NEOTECTONICS OF THE SOUTHERN SUMATRAN FOREARC

M. Ma'ruf Mukti*
Satish C. Singh*
R. Moeremans*
N. D. Hananto**
H. Permana**
I. Deighton***

ABSTRACT

The structural features in the Mentawai forearc have been interpreted as products of the compression of the accretionary wedge and forearc basin sediments with high-quality industry-standard seismic reflection data. Compressional phases since the Late Miocene initiated (a) the landward vergent fold-thrust belt in the Mentawai Fault Zone (MFZ), (b) reactivation of seaward vergent imbricated thrusts in the retro-accretionary wedge, and (c) uplift of the accretionary wedge and some parts of the forearc basin. The landward vergent fold-thrusts formed as forward-breaking structures toward the northeast. These structures were disrupted by mud diapirism since the Pliocene. The landward vergent fold-thrust belt is rooted at depth to the Main Backthrust that lies at the boundary between the accretionary wedge and continental backstop. The alignment of the fold-thrust belt is controlled by the geometry and position of continental backstop. The seaward vergent imbricated thrusts were contracted and deformed sediments in the overlying piggy-back basin, indicating the shortening of the accretionary wedge since early Middle Miocene. In the northwest, the MFZ is developed on the western margin of the present forearc basin, whilst in the southeast it is near the present basin depocenters. The accretionary wedge formed as a narrower zone in the northwest area. The slope of the Pliocene sediments is highly rotated in the northwestern area. Those features suggest that the northwest part of the accretionary wedge underwent higher compression and tilting. The location of the higher uplifted forearc area coincides with the locus of impingement of the Investigator Ridge. The compression of the forearc is suggested to be controlled by the combination of the geometry and position of the continental backstop, and the subducting bathymetric high in the oceanic plate. These factors govern the neotectonic features in the southern Sumatran forearc.

INTRODUCTION

The present-day subduction along offshore Sumatra represents a classical example of oblique subduction. Deformation in such oblique settings is characterized by slip partitioning between the orthogonal and the arc parallel component of motions. These two components are represented by the megathrust and Sumatra Fault (McCaffrey, 2000). The Mentawai Fault (MF) has developed along a linear NW-SE trend following the western margin of the forearc basin from Nias Island to Sunda Strait (Diament et al., 1992). The MF is probably connected to the West Andaman Fault (WAF) to the north (Izart et al., 1994) and formed a major structure along the western Sunda margin (Figure 1).

Uncertainties remain as to the origin of the Mentawai Fault Zone (MFZ). This fault zone was previously interpreted as a strike-slip setting based on positive flower structures on seismic profiles and the continuous linearity of the structure on the geographic map (Diament et al., 1992). Samuel et al., (1995) suggested that the MFZ has developed as an inversion of previous extensional faults. Results of seismic tomography and seismic reflection data have suggested the idea of backthrusting along the WAF (Chauhan et al., 2009). Recent results based on shallow seismic reflection and bathymetry data show that the MFZ was formed by a set of landward vergent backthrusts in front of Siberut Island (Singh et al., 2010). Deep seismic reflection studies were able to image the backthrust down to a depth of 20 km in the Sumatra subduction zone (Chauhan et al., 2009; Singh et al., 2011a). Shallow failures along

---

***	IPG Paris**
****	Geotek – LIPI**
*****	TGS**

the backthrust can be explained by coseismic displacement during moderate-earthquake clusters in 2005 and 2009, based on analysis of geodetic and earthquake focal mechanisms data (Wiseman et al., 2011). The backthrust might have ruptured co-seismically during the 2004 and 2007 earthquakes, based on a comparative study of deep images across the locked zone and the 2004 and 2007 ruptured areas (Singh et al., 2011a). Recent uplift has been found on one of the islands, west of Simeulue (Meltzner et al., 2010), indicating that the backthrust might have ruptured co-seismically during the 2004 great Sumatra earthquake.

The geometry of structures developed in the forearc area is very important for studying the megathrust coseismic failures and for producing seismic hazard assessments, particularly in the Mentawai Locked zone. In this area, the structures are actually related to the backthrusting of the retro-accretionary wedge. We present the structural style of neotectonic features along the MFZ and the forearc high, the distribution along the southern Sumatran forearc, and discuss the possible controlling factors of the deformation.

DATA AND METHOD

Seismic reflection data were provided by CGGVeritas and TGS (Figure 1). Deep seismic reflection profiles were acquired by CGGVeritas using the Geowave Champion marine vessel towing three streamers. One streamer was 15 km long, the longest streamer ever used and towed at 22.5 m water depth. Two additional 6-km long streamers were towed at 7.5 m and 15 m water depths. An array of airguns with a total volume of 9600 cubic inches were used as source and deployed at 15 m depth (Singh et al., 2009). The shot spacing was 50 m and the record length was 20 s. The data were resampled to 4 ms and processed using 2-90 Hz anti-alias filter. An iterative velocity analysis was used in combination with 4-6 passes of a radon multiple removal technique. The data were processed using a pre-stack Kirchhoff depth migration technique.

