The growth of forearc highs and basins in the oblique Sumatra subduction system

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Abstract

Strain partitioning in an oblique subduction system controlled the development of a major shear zone near volcanic arc and additional strike-slip displacements that uplifted the forearc high and detached from the forearc basin. However, previous and recent studies in the Sumatra forearc also proposed that the forearc high areas have developed due to several processes that include flexural uplift, basin inversion, uplift of older accretionary wedge, and backthrusting in the landward edge of the accretionary wedge. We reviewed those observations to understand the uplift mechanisms of forearc high and the formation of the forearc basin in the oblique Sumatra subduction system. Observation of recent seismic reflection data shows that the interplay between trenchward-vergent thrusts and arcward-vergent backthrust has played a major role in the uplift of forearc high. The uplifted sediments on the forearc high were previously formed in a forearc basin environment. The present-day morphology of the forearc high and forearc basin is related to the uplift of the accretionary wedge and the overlying forearc basin sediments in Pliocene. Regardless of obliquity in the subduction system, the Sumatran forearc region is dominated by compression that plays an important role in forming Neogene basin depocenters that elongated parallel to the trench.

Keywords: oblique subduction; strain partitioning; forearc; thrust fault; strike-slip fault.

1. Introduction

In an oblique subduction zone, strain partitioning occurs between displacement on the subduction megathrust and strike-slip motion parallel to the trench[1–3] and plays an important role in forearc region configuration and development[4–7]. Along the oblique Sumatra subduction zone, the arc-parallel motion is accommodated by the Sumatran Fault (SF), which together with the trench bounded a sliver plate in between[1,2] (Fig. 1). This hypothesis is expanded by a suggestion that other major faults take place in the forearc region. These shear zones, the Mentawai Fault (MF) and West Andaman Fault (WAF), separate the forearc basins from the forearc high, which is occupied by the uplifted accretionary wedge complex[8–11]. However, recent data from Andaman and Sumatra forearc show that even though obliquity occurs in this convergent margin, the forearc high is bounded by compressional structures with minor strike-slip motion[12–16]. Furthermore, previous studies in the Sumatra forearc proposed that deformation in the forearc high areas also include flexural uplift, basin inversion, and uplift of older accreted materials[16–18]. This paper reviews several schemes on the forearc high's growth related to oblique subduction and its implication to subsidence of the forearc basin.

2. Geologic setting

Oblique subduction of the Indo-Australian plate beneath the western Sunda margin at a convergence rate of 43 to 60 mm/yr, formed strain partitioning between the trench-perpendicular displacement within the subduction megathrust and the trench-parallel motion along the SF zone[1]. Several large earthquakes had been recorded along with this oblique subduction system[23–27] that became the site for a northwest-trending forearc high area. Other terms applied for this area of the trench-slope break (i.e., outer arc ridge, outer arc high) have been discussed based on the morphology and origin of the tectonic features on the forearc region[28]. Some of these forearc high areas are exposed above sea level, from Simeulue Island in the northwest to Enggano in the southeast (Fig. 1). Farther north, the islands of Andaman–Nicobar islands make up the northern extension of the forearc high area. Whereas to the east, the forearc high is observed on the bathymetry of the south Java and Lesser Sunda forearc[29,30].

The origin of the Sumatran forearc high have been interpreted due to the uplift accretionary wedge complex in relation with strike-slip displacements due to strain partitioning[10,31–33], inversion-controlled uplift[16], homoclinal flexure and reverse fault[17,34,35], uplift of the Paleogene accretionary wedge[18], arcward-vergent backthrusts[12,13,15,36] (Fig. 2). The Sumatran accretionary wedge complex itself is developed due to the incorporation of Sunda trench sediments[18,33,37,38]. Structures developed in the forearc high have been interpreted as either thrust faults or inverted normal faults[12,15,16,18,35] and shear zones[9,32,33,39]. Rocks exposed on the forearc high islands are of sedimentary origin, with basement rocks having a mixture of continental and oceanic origin[16,17,35].

To the east of the forearc high, the Paleogene and early Neogene forearc basins formed in localized depocenters bounded by north-trending faults[32,38,40–42] related to transtensional setting between two major strike-slip faults, the WAF-MF and SF[40–42]. The SF extends along the backbone of Sumatra Island. This large strike-slip fault zone enters the Andaman Sea in the northern part of Sunda margin[13,43] and merged with another major strike-slip fault, the WAF[44]. In the southeastern culmination of the SF, the Semangko pull-apart basin developed between Sumatra and Java[45–49].

The Sumatran forearc high margin has been interpreted to have formed by major shear zones based on observation of seismic data[8,10,11,32]. However, earlier observations on this fault zone on land and offshore suggest either homoclinal flexure or inverted-normal faults along the edge of forearc high[16,34,35]. Based on observation of high-resolution seismic reflection data, the arcward boundary of the Sumatra accretionary wedge is occupied arcward-vergent backthrusts[12,13,15,36,50] that continued at depth to a trenchward dipping backstop[15,51].

3. Observations on the Sumatran forearc

Here we described our observations on the previous published structural and stratigraphic interpretation along the Sumatran forearc basins.

