1 Geological structure of the Offshore Sumatra forearc region estimated from High-Resolution MCS
2 reflection survey
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1 Abstract

2 To investigate detailed fault distributions and shallow geological structure offshore northwestern
3 Sumatra, we obtained high-resolution Multi-Channel Seismic (MCS) reflection data around the
4 Sunda Trench, trench slope, and forearc high regions offshore northwestern Sumatra. In general,
5 trench-parallel anticlinal ridges are distributed from trench slope region to forearc high region. Two
6 kinds of different vergence systems are characterized in the Sumatra forearc region; landward
7 vergence is dominant in the lower trench slope region, and seaward vergence is dominant in the
8 forearc high region. Moreover, piggyback or slope basins are recognized between anticlinal ridges.
9 Deformation in the uppermost part of these basins, that is referred to 'recent' deformation in this
10 paper, can be identified not only along major thrusts but also between major thrusts and the lower
11 trench slope, suggesting these are related to recently active faulting. Several but the largest number
12 of such deformation are distributed along a major thrust located in the middle of the forearc high
13 region, whereas few are done along other major thrusts.

14

15 Keywords

16 High-Resolution MCS reflection data, fault distribution, recent deformation, 2004
17 Sumatra-Andaman Earthquake, tsunami,

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1 1. Introduction

2 On 26th December 2004, the Sumatra–Andaman Earthquake (Mw 9.1-9.3) occurred offshore
3 northwestern Sumatra and then ruptured the megathrust for over 1,300 to 1,500 km mostly to the
4 north along the Sunda Trench (e.g. Lay et al., 2005) (Fig. 1). The great earthquake generated huge
5 tsunami that struck many countries around the Indian Ocean. In particular, a huge tsunami of more
6 than 20 m in height on average struck the west coast of Aceh in northern Sumatra (Tsunami survey
7 team, 2005).

8 Data about the geologic framework of the forearc high region of the Sumatra forearc was scarce
9 before the 2004 event. After the earthquake, several international marine geological and geophysical
10 surveys investigated the morphology, the geological structure, and the seismic activities in the
11 Sumatra forearc region, including the Sunda Trench, trench slope, forearc high and the Aceh Basin
12 (Fig. 1). Generation mechanism of the huge tsunami during the 2004 great earthquake remains
13 unsolved although several different fault models were proposed by previous studies (e.g. Soh et al.,
14 2005; Henstock et al., 2006; Plafker et al., 2006; Sibuet et al., 2007; Hirata et al., 2008). Based on
15 their offshore survey, Sibuet et al. (2007) presented an idea that the Upper Thrust in the forearc high
16 region displaced coseismically to contribute the huge tsunami generation. Hirata et al. (2008, 2010)
17 and Lin et al. (2009) proposed that the secondary tsunami source is located around the Middle Thrust
18 (the Median Thrust of Sibuet et al., 2007). On the other hand, Fisher et al. (2007), Mosher et al.
19 (2008), and Gulick et al. (2011) suggested that the huge tsunami was a product resulted from
20 coseismic motion of the entire forearc high. Using Ocean Bottom Seismograph (OBS), aftershocks of

1 the 2004 event offshore Aceh on the northwest coast of the Sumatra were accurately located and
2 found to be concentrated on or near the megathrust between the subducting slab and overlaying plate,
3 but also in the accretionary wedge beneath the forearc high (Araki et al., 2006; Sibuet et al., 2007).
4 The generation mechanism, that is the earthquake fault model, of the December 26, 2004 huge
5 tsunami off northwestern Sumatra would have to be consistent with aftershock distribution
6 determined from the OBS observation.

7 After the 2004 tsunamigenic event, several seismic reflection surveys have been conducted in
8 offshore northwestern Sumatra (e.g. Fisher et al., 2007; Seeber et al., 2007; Mosher et al., 2008;
9 Gulick et al., 2011; Singh et al., 2012). In particular, Fisher et al. (2007) reported that the Sumatra
10 forearc region is characterized by anticlinal ridges and piggyback basins using single-channel
11 seismic profiles. Gulick et al. (2011) reported that the resultant subsurface images show several
12 geologic characteristics and the dewatering system of the Sunda margin. Moreover, Singh et al.
13 (2012) described the crustal and upper mantle structure beneath the forearc high region using deep
14 seismic profiles. However, a seismic reflection survey that focused detailed shallow subbottom
15 structure had not yet been conducted. If the 2004 coseismic deformation were preserved in
16 subsurface of the seafloor, it may be recorded in the shallow part of the sedimentary sequence.