Independently, TGS had acquired deep seismic reflection data in the forearc basin. There are 36 lines spaced at a 20 km interval crossing the forearc basin along with 6 basin-parallel lines. The data were acquired using a 7.95-km long streamer towed at 7 m depth, with 3940 cubic inch air gun sources towed at 5 m depth. The shot spacing was 37.5 with 12 s record length. The data were resampled to 4 ms and processed using a Kirchhoff pre-stack time migration technique.

Swath bathymetric data set was acquired by several working groups during different cruises (Berglar et al., 2010) and complemented by global bathymetry (Smith and Sandwell, 2007) (Figure 1). The surface expression of faults in the deformation zone can be observed in the bathymetric map.

The temporal variation of the structures is constrained by the growth strata (Suppe et al., 1992). Stratigraphic intervals are divided into seismic units that are bounded by major seismically defined stratigraphic surfaces, which often correlate with important geological events. The age of seismic units is controlled by well data in the shallow forearc basin.

STRUCTURAL INTERPRETATION

There are two major features expressed on the bathymetry, the NW arcuate shaped ridges convex toward the east in the MFZ and parallel-subparallel NW trending ridges in the forearc high (Figure 2). On the seismic profiles these ridges are actually anticlines formed due to faults developed in their cores. Backthrusts and fold-thrusts are developed in the MFZ, and imbricated thrusts are formed beneath the forearc high (Figure 3). Based on the extrapolation of well data in the inner forearc basin and outcrop in the forearc high, the sediments in the deeper forearc are divided in to six unit, Unit A-B which correspond to the Pliocene-recent sediments, Unit C-E (Late – Middle Miocene) and Unit F (Early Miocene). These strata constrain the temporal interpretation of the structures developed in the forearc.

Backthrusting and fold-thrust

Beneath the main ridge, Anticlinal Ridge 1 (AR1), high-angle thrusts deformed the sediments (Figure 3). To the east, Anticlinal Ridge 2 (AR2) formed as structure parallel-subparallel to AR1. To the north, this ridge exhibits more convexity, and in some places is covered by young sediments. The high angle thrusts beneath AR1 seem to be rooted at depth with the landward verging imbricated thrusts that deformed the inner part of the accretionary wedge, the Main Backthrust (MBT) (Figure 4). There is no indication of deformation or vertical displacement on the horizon beneath the accretionary wedge, or the top Paleogene. Therefore we suggest that the MBT is developed along the southwest dipping continental backstop. This continental backstop continues downward with southwest dipping slope to the top of the oceanic crust. The geometry of this continental backstop was confirmed by seismic refraction and gravity modeling (Kopp and Kukowski, 2003).

Beneath AR2, anticlines developed due to a landward vergent thrust that deformed the sediments up to Unit B, named herein as the Frontal Backthrust (FBT) (Figure 4). There is no indication of folding or vertical displacement on the continental backstop, hence we suggest that these thrusts continue downward into the gently dipping detachment fault and are rooted into the MBT. The detachment fault initiated toward the east, indicated by off set of Unit E-F and folding of sediments up to Unit B.

The initiation of high angle thrust beneath AR1 can be traced to the Late Miocene. To the east, the FBT1 is formed afterward as indicated by folding up to Unit C beneath AR2 in the west. A younger deformational event formed the gentle anticline that built AR2 in the east, confirmed by folding of sediments up to Unit B.

Further north, AR1 and AR2 are also represented by folding and thrusting deforming the sediments (Figure 5). The growth strata confirm the temporal variation of the structures, and we interpret that the fold-thrust belt is developed landward side, similar to the one in the southeast. Locally, fold-thrust structures are also formed to the west, and formed contemporaneously with those in AR1. These fold-thrust structures seem to be related to the MBT through the detachment fault developed beneath Unit F since there is no indication of coeval deformation in the underlying sediments. The lower part of Unit E is characterized by a chaotic to less reflective seismic zone, visually equivalent to the shale dominated unit in the shallow area. This detachment fault accommodates the shortening of the forearc basin sediments. Collapse structures are formed above the anticlines, to the west of AR1 (Figure 5). These structure are interpreted to have formed by mud diapirism. A mud volcano exists to the east of the MBT, within the fold-thrust belt typically as ~2 km diameter conical features on the seafloor (Figure 2B).

Imbricated thrusts

A northwest trending group of ridges is observed on the seafloor along a ~40-km wide structural forearc high (Figure 2D). The traces of the limbs of these parallel-subparallel ridges makes up the observed regional trend of these structures, and mimics the trend of the frontal thrusts in the deformation front (Singh et al., 2011b). On the seismic profiles, anticlines make up these ridges, and involve sediments up to Unit B age (Figure 3). These anticlines formed by seaward vergent thrust faults that seem to have rooted at depth into the imbricated thrusts. These imbricated thrusts are formed with overturned anticlines and tightly squeezed synclines on the top of the accretionary wedge. These structures were developed as 6-7 closely-spaced thrusts and named herein as the Forearc High Thrusts (FHT). These thrusts are interpreted to have formed due to the contraction of the retro-accretionary wedge and subsequently created piggy-back basins in the forearc high. The sediments of the lower unit appear with more intense deformation compared to the overlying units. Due to the further contraction of the accretionary wedge, the thrusts were back-rotated and induced the uplift of the forearc high.

