km in this profile. The seawater depth in Line 5 is in an average range of 2.3 seconds (two way travel-time), or equal to 1.72 km and in the trench is 6 seconds (TWT) or 4.5 km.

3.1. Seaward and landward vergence

The interpretation of seaward and landward vergence is related to the fold direction and shortening. A previous research study identified two-post seismic activities at lower and middle thrust, while upper
thrust is seismically not active [18]. The seaward dipping has a role in sedimentary sequences along with the oceanic crust [22]. The construction of landward vergence was developed during the rapid accretion of water-rich sediments [26]. Our seismic profile shows the structures existence in the landward vergence, which are main and lower thrusts. Meanwhile, the middle and upper thrust structures are discovered in the mix and seaward vergence. The seaward, mix and landward vergences are shown as an internal structure upward convex, which is known as anticlinal ridges [22]. We suggested that the seaward and landward vergences within our study area have implications in accretionary processes, similar to the Cascadia or Nankai Through [27], [28].

Figure 3 Seismic Profile Migrated data. a) Seismic Profile Sumut07 from SO-198 acquired in 2008 (VE=~3.5x). b) Seismic Profile Line05 from KH-10-5 acquired in 2010 (VE=~2.5x).
3.2. Trench Slope, fore-arc high and oceanic crust
The interpretation of the structural framework is different, in which the trench was formed by landward vergence. Meanwhile, the fore-arc high was formed by mix and seaward vergences that formed earlier due to the incoming subduction lithosphere. The morphology in the fore-arc high recognized as sub-parallel anticlinal ridges with most of the ridges appear to be single anticline [22]. The pre-decollements in profile sumut07 and Line05 are hypothesized to be extended to the landward boundary slips [16]. Meanwhile, the absence of the continuous outs-of sequence thrust in both seismic profiles, where the thrusts are in landward and mix vergence, is due to recent deformation. The potential scenario is that the co-seismic motion is in the entire northwestern Sumatra fore-arc near the oceanic crust [16], [19], [20], [22].

3.3. Aceh Basin and West Andaman Fault
The West Andaman Fault (WAF) has a kinematic role into the partitioning of the strain on the margin of northwest Sumatra fore-arc region [24]. The WAF was expected to be related to Sagaing Fault, which is a series of spreading centres and transform fault from Andaman Sea [29]. The WAF does not seem penetrate to the surface, which indicates that it is not currently active. The Aceh basin has a
water depth of ~3.5 seconds two-way travel time or nearly ~2.7 km, with particularly flat seafloor and manifested by layered sediment.

![Image](image_url)

**Figure 5** Projection of interpreted profile from seismic profile Sumut07, bathymetry data and Modified model of post-Seismic 24\(^{th}\) Dec 2004 Eq. (20 February – 13 March 2005) (Sibuet et al., 2007)

A previous study indicated a branching of two active thrust faults (lower and middle thrust fault) in the interplate zone [18]. It is different with our seismic profiles which do not show any branching of the two thrust faults. The invisibility of this branching is not only in the Sumut07 profile, but also it is unseen as well in the seismic profile Line05. These observations suggested that the interior structures within the distance between both of our seismic profiles seem to be consistent. Another study from Frederik et al. 2015 [24], suggested that in the near trench (before main thrust), the “blind” normal faults are extended into the pre-decollement. In the other hand, these normal faults are hard to recognize from both of our seismic profiles with amplitude signal and its relation to the extension to the pre-decollement.

Sibuet et al. 2007 [18], suggested that during the 2004 earthquake, the co-seismic motion was transferred along a splay fault from the slab to the upper thrust fault. We did not find a continuous outs-of-sequence thrust. It is possible that the absence of continuous out-of-sequence thrust caused kinematic rupture processes in the deeper part along entire fore-arc region. This kinematic rupture derived co-seismic transfer such as recorded in the past mega-earthquake. Previous study used sandbox experiment proposed a model with a rigid backstop, which is seaward dipping and extends from under the Aceh Basin to beneath the mixed vergence zone [24]. If we complemented this model with our consistent interior structure interpretation, it can be assumed that below mix vergence zone there was a stronger area than the accretionary prism and caused deformation. Then, our result agrees
with the statement from previous research studies, that proposed a deeper deformation with such a staircase subduction type (bending and unbending) within this area [18], [21].

4. Conclusion
We concluded that the deformation zone in the northwestern of Sumatra fore-arc is characterized as a parallel anticlinal ridge to the trench slope. The anticlinal ridge is recognized as seaward, mix and landward vergence thrust system, with dominantly landward vergence system. There are morphology and structures deformation correlation in our bathymetry and seismic data interm of near surface deformation zone. Firstly, these structures and features are classified as main thrust, lower thrust, middle thrust, upper thrust, piggy-back basin and WAF. Secondly, we notified the absence of the continuous out-of-sequence thrust (ramp) in the middle and lower thrust in our seismic profile. Lastly, we acknowledge that the seaward geometry vergence is followed by a complex strain-partitioning and West Andaman Fault in the Aceh Basin.

Finally, our conclusion suggest that the seaward, mix and landward vergence thrust as the result of recent deformation. The relation to the earthquake and kinematics subduction is hardly to explain, since it is more complex than the 2D profile could provide. But the analysis from our interpretation suggests the absence of the continuous out-of-sequence thrust (ramp) derived the rupture processes. This rupture triggered a slip at decollement from the deeper part in the entire fore-arc region. In the southwest of the upper thrust fault, there is a zone where the earthquake potentially occurred. As consideration, in the future the co-seismic rupture might potentially propagated closer to the Sunda Trench due to the thick of the accretionary wedge and incoming sediments.

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