17 To investigate detailed shallow geological structure off northwest Sumatra, we conducted the
18 cruise KH-10-5 cruise using *R/V Hakuho-Maru* in November 2010 (Fig. 1). This cruise deployed
19 high-resolution Multi-Channel Seismic (MCS) reflection, a shipboard subbottom profiler (SBP), and
20 swath bathymetry.

1 We present high-resolution seismic reflection images of the shallow structure around the Sunda
2 Trench, trench slope, and forearc high regions offshore northwestern Sumatra. This paper also shows
3 geological structure and previously unrecognized deformation features such as the uppermost
4 deformation in sedimentary sequence in the forearc high region. Our detailed mapping of thrust
5 faults and recent sediment deformation allows more specificity generation mechanism of the 2004
6 huge tsunami hitting the west coast of Aceh.

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8 2. Geological setting

9 In the Sunda Trench, the Indo-Australian Plate obliquely subducts beneath the Sunda Plate with
10 convergence rate from 61 mm/yr (N17°E) in the south to 51 mm/yr (N11°E) in the north
11 (Prawirodirdjo and Bock, 2004) (Fig. 1). Morphologically, the Sunda forearc can be classified into
12 four main regions: trench floor, trench slope, forearc high, and forearc basin (Aceh basin).

13 Pre-2004 investigations characterized the Sunda forearc region as an accretionary prism (e.g.
14 Moore and Curray, 1980). Sediments of the Sunda Trench are thought to have originated from the
15 Bengal and Nicobar fans (Curray and Moore, 1974). It is also recognized that arc parallel dextral
16 strike-slip fault systems (i.e. the Great Sumatra fault, West Andaman fault and Mentawai fault)
17 developed on the landward side of the Sunda forearc to absorb part of the dextral motions associated
18 with the oblique plate convergence (e.g. Fitch, 1972; Moore et al., 1980; Sieh and Natawidjaja,
19 2000).

20 After the 2004 tsunamigenic event, many surveys were conducted in the Sunda Trench. The

1 sedimentary sequence in the Sunda Trench over the subducting Indo-Australian Plate is over 4 km
2 thick, according to several MCS profiles (Gulick et al., 2011). The trench slope is characterized to be
3 caused by faults and folds based on the deformation morphology (e.g., Seeber et al., 2007; Mosher et
4 al., 2008). Moreover, recent seafloor deformation has also been identified in the trench area
5 (Henstock et al., 2006; Mosher et al., 2008).

6 As for the forearc high region, although we have little information the forearc high region due to
7 limited number of studies before the 2004 tsunamigenic event, many surveys were conducted after
8 the 2004 event. The morphology of the forearc high region is characterized by a series of
9 NNW-trending ridge and trough structure with high relief. These ridge and trough structures are
10 morphological expressions of anticlines and synclines caused by thrust faults (Sibuet et al., 2007;
11 Graindorge et al., 2008). From a detailed examination of the aftershock distribution and sea floor
12 morphology, Sibuet et al. (2007) highlighted four thrust fault systems: Main Thrust, Lower Thrust,
13 Middle Thrust (originally, “Median” Thrust), and Upper Thrust (Fig. 1). In addition, Sibuet et al.
14 (2007) reported that thrust-faults with both seaward and landward vergences were imaged in the
15 swath-bathymetric data and 3.5 kHz SBP profiles. The boundary between the Aceh basin and the
16 forearc high region is marked by the West Andaman Fault with flower structure suggesting
17 strike-slip deformation in the landward rim of the forearc high region (e.g., Seeber et al., 2007).
18 Moreover, Singh et al. (2011) have imaged backthrusts down to 15–20 km depth beneath the West
19 Andaman Fault using deep seismic reflection data.