Uplift of the forearc

Fold-thrust belts in the MFZ formed as parallel to subparallel anticlinal ridges on the seafloor, with arcuate ridges convex toward the northeast. The convex ridges are reflecting the propagation of the structures toward the northeast. Thrust events were developed in the area of the MBT, suggesting the presence of backthrusts (Figure 6). The MFZ expresses the boundary between the accretionary wedge and continental backstop in the subsurface. The continental backstop is formed by the Paleogene sediments and basement, which overly the continental crust (Figure 7).

In the northwest, the MFZ is developed on the western margin of the present forearc basin, whilst in the southeast it is near the present basin depocenters, hence suggesting that the accretionary wedge formed as a narrower zone in the northwest area. The slope of the Pliocene sediments is highly rotated in the northwestern area. This observation suggests that the northwest part the accretionary wedge underwent greater compression and tilting. The location of the uplifted and tilted area also coincides with the locus of impingement of the Investigator Ridge. The topography of the subducted ridge appears to influence seismicities at all depth intervals (Lange et al., 2010). It is likely that ridges on the subducted oceanic plate controlled the neotectonic structures on the forearc area.

CONCLUSIONS

Compressional phases in the forearc since the Late-Miocene initiated (a) the landward vergent fold-thrust belt in the Mentawai Fault Zone (MFZ), (b) reactivation of seaward vergent imbricated thrusts in the retro-accretionary wedge, and (c) uplift of the accretionary wedge and some parts of the forearc basin.

The landward vergent fold-thrusts formed as forward-breaking structures toward the northeast. These structures were disrupted by mud diapirism. The landward vergent fold-thrust belt is rooted at depth to the Main Backthrust that lies at the boundary between the accretionary wedge and continental backstop. The alignment of the fold-thrust belt is controlled by the geometry and position of the continental backstop.

Fold-thrusts in the forearc high were reactivated during the contemporaneous compression of the forearc basin. These structures deformed the sediments in the piggy-back basin and seem to be rooted at depth with the seaward vergent imbricated thrusts.

The accretionary wedge formed as a narrower zone in the northwest area, due to locally increased compression and tilting. The location of the uplifted forearc area coincides with the locus of impingement of the Investigator Ridge on the forearc. The compression of the forearc is suggested to be controlled by the combination of the geometry and position of the continental backstop and the subducting bathymetric high in the oceanic plate. These factors governed the neotectonic features in the southern Sumatran forearc.

ACKNOWLEDGEMENTS

The authors thank CGGVeritas and TGS for providing the seismic data and MIGAS for giving permission to publish this work. Special thank to Derik W. Kleibacker for his comments and edit on the manuscript. We also thank the technical committee for accepting our contribution to this IPA meeting.

REFERENCES

Berglar, K., Gadicke, C., Franke, D., Ladage, S., Klingelhoefer, Djajadiharddja, Y.S., 2010. Structural evolution and strike-slip tectonics off north-western Sumatra. Tectonophysics 480, 119-132.

Chauhan, A.P.S., Singh, Hananto, N.D., Carton, H., Klingelhoefer, F., Dessa, J-X., Permana, H., White, N.J., Graindorge, and SumatraOBS Scientific team, 2009. Seismic imaging of forearc backthrust at northern Sumatra subduction zone. Geophysical Journal International, doi: 10.1111/j.1365-246X.2009.04378.x.

Izart, A., Kemal, B.M., Malod, J.A., 1994. Seismic stratigraphy and subsidence evolution of the northwest Sumatra forearc basin. Marine Geology 122, 109–124.

Kopp, H., Kukowski, N., 2003. Backstop geometry and accretionary mechanics of the Sunda margin, 2003. Tectonics 22, 6, 1072, doi:10.1029/2002TC001420

Lange, D., Tilmann, F., Rietbrock, A., Collings, R., Natawidjaja, D.H., Suwargadi, B.W., Barton, P., Henstock, T., Ryberg, T., 2010. The Fine Structure of the Subducted Investigator Fracture Zone in Western Sumatra as Seen by Local Seismicity. Earth and Planetary Science Letters 298, 47–56

McCaffrey, R., Zwick, P., Bock, Y., Prawirodirdjo, L., Genrich, J., Stevens, C.W., Puntodewo, S.S.O, Subarya, C., 2000. Strain partitioning during oblique plate convergence in northern Sumatra: Geodetic and seismologic constraints and numerical modeling, Journal of Geophysical Research 105, 28,363-28,376

Meltzner, A.J., Sieh, K., Chiang H-W., Shen, C-C., Suwargadi, B.W., Natawidjaja, Philibosian B.E., Briggs, R.W., Galetzka, 2010. Journal of Geophysical Research 115, B10402, doi:10.1029/2010JB007499.