3.1. Strain partitioning, sliver plates, and shear zones

The early proposal of strain partitioning in Sumatra forearc has been suggested by the distribution of the trench-perpendicular and trench-parallel convergence motions in the subduction megathrust and along SF, respectively[1,2,52]. The Sumatra Fault zone stretches more than 1700 km along the axis of the island with 20 major defined segments[21]. These fault segments, which range from 60 to 200 km in length, have ruptured historical earthquakes between M6.5 to M7.7[53]. In its southeasternmost segment, SF formed a pull-apart basin caused by a step over between a segment of SF and another shear zone to the south of Java, the Ujung Kulon Fault (UKF)[10,47,48]. The UKF exhibits a distinct narrow valley and linear ridges observed on the seafloor bathymetry from the south of the pull-apart basin farther southeast toward the accretionary wedge[54].

This concept of strain partitioning in the Sumatra subduction system is expanded that trench-parallel deformation occurred in the area between the SF and the trench[8]. They argued that another major strike-slip fault zone developed in the area between the forearc high and basin referred to as MF (Fig. 1)[8]. This shear zone formed as a 600-km-long linear feature in the western boundary of the forearc basins extending from Nias to Sunda Strait, exhibiting many positive flower structures on the seismic profiles[8,10].

Later on, the concept of strain partitioning in Sumatra is described by a model of two sliver plates here referred to as the Mentawai and Aceh sliver plates that host the forearc basin (Fig. 1)[10]. This model proposed that the trench-parallel strain is facilitated along three major shear zones: SF, MF, and WAF (Figs. 1 and 2A). The MF is attenuated farther north and connected to SF through Batee Fault (BF). The accretionary wedge itself is moving northwestwards along MF. Therefore, SF and MF bounded the elongate Mentawai sliver-plate. In northern Sumatra, SF and WAF bound the Aceh microplate. The WAF shows vertical offsets of reflectors along the western edge of the northern Sumatra forearc basins[11,32]. WAF appears to have crossed the accretionary wedge and developed farther west on the seafloor[11,55]. Farther south, this fault appears to have continued to a complex of anticlinal structures interpreted as Tuba Ridge[9,10,31,32] and bounded by another shear zone developed within the forearc basin. This shear zone has been interpreted as the southern extension of the WAF[9–11,32,55]. Malod & Kemal

(1996) argued that the flexural bending in the forearc basement under the accretionary wedge, thrust faults in Banyak Islands, and anticlinal ridge near Simeulue indicate the activity of strike-slip displacement between this sliver plate and accretionary wedge[10]. Fig. 3A shows examples of deformation in the boundary between the northern Sumatra forearc high and forearc basin related to the activity of strike-slip fault[11]. The faults observed on the seismic profiles are classified into five groups; Group I to IV are part of strike-slip faults that cut through the seafloor, whereas Group V faults are for thrusts that appear as blind faults. Here we can clarify that the arcward-vergent blind thrust fault is formed earlier than the strike-slip faults, suggesting different initiation times.

The sliver-plates concept in the Sumatran forearc is updated by a hypothesis that large-scale strike-slip duplexes formed in the forearc basins (Fig. 3B)[31]. They recognized a set of strike-slip faults relating SF and MF zones based on observations of swath bathymetry, high-resolution sub-bottom profile, and seismic reflection data. These strike-slip faults detached four horses within a large duplex. These authors proposed that each horse structure includes a single forearc basin with varied depositional patterns since at least the Middle–Late Miocene: the Bengkulu, Nias, Simeulue, and Aceh basins. These duplexes spread northward along the Sumatran forearc up to the Early Pliocene. The connecting splay faults, the Siberut and Batee faults, formed near Batu and Banyak islands. Furthermore, several authors suggested that during Paleogene and early Neogene, a part of the strike-slip displacements is transferred within the forearc basins[38,40–42]. They argued that the Paleogene South Sumatra forearc basins developed as localized depressions within a transtensional setting. In contrast, north-trending faults bound the sub-Neogene depressions in the north Sumatra forearc.

3.2. Basin inversion-controlled uplift

Uplift of the Sumatran forearc high might also have formed due to a subduction-driven deformation, represented by the inversion of the Oligocene-Early Miocene forearc basins that initially formed along the trenchward margin of the forearc (Fig. 4)[16]. Based on field observation in Nias, these authors interpreted the inverted faults formed in a northwest trend parallel to the axis of the island. These inverted faults were initially formed as normal faults that constructed several trench-parallel depocenters along the present-day forearc high axis. This basin inversion took place within two stages: the first stage was initiated in the Early Miocene, restricted in the western area of the island, while the second inversion occurred in Pliocene and involved the whole area of Nias. The linearity of the Mentawai Fault appears to have been controlled by the rate and obliquity of the subduction system.

Furthermore, previous study also revealed that the rocks overlying the basement of Nias Island were of Paleogene deep marine strata deposited in the former forearc basin[16]. Hence they were not part of accreted sediments from the trench. The accretionary wedge is developed farther southwest of Nias Island. The basement rocks comprise ophiolitic materials suggesting their source is related to the accretionary wedge environment.