20

1 3. Data and Methods

2 3-1. Multi-channel seismic survey

3 We collected approximately 900 km (~484.3 nautical miles) of MCS profiles during the KH-10-5
4 research cruises with *R/V Hakuho-maru* (JAMSTEC) in November 2010 (Fig. 1). In this survey, we
5 used a GI gun made by the *Sercel* as the control source. The seismic source was generated by the GI
6 gun comprising a total volume of 150 cubic inch (G: 45 cubic inch, I: 105 cubic inch) operated at air
7 pressure of 120 bars (~1750 psi). The gun shot interval of every 10 seconds corresponds to
8 approximately 20 m at a ship speed of about 4 knots. The receiver array was a 1200m-long,
9 48-channel streamer cable with group spacing of 25 m, towed at a water depth of 7 m. The recording
10 length was 8 seconds and sampling rate was 1 millisecond. MCS data were recorded as SEG-D
11 format on board and were reformatted to SEG-Y format with navigation information after the cruise.
12 Processing of MCS data included the following: trace editing, Common Mid-Point (CMP) sorting
13 (CMP interval was set 6.25 m for enhancement of horizontal resolution), bandpass filtering, gain
14 recovering, deconvolution, velocity analyses, Normal Move-Out (NMO), CMP stacking, time
15 migration, bandpass filtering, top mute, and automatic gain control (AGC). Due to relatively short
16 streamer cable length, we could not resolve the seismic velocity in the deeper part of the forearc high
17 region.

19 3-2. Swath bathymetric data

20 The bathymetry survey was conducted using SeaBeam 2120 equipped on *R/V Hakuho-maru*

during MCS survey. We also used other bathymetry data acquired during NT05-02 and KY09-09 cruises (Hirata et al., 2012), and compiled three cruises bathymetric data. Our bathymetric data filled unsurveyed areas along the Middle Thrust.

4. Results

Our study area is the Sumatra forearc region, which can be divided into three regions; trench, trench slope, and forearc high (Fig. 1b). In addition, the trench slope is subdivided into upper and lower slope on the basis of a morphological slope angle change (Figs. 1b and 2). Slope angle of the upper slope region is a steeper than the lower slope region. Our new MCS profiles images clearly down to 1.6 sec. (TWT; Two-Way Travel Times) in the trench and trench slope regions (Fig. 2), yet not enough to image the top of the oceanic plate. Moreover, our new profiles are also successful in obtaining clear images down to 2.0 sec. (TWT) in the forearc high region (Fig. 3).

The seismic profiles and bathymetric map clearly imaged the system of faults and folds trending NW-SE or NNW-SSE direction in the Sumatra forearc region (Fig. 4). Among these, the four major thrust faults systems defined by Sibuet et al. (2007) are confirmed; the Main, Lower, Middle and Upper Thrusts (Fig. 1). Strikes of these thrusts strike NNW-SSE direction, corresponding to the morphological trends. Sibuet et al. (2007) reported that these major thrust faults might be splay faults in the example of the Nankai Trough (Park et al., 2002); they originated at or near the décollement and propagated to the surface through the accretionary wedge (Fig. 1). Moreover, intermittent N-S trending geomorphic lineaments are recognized in the central part of the

bathymetric map (Figs. 1 and 4). These lineaments are interpreted as the dextral strike-slip faults (Permana et al., 2011).

4-1. Trench and trench slope region

Fig. 2 shows that the sedimentary structure of the trench regions can be imaged down to 1.6 sec. (TWT) below the seafloor. Although the lower limits of the trench sedimentary sequence cannot be determined, it is thought that the thickness of the sedimentary sequence is more than 2 sec. (TWT). Reflectors of the sedimentary sequence in the Sunda Trench are largely parallel, horizontal, and are consistent with undisturbed stratification. They are interpreted as trench-fill sediments with no evidence of unconformities, thickness changes, and deformation. In addition, some lenticular bodies and discontinuously reflections are imaged in the sedimentary sequence. These are interpreted to be a buried channel, as in previous studies (Mosher et al., 2008).