Pesicek, J.D., Thurber, C.H., Zhang, H., DeShon, H.R., Engdahl, E.R., Widiyantoro, S., 2010. Teleseismic double - difference relocation along the Sumatra - Andaman subduction zone using a 3 - D model, Journal of Geophysical Research 115, B10303, doi:10.1029/2010JB007443

Prawirodirdjo, L., Bock, Y., 2004. Instantaneous global plate motion model from 12 years of continuous GPS observations, Journal of Geophysical Research 109, B08405, doi:10.1029/2003JB002944.

Samuel, M.A., Harbury, N.A., Jones, M.E., Matthews, S.J., 1995. Inversion of an outer-arc ridge: the Sumatran Forearc, Indonesia, *in* Buchanan, J.G., Buchanan, P.G., (eds.), Basin

Inversion, Geological Society Special Publication 88, 473–492.

Singh, S. C., Hananto, N.D., Chauhan, A.P.S., Permana, H., Denolle, M., Hendriyana, A., Natawidjaja, D., 2010. Evidence of active backthrusting at the NE margin of Mentawai Islands, SW Sumatra, Geophysical Journal International 180, 703–714, doi:10.1111/j.1365-246X.2009.04458.x.

Singh, S.C., Hananto, N.D., Chauhan, A.P.S., 2011a. Enhanced reflectivity of backthrusts in the recent great Sumatran earthquake rupture zones. Geophysical Research Letters 38, L04302, doi:10.1029/2010GL046227.

Singh, S.C., Hananto, N., Mukti, M., Permana, H., Djajadiharja, Y., Harjono, H., 2011b. Seismic images of the megathrust rupture during the 25th October 2010 Pagai earthquake, SW Sumatra: Frontal rupture and large tsunami. Geophysical Research Letters 38, L16313, doi:10.1029/2011GL048935

Singh, S.C., Midenet, S., Djajadihardja, Y.S., 2009. Seismic survey of the locked and unlocked Sumatra subduction zone, Eos Trans. AGU, 90 (49), 471–478.

Smith, W. H. F., Sandwell, D.T., 1997. Global seafloor topography from satellite altimetry and ship depth soundings. Science 277, 1957-1962.

Suppe, J., Chou, G.T., Hook, S.C., 1992. Rates of folding and faulting determined from growth strata. *In* McClay, K.R., (ed), Thrust Tectonics, Chapman and Hall, London, 105-121.

Wiseman, K., Banerjee, P., Sieh, K., Bürgmann, R., Natawidjaja, D.N., 2011. Another potential source of destructive earthquakes and tsunami offshore of Sumatra. Geophysical Research Letters 38, L10311, doi:10.1029/2011GL047226.

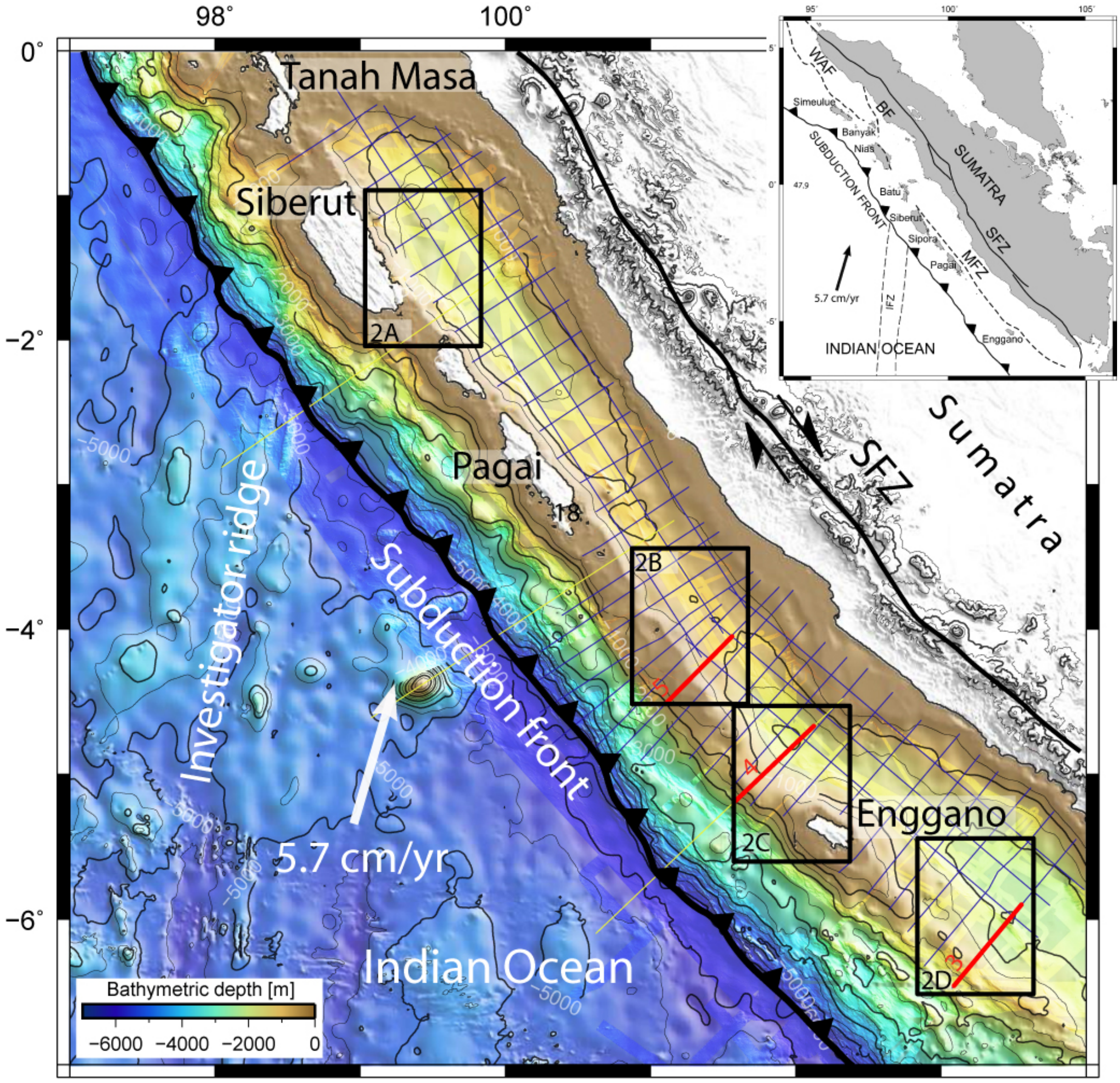

Figure 1 - Location map. Red lines are seismic profiles shown in this study. Yellow lines are seismic data provided by CGGVeritas. Blue lines represent data from TGS. Black rectangles show zoom in bathymetric features along MFZ. Boxes with numbers are the zoom in bathymetry shown in Figure 2 and 10. White arrow is the convergence vector after Prawirodirdjo and Bock (2004). Thick contour lines represent 1000 m interval. Inset is the tectonic setting of Sumatra, MFZ=Mentawai Fault Zone, Sumatra Fault Zone (SFZ), Batee Fault (BF), West Andaman Fault (WAF), Investigator Fracture Zone (IFZ).