Around CMP#21000 of Fig. 2, the morphological slope angle is changed. In addition, the sedimentary sequence in the trench is continuously distributed to CMP#19400 of Fig. 2. In the lower trench slope region (Fig. 2a), the sedimentary structure can be imaged down to ~2.7 sec. (TWT) below the seafloor. The lower limits of the trench slope sequence and the plate boundary are unclear. Reflectors are largely parallel and seaward-dipping. The tilted sequence can be traced from the landward edge of the trench floor to CMP#18700 in Fig. 2. Near the toe of the lower trench slope, we can identify both seaward- and landward-dipping faults with very small amounts of displacement.

1 The trench slope region is characterized by ridges and troughs morphology striking NNW-SSE,
2 parallel to the trench. These ridges and troughs morphology have typically ~1 km of bathymetric
3 relief. In the trench slope sequence, seaward-dipping discontinuities are predominant but
4 landward-dipping discontinuities are also recognized (Fig. 2). Especially, seaward-dipping
5 discontinuities of the sequence are clearly recognized at CMP#17650, #18830, and #19400 (Fig. 2).
6 These are interpreted as seaward-dipping thrust faults that reach and cut the seafloor. The internal
7 structure of the ridges shows an upward convex arch structure. Thus, it is thought that these ridges
8 are bathymetric expression of anticlines. Within these ridges, kink folds are also recognized. An
9 upward convex arch structure between CMP#18700 to #17900 is interpreted as the anticline. In this
10 ridge, tilted beds intersect the seafloor, indicating erosion. Such outcrop of bedding caused by
11 erosion is widely recognized in the bathymetric map (Fig. 1). Around CMP#17300 of Fig. 2, a
12 landward-dipping reflector is observed in the sedimentary sequence. This structure can be interpreted
13 as a landward-dipping thrust fault and corresponds to the Main Thrust or the Major Thrust Fault
14 defined by Sibuet et al. (2007) (Fig. 2).

15 Folding in the trench slope develops as the result of subduction-related accretion and shortening
16 of trench sediments. In order to estimate the tectonic shortening absorbed by folding in the lower
17 trench slope, we restore the folded section compare the distance between the horizontal distances
18 and the seafloor total extension to CMP#17400-21000 of Fig. 2. This 22.5 km long deformed section
19 of the lower trench slope region has shortened by at least 8-9 km or 35-40%. However, the amount
20 of the shortening deformation might be greater because the seafloor erosion is observed in lower

1 trench slope region.

2

3 4-2. Forearc high region

4 In the forearc high region, accretionary structure can be imaged down to 2.0 sec. (TWT) below
5 the seafloor. Reflectors of this sedimentary sequence are largely parallel. The morphology is
6 characterized by a series of sub-parallel ridges and troughs trending NW-SE or NNW-SSE (Fig. 1).
7 Their bathymetric relief is typically about 1 km. Upward convex arch structure reveals that these
8 ridges are anticlines. Within anticlinal ridges, landward-dipping reflectors are well developed at the
9 landward part of these ridges (CMP#9500-10000 of Fig. 3). The anticlinal axes are separated
10 between 10 and several km. Synclines between them are often accompanied by slope basins (Moore
11 and Karig, 1976) (Fig. 1). These basins recognized in the forearc high region are interpreted as
12 piggyback basins according to the interpretation by Fisher et al. (2007).

13 Faults are recognized as discontinuities in the sedimentary sequence, sometimes marked by
14 reflectors. They are mostly found in the seaward rim of ridges and are both seaward- and
15 landward-dipping, although landward-dipping thrust faults are dominant in the forearc high region.

16 The internal structure of anticlinal ridges show tilted fault-blocks and folds with kink deformation
17 at a range of scales. Most ridges correspond to a single anticline (e.g. CMP#980-1700 of Fig. 5). But
18 some ridges, particularly in the forearc high region, are anticlinoria, composed of multiple closely
19 spaced and imbricated anticlines (CMP#9930-10000 of Fig. 3).