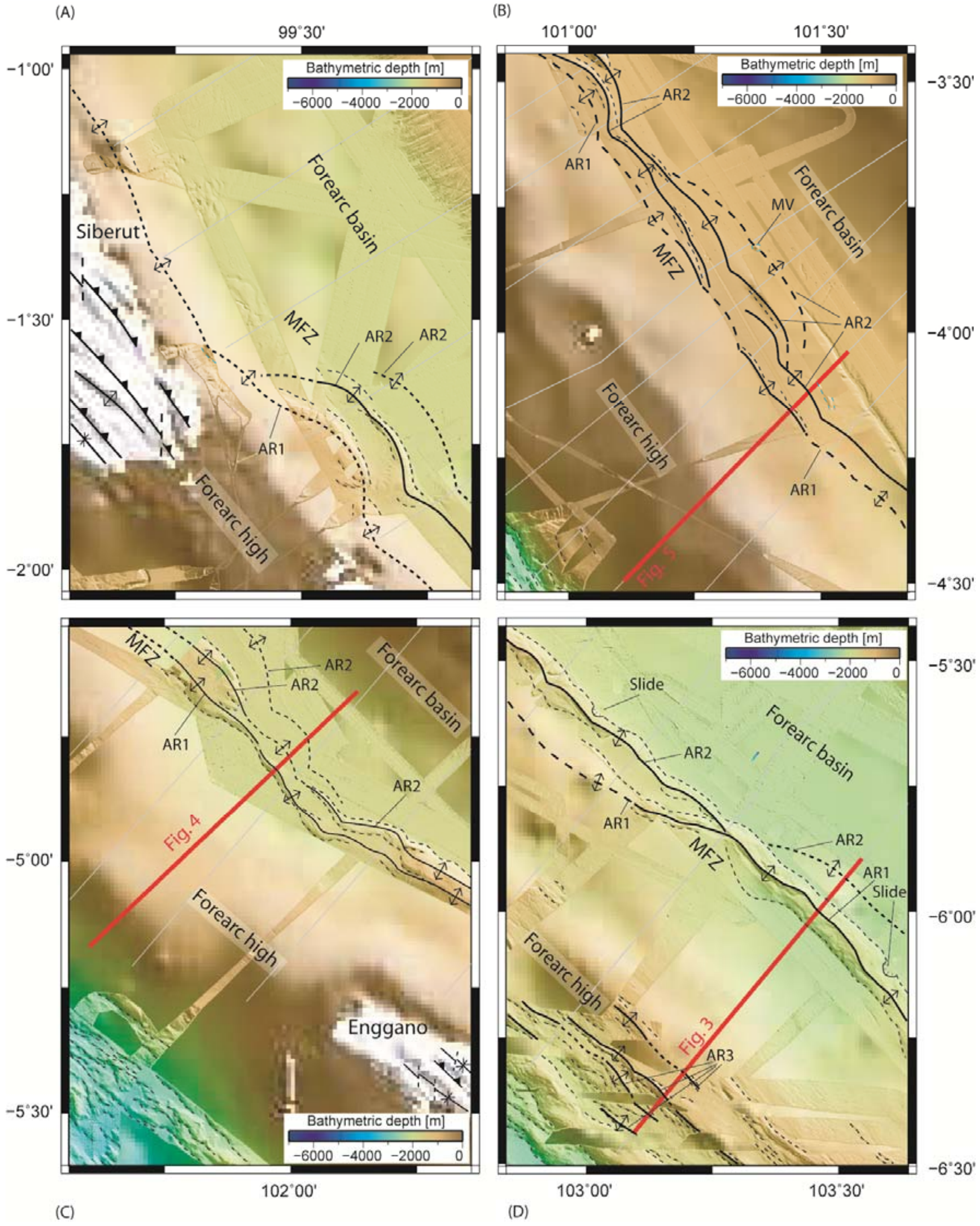

Figure 2 - Bathymetric features of MFZ. AR=Anticlinal Ridge. Solid thick black line is the axis of the anticline. Dashed tick line marks the continuation of axis of the anticline observed on the seismic profiles. Dashed thin black line represents the direction of southwest and northeast limb of the anticlinal ridge on the seafloor. MV=mud volcano. Thin highlighted grey lines represent the seismic lines. Red lines are the seismic profiles shown in this paper.

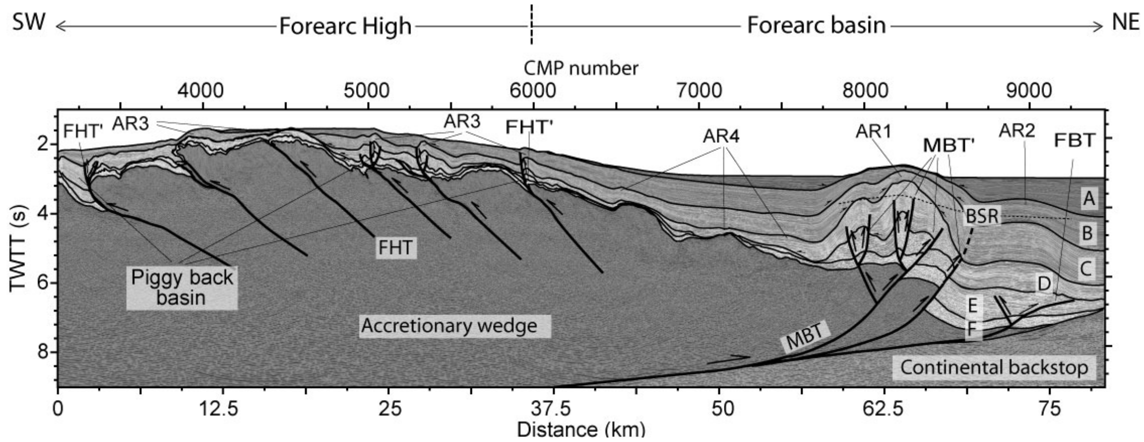

Figure 3 - Interpreted seismic section of line 135-SSS. AR=Anticlinal Ridge, MBT=Main Backthrust, FBT=Frontal Backthrusts, FHT=Forearc High Thrust. Unit A–F represent unit of forearc basin sediments of Early Miocene – recent age.

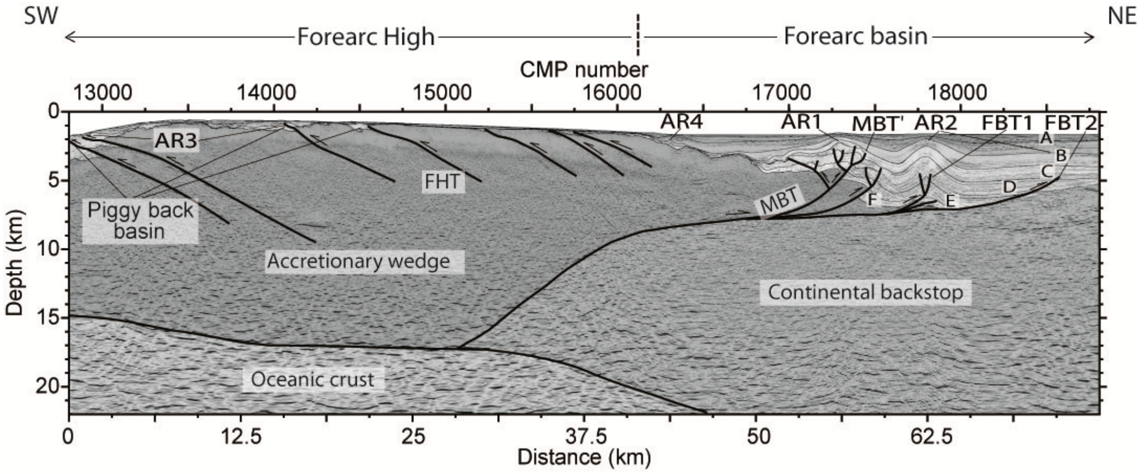

Figure 4 - Interpreted seismic section of line CGGV040 across the MFZ. AR=Anticlinal Ridge, MBT=Main Backthrust, FBT=Frontal Backthrust, FHT=Forearc High Thrust Unit A – F represent unit of forearc basin sediments of Early Miocene – recent age.

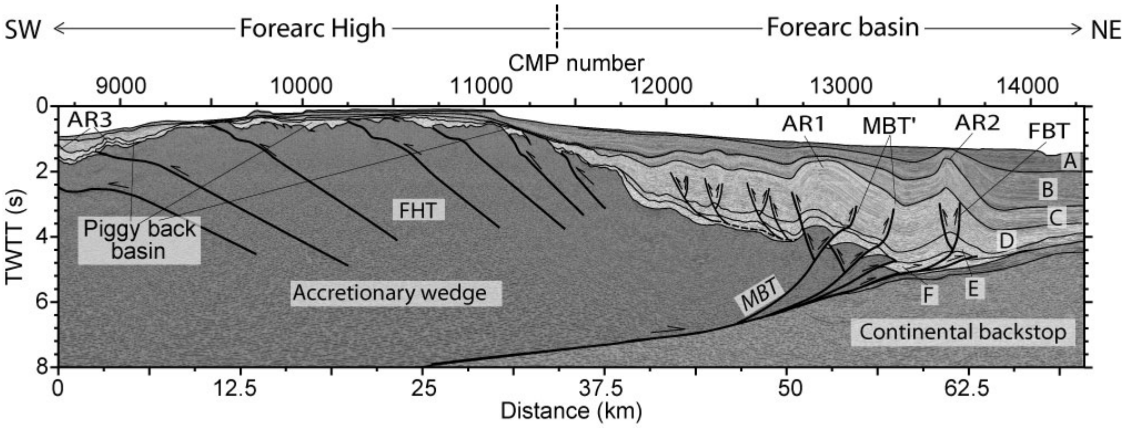

Figure 5 - Interpreted seismic section of line 223-SMI across the MFZ. AR=Anticlinal Ridge, MBT=Main Backthrust, FBT=Frontal Backthrust, FHT=Forearc High Thrust. Unit A–F represent unit of forearc basin sediments of Early Miocene – recent age.