20 Active erosion of anticlinal ridge is also recognized in the forearc high region. Internal reflectors

1 of the folded and tilted sedimentary sequence terminate at the seafloor of anticlinal ridges and
2 suggest that the forearc high region has suffered substantial erosion (CMP#10000-10500 of Fig. 3;
3 CMP#980-1700 of Fig. 5). In CMP#2500-4400 of Fig. 6, channels oblique to slope direction suggest
4 that bedding is parallel to the NE flank of a broad ridge. At the scale of Fig. 6, both sides of the
5 broad ridge are similarly steep, but exhibit different patterns of erosional scars. The scars on the
6 landward side of the ridge tend to be oblique to the slope direction (Fig. 6). This pattern of erosion is
7 typical of bedding slopes on land. The scars on the seaward of the ridge are instead parallel to slope
8 and with steps typical of mesa erosion. Another sample of similar erosion pattern is seen on the scar
9 morphology (CMP#4500-5800 of Fig. 7a) (Seeber et al., 2007). Fig. 6b shows that the upper
10 sequence of an anticlinal ridge is missing, probably because of erosion. This morphology is common
11 and suggests pervasive erosion of the anticlinal ridges. However, this erosion is likely to be
12 superficial because relatively little sediment is ponded in the piggyback basins.

13 Thickness of the piggyback basins sediments can be imaged down to a maximum of 0.7-0.8 sec.
14 (TWT) below the seafloor (CMP#950-1850 of Fig. 7b). The youngest uppermost part of piggyback
15 basin sediments, are mostly parallel and flat-lying (Figs. 7b and 8). The older and lower part of this
16 basin-fill consists of relatively continuous and landward tilted reflectors that onlap the flanks of the
17 basin (Fig. 8). In order to identify the most recent crustal movements in the forearc high region, we
18 focus on the deformation in the uppermost part of piggyback basin and slope cover sediments. If
19 these young sediments are deformed, this deformation is even younger. These young sediments are
20 present in the forearc high region, but only locally. Where the seafloor is also deformed, the

1 deformation is considered particularly young (Fig. 9). Locations of recent deformation recognized on
2 our seismic profiles are compiled on Fig. 4 by star symbols.

3

4 5. Discussion

5 5-1. Opposing vergence across the Sumatra forearc

6 Our seismic profiles imaged the shallow internal structure of the Sumatra forearc, including the
7 Sunda Trench, trench slope, and forearc high regions. The morphology of these regions is
8 characterized by multiple sub-parallel ridges and troughs. We recognize two distinct vergence
9 regimes, separated by the Main Thrust. Landward vergence is dominant in the seaward region from
10 the Main Thrust, but seaward vergence is dominant in the landward region from the Main Thrust.

11 In the lower trench slope region, landward vergence is prevalent along the northwestern Sumatra
12 (Mosher et al., 2008). Landward vergence in the trench slope is also reported from Cascadia margin
13 (e.g. Goldfinger et al., 1992; MacKay et al., 1992; Goldfinger et al., 1996; Adam et al., 2004). We
14 refer to the seaward-dipping thrust fault at the base of the sedimentary sequence as the detachment
15 fault (Fig. 2). This detachment fault is thought to branch off the décollement. Around
16 CMP#17900-19800 of Fig. 2, seaward-dipping discontinuities of the sedimentary sequence are
17 inferred to be fault planes. These seaward-dipping thrust faults branch off from the detachment fault
18 and are thought to play an important role in the offscraping of the sedimentary sequence overlying
19 the oceanic crust. Moreover, we interpret anticlinal ridges as landward-vergent ramp anticline
20 formed by the offscraping of incoming sediments (Fig. 2). We interpret that the landward-vergent

1 anticlines and seaward-dipping thrust faults play a key role in the accretion processes. Similar
2 structures are observed in the Cascadia margin (Adam et al., 2004) and interpreted as ‘passive-roof’
3 by Fisher et al. (2007). Observed structures may be consistent to shallow expression of passive-roof
4 deformation. We will discuss this later.

5 The development of landward vergence was interpreted to be the result of the rapid accretion of
6 water-rich sediments and low basal shear stress (e.g. Seely, 1977; MacKay et al., 1992), or backstop
7 geometry and composition (e.g. Mosher et al., 2008). Mosher et al. (2008) noted that
8 landward-vergent structure offshore northwestern Sumatra have high dip angles and suggested that a
9 steep local backstop drives the landward vergence. In line with this hypothesis, they presumed
10 landward vergence to be widely distributed on the forearc high region. However, landward vergence
11 is only identified in the lower trench slope and is typically with comparatively low slope angles
12 (~7-10 degrees) (Fig. 2). Moreover, we do not recognize the seaward-dipping structure in the upper
13 trench slope and forearc high regions, which might act as a backstop. Thus, the steep local backstop
14 suggested by Mosher et al. (2008) is eliminated from the possible hypotheses accounting for
15 landward vergence in the lower trench slope.