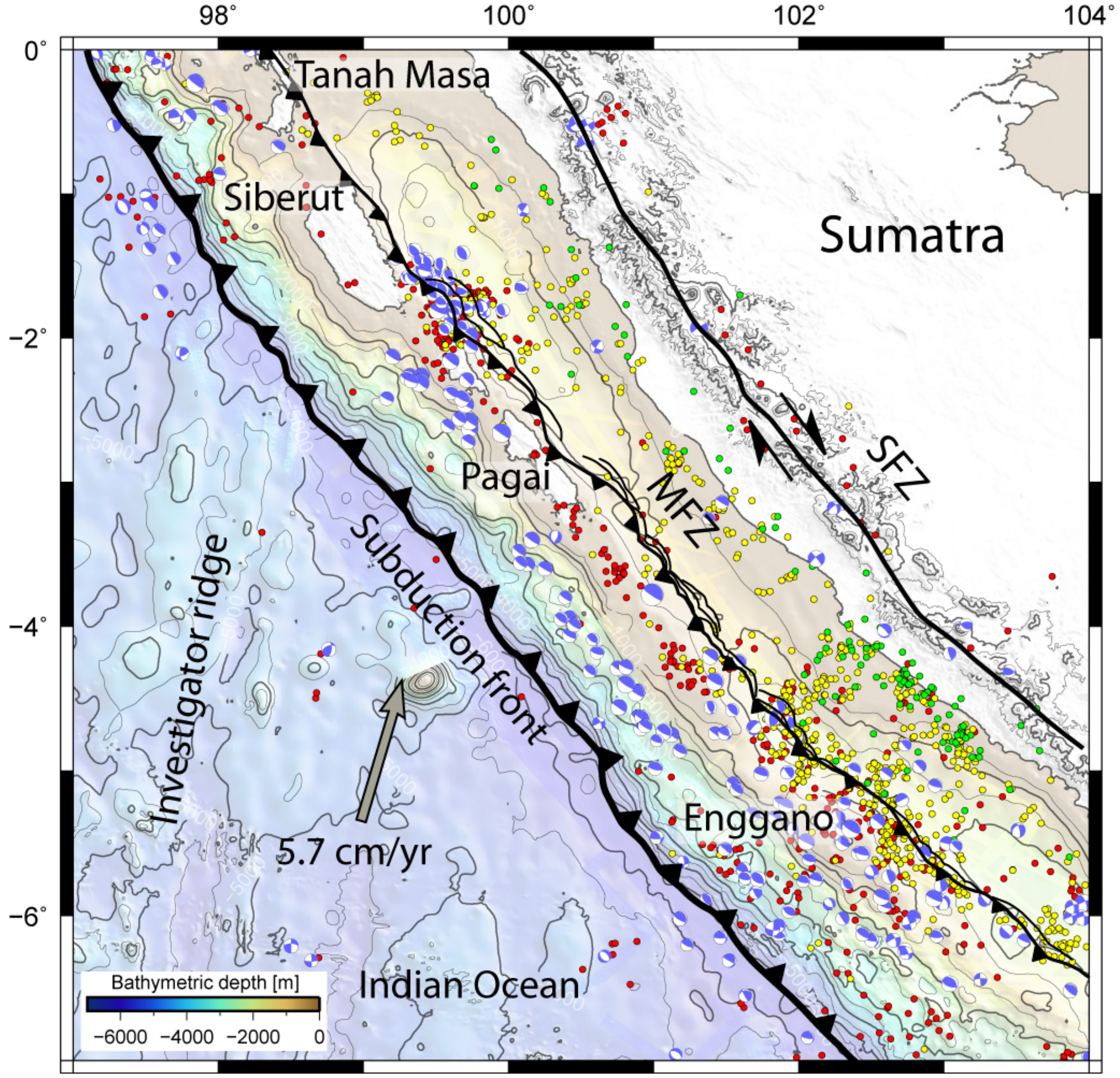

Figure 6 - Map of the MFZ along the basin. Black solid line represents the projection of MBT. Thin black lines represent axis of folds formed in the fold-thrust belt. Red, yellow and green circles represent relocated earthquakes with depth of 0-30, 30-60, and 60-90 km, respectively (Pesicek et al., 2010). Beach balls represent the GCMT focal mechanisms plotted at their centroid locations (1976-2010) for earthquake ~ 30 km depth.

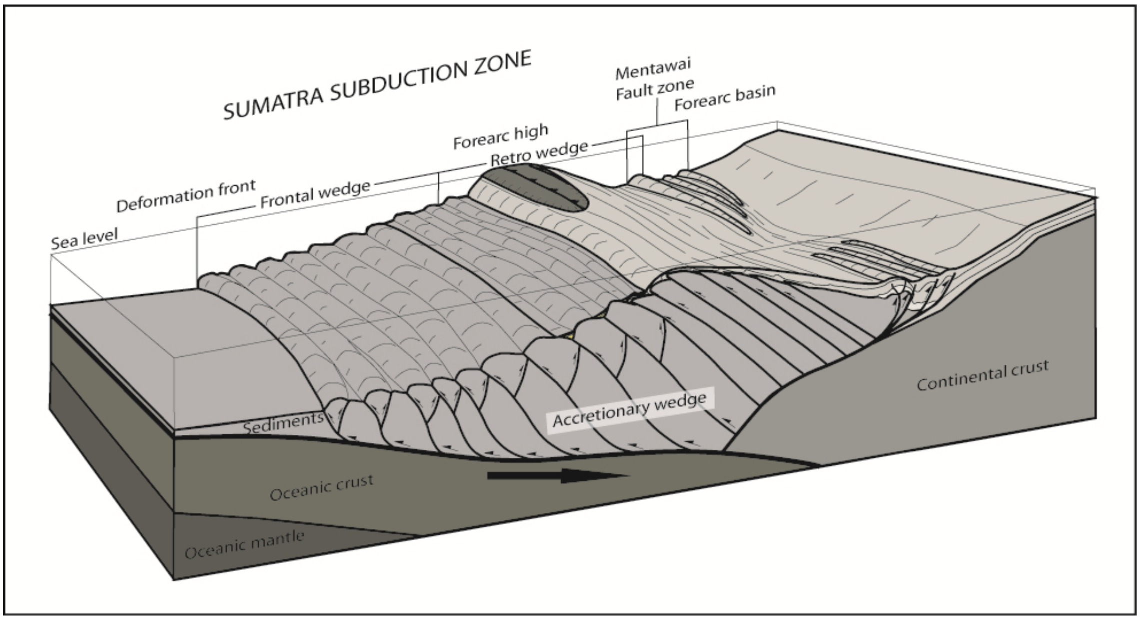

Figure 7 - Schematic tectonic framework of Sumatra subduction zone in the Mentawai forearc area. The imbricated thrust in the frontal wedge is adapted from Singh et al. (2011b).