16 The thick oceanic sediments incoming the Sunda Trench originated from the Bengal and Nicobar
17 Fans (e.g. Moore and Curray, 1980; Dean et al., 2010; Gulick et al., 2011). Dean et al. (2010)
18 suggested that the basal horizon offshore North Sumatra is a zone of low-density and elevated pore
19 pressure relative to overlying sediments. The rapid accretion of water-rich sediments contributes to
20 their mechanical weakness. Our observations do not add to this hypothesis, but are inconsistent with

1 the backstop hypothesis. Of these two, therefore, we favor the hypothesis that low basal shear stress
2 is responsible for the landward vergence along the lower trench slope, but cannot rule out other
3 hypotheses.

4 In contrast with the lower trench slope, we find the forearc high region to be characterized by
5 seaward vergence (e.g., Sibuet et al., 2007). In this respect, the forearc high region is similar to the
6 Makran region and many others (e.g. Smith et al., 2012). The development of anticlinal ridges
7 indicates existences of active deformation for long period. Sibuet et al. (2007) reported thrust faults
8 oriented N340° (parallel to the trench) with both seaward and landward vergence. Although both
9 seaward- and landward-dipping thrust faults are also identified on our seismic profiles,
10 landward-dipping thrust faults are dominant. Within anticlinal ridges, landward-dipping reflectors
11 are recognized at the landward part of ridges (CMP#9500-10000 of Fig. 3). The cover sediments on
12 the forearc high region tend to be tilted landward (Fig. 8). Moreover, deformation that might be
13 caused by hypothetical seaward-dipping faults is not identified. Therefore, these observations
14 suggest that the formation of the forearc high region is mainly controlled by landward-dipping thrust
15 faults. Fisher et al. (2007) took notice of observed wavelength (~13 km) between anticlinal ridges
16 and reverse vergence across the both ends of the forearc high region and then attributed these
17 characteristics are consistent with a 'passive-roof'. Regrettably, we could not obtain any seismic
18 imaging that confirms such 'passive-roof' deformation on our seismic profiles, because of our
19 seismic reflection tool tuned up for high-resolution and shallow exploration.

20 Structural frameworks of the lower trench slope and forearc high regions are distinctly different.

1 The lower trench slope region, which comprises the current accretionary prism, is formed by
2 landward vergence, possibly because water-rich sediments are accreted. On the other hand, the
3 forearc high region, which contains old accreted sediments structured by old thrust fault and folds, is
4 characterized by seaward vergence. Thus, we suggest that this seaward vergence has developed in
5 earlier times. The difference between modern and old trench sediments is probably controlled by the
6 water content of the incoming sediments. Water-rich sediments are offscraped by the
7 seaward-dipping thrust faults in the lower trench slope (e.g. Mackey et al., 1992). In contrast,
8 seaward vergence develops offshore Nias Island because an oceanic basement highs limits
9 southward fan turbidite transport (Dean et al., 2010). We suggest that the former geological
10 framework of the forearc high region is thought of as the analog of the modern offshore Nias Island
11 region.

12

13 5-2. Recent deformation in the piggyback basin

14 Piggyback basins with enclosed drainages are distributed between ridges in the forearc high
15 region (Fig. 8). Similar basins located in the forearc high region offshore western Nias Island has
16 been reported as "slope basins" (Stevens and Moore, 1985). It is difficult to discuss age and origin of
17 basin fill sediments based on only our seismic data. As individual basins are largely isolated from
18 each other, the origin of basin sediments may be supplied by mass movements of material eroded
19 from anticlinal ridges, and parallel stratified subsurface sediments probably correlate with recent
20 sediments.

1 The uppermost part of the sediments is parallel and flat-lying in most of the piggyback basins of
2 the forearc high region (Figs. 7 and 8). In several of these basins, however, we recognized
3 deformation in the uppermost part, and thus most recent part, of the sediments (Fig. 4). For
4 piggyback basins along the Middle Thrust, in the northern part of our study area, from Line 1 to 5
5 (north part), deformation of uppermost basin sediments, i.e., 'recent' deformation in a geological
6 time scale here, is only recognized in Line 3 (Fig. 5). In the central to southern part of the present
7 study area, from Line 6 to 14, 'recent' deformation is recognized in multiple basins on many lines
8 (Fig. 9). In particular, deformation in the upper part of the piggyback basin and at the seafloor is
9 clearly recognized around the Middle Thrust in lines 12c and 13 (Fig. 9). In addition, relatively fresh
10 slope failure morphology is also recognized around the Middle Thrust across Line 8 on the
11 bathymetric map (Hirata et al., 2010) (Fig. 9a). Such slope failure morphology has a possible a result
12 of recent fault activity. From these results, we conclude that the Middle Thrust has been active
13 'recently', including possibly as part of the 2004 event. In addition, 'recent' deformation is not
14 recognized around the Upper Thrust of Sibuet et al. (2007), and is done at only one location around
15 the Lower Thrust. Therefore, we suggest that the Middle Thrust has been most active 'recently'
16 among major thrust faults within the forearc high region.

17 Deformation in the uppermost part of sedimentary sequence, that is can also be recognized in
18 several basins between the lower trench slope and Middle Thrust (Fig. 4) and between the Middle
19 and Upper Thrust (Fig. 10). All of the 'recent' deformation identified at piggy-back basins between
20 the lower trench slope and the Upper Thrust suggest recently active faulting there, possibly some of

1 them activated during the 2004 great earthquake. However we cannot examine the possibility further
2 because of seismic reflection data only.

3 4 6. Conclusion

5 Using high-resolution MCS and bathymetric data, we clarified the detailed distribution of faults
6 and folds offshore northwestern Sumatra. Anticlinal ridges sub-parallel to the trench are distributed
7 from the trench slope to forearc high. We identified regions of distinct vergence; landward vergence
8 is dominant in the lower trench slope, while seaward vergence is dominant in the forearc high region.
9 In the lower trench slope region, our data clearly showed seaward-dipping thrust faults and
10 landward-vergent ramp anticlines. These faults and anticlines play a major role in the growth of the
11 accretionary prism along the Sunda Trench. In the forearc high region, landward-dipping thrust
12 faults are dominant and tend to strike NNW-SSE near the seaward rim of each ridge. Major thrusts
13 defined by Sibuet et al. (2007) were also recognized on our high-resolution MCS profiles and
14 bathymetric map. We recognized recent deformation in a number of piggyback basins located within
15 the forearc high region. Many of them were distributed along the Middle Thrust. However, to
16 address whether the deformation was in fact coseismic with the 2004 event requires more detailed
17 offshore data focused on the 'recent' deformation identified in the present study. Especially effective
18 would be surveys by deep-tow and ROV coupled with sediment sampling at the seafloor.

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1 Figure caption

2 Figure. 1:

3 Study area: (a) A bathymetric map with KH-10-5 MCS survey lines offshore northwestern Sumatra.
4 Our bathymetric data are merged with bathymetric data collected by other cruises (Henstock et al.,
5 2006; Sibuet et al., 2007). The inset shows that the regional tectonic setting of the Sumatra
6 subduction zone. Black arrows in inset figure indicate the plate motions (Prawirodirdjo and Bock,
7 2004) and fault distributions (modified from the original of Graindorge et al., 2008). Blue bold lines
8 are the position of MCS profiles shown in Figs. 2, 3, 5, 6, 7, and 8. Blue dotted lines are the position
9 of the bathymetric profile of the offshore northwestern Sumatra shown in Fig. 1b. Terminology of
10 thrust faults name and location in the bathymetric map are based on the Sibuet et al. (2007). M'T:
11 Main Thrust, LT: Lower Thrust, MT: Middle Thrust, and UT: Upper Thrust. (b) Bathymetric profile
12 of offshore northwestern Sumatra.

13

14 Figure. 2:

15 MCS Line 5 profile of the trench and the lower trench slope regions (time migrated section): (a)
16 Non-interpreted seismic profile of Line 5 between CMP#17350 to #22230, and (b) interpreted
17 seismic profile. This profile shows a typical example of the sedimentary sequence of the trench
18 region and the landward vergence in the lower trench slope region. Location of the profile is
19 shown in Fig. 1. Vertical exaggeration (VE) is calculated using $V_p = 1,500$ m/s.

20

1 Figure. 3:

2 MCS Line 5 profile of the forearc high region (time migrated section): (a) Non-interpreted
3 seismic profile of Line 5 from CMP#5750 to #12050, and (b) interpreted seismic profile.

4 This profile shows an example of landward-dipping thrust faults, anticlinal ridges and piggyback
5 basins in the forearc high region offshore northwestern Sumatra. An abbreviation of “MT”
6 indicates the Middle Thrust. Location of seismic profile is shown in Fig. 1. VE is calculated
7 using $V_p = 1,500$ m/s.

8

9 Figure. 4:

10 Map showing geologic and geomorphic interpretation of our study area offshore northwestern
11 Sumatra. Thrust faults (red bold line), faults (red line), anticlines (blue line), synclines (green
12 line), and erosive outcropping surface (ellipse using black dashed line) are identified based on
13 MCS profiles and bathymetric map. Lineaments (black line) are based on the bathymetric map.
14 The position and interpretation of the N-S trending dextral strike-slip fault (cyan line) is from
15 Permana et al. (2011). Red stars (☆) locate recent deformation.

16

17 Figure. 5:

18 MCS Line 3 profile of the forearc high region (time migrated section): (a) Non-interpreted
19 seismic profile, and (b) interpreted seismic profile. The Middle Thrust is clearly identified at
20 CMP#2100 and deforms the upper part of the piggyback basin. An abbreviation of “MT”

1 indicates the Middle Thrust. Location of the profile is shown in Fig. 1. VE is calculated using V_p
2 = 1,500 m/s.

3

4 Figure. 6:

5 Close up of an eroded anticline with outcropping strata (Line 11, time migrated). (a)

6 Bathymetric map with Lines 11 and 12c (see CMP#4500-5800 of Fig. 7a) across the anticlinal

7 ridge. (b) Close up profile between CMP#2310 to #4650 of Line 11. The surface sequence of an

8 anticlinal ridge is eroded along bedding and is recognized by the outcrop of the bed. Location of

9 seismic profile is shown in Fig. 1. VE is calculated using $V_p = 1,500$ m/s.

10

11 Figure. 7:

12 The largest Piggyback basins with sediments in the forearc high region: (a) Seismic profile of

13 Line 12c (time migrated section), (b) Close up of profile from CMP#4400 to #6300, and (c)

14 interpreted close up profile. The close up profile shows the largest piggyback basin with

15 sediments in the southwestern part of the forearc high region. Location of seismic profile is

16 shown in Fig. 1. VE is calculated using $V_p = 1,500$ m/s.

17

18 Figure. 8:

19 Piggyback basins with sediments deposited mostly after folding and eroded anticline ridges on

20 the forearc high region. (a) Close up profile between CMP#4400 to #6300 of Line 1 (time

migrated section), (b) Interpreted close up profile. This profile shows landward tilted reflector of piggyback basin sequence. Location of seismic profile is shown in Fig. 1. VE is calculated using $V_p = 1,500$ m/s.

Figure. 9:

Slope-failure morphology and recent deformation around the Middle Thrust. (a) Map showing the Middle Thrust in the south part of our survey area. Slope-failure morphology can be identified along the Middle Thrust (Hirata et al., 2010). (b) Close up profile of Line 12c from CMP#5450 to #6820. (c) Close up profile of Line 13 from CMP#3760 to #5400. These profiles show the upper part of the sedimentary basin around the Middle Thrust. “MT” locates the Middle Thrust. VE is calculated using $V_p = 1,500$ m/s.

Figure. 10:

Locations of typical recent seafloor deformation identified between the Middle and Upper Thrusts in the forearc high region. (a) Location map with bathymetry, (b) Close up profile of Line 4 from CMP#7450 to #6000, (c) Close up profile of Line 5 from CMP#3580 to #4650, (d) Close up profile of Line 12c from CMP#9100 to #10580. These profiles show that recent deformation has occurred between the Middle and Upper Thrusts. VE is calculated using $V_p = 1,500$ m/s.

Figure 3

Fig. 7