3.3. Homoclinal flexure in the landward margin of forearc high

Large flexures have been observed in one of the forearc high islands related to a high-angle reverse fault at depth[34,35] (Fig. 5). The flexures were formed along the eastern edge of Nias Island parallel to the trench. These large flexures and arcward-vergent reverse faults appear to have developed in the arcward margin of forearc high. These reverse faults uplifted and deformed mass of the lower trench slope, which was assumed to migrate westward when the accretionary wedge widened during Neogene[17]. Based on their observation of the seismic profiles, Karig et al. (1980) suggested that the reverse faults beneath the flexure flatten at depth seem neither related to the Paleogene continental margin nor the leading edge of the trapped oceanic crust[35]. Furthermore, most displacements along the flexure in Nias occurred during a short interval in the late Pliocene, as suggested by a sharp unconformity and by the rapid inversion of paleobathymetry across the flexure[34]. Therefore, we can conclude that the initiation of the reverse faults postdates the growth of the trenchward-vergent imbricated thrusts in the accretionary wedge.

3.4. Uplift of older accretionary wedge complex

Based on seismic reflection data acquired during cruise SO137 with the German R/V Sonne, Schluter et al. (2002) found that the accretionary wedge could be divided into two morphological segments with different deformation styles (Fig. 6)[18]. The first segment is the inner wedge (accretionary wedge I) located beneath the forearc high, and the second one is the outer wedge (accretionary wedge II) that stretches from the trenchward boundary of the inner accretionary wedge to the trench. The accretionary wedge I characterized by 5 to 6 trenchward-vergent thrust faults is separated from the accretionary wedge II by a trenchward-vergent detachment. The outer wedge developed farther down to the trench with more complicated internal structures than the inner wedge.

In the early Paleogene, the subduction system formed the accretionary wedge I along the Sunda margin[18]. Due to continuous convergence, the inner wedge and the seaward portion of the margin underwent uplift and erosion. Later on, the inner wedge was acted as a buttress against the outer wedge formed by the off scrapping of younger trench-fill sediments. The outer wedge formation initiation induced the initial uplift of the inner wedge during the middle-late Miocene. The trenchward-vergent detachment zone between the younger accreted sediments and the Paleogene wedge (accretionary wedge I) also plays a role in the initial uplift and tilting of the inner wedge. The inner wedge started to form the present-day forearc high in the early-middle Miocene.

3.5. Doubly-vergent thrusts

In the southern Sumatran forearc high, low-angle trenchward-vergent thrust faults have been observed beneath the seafloor (Fig. 7A), here called forearc high thrusts (FHT)[15]. The flat seafloor of the forearc high that was covered by Pleistocene carbonates appears to have been tilted arcward, indicating an active deformation within the forearc high. To the east of the Enggano forearc high, arcward-vergent thrusts have been observed in the core of anticlines within the MF zone (Fig. 7A)[15]. These authors argued that in the beginning, the trenchward-vergent thrusts might have developed as overturned anticlines that later broke as thrusts due to continuous compression in the accretionary wedge. These thrusts deformed the accretionary wedge sediments as indicated by the appearance of chaotic reflectors beneath the top of the wedge. These trenchward-vergent thrust faults appear to have continued into a deep-seated arcward-vergent backthrust fault at depth beneath the forearc high that continued up dip to the thrust faults in the core of the Mentawai Fault Zone (Fig. 7A). The interplay between these two opposing direction thrust faults appears to have responsible for the forearc high uplift.

A similar pattern of trenchward-vergent thrust faults in the forearc high has been observed in the southeasternmost part of the south Sumatra forearc[18], in the northern Sumatran forearc[12,13,36,50]. Northwest-trending thrust faults have also been mapped in the Sumatran forearc high islands[42,56–59]. These observations show that these trenchward-vergence thrust fault belts dominated the deformation along the entire Sumatra forearc high. Whereas for the arcward-vergent thrusts along the landward boundary of the accretionary wedge, this fault zone appears to have developed close to the forearc high in the northern Sumatra forearc basins[12,13,50], as compared to the equivalent fault zone in the southern Sumatra, which formed in the deep forearc basin[8,15,18].

The two divergent structures of the trenchward-vergent thrusts in the forearc high and arcward-vergent thrusts in the landward margin of accretionary wedge have been suggested as previously two reverse kink bands confined a box fold structure in the early stage of accretionary wedge growth[15]. Similar mechanisms have been observed in analog and numerical sandbox modelings of accretionary wedge formative processes[60–65].

3.6. Forearc basin stratigraphy and subsidence history

Based on the present-day bathymetry, the forearc basins can be distinguished into the northern and southern Sumatra basins (Fig. 1). The name northern Sumatra forearc basin here applied loosely to the depression in the forearc stretches from the northern part of west Sumatra offshore to the southeast near Batu Islands. In comparison, the southern Sumatra forearc basin expands from the east of Mentawai Islands to the southeast near Sunda Strait.

3.6.1. Northern Sumatra

The northern Sumatra forearc basins include the Meulaboh Basin[20,66] or Sibolga Basin[67], and Nias Basin[20,50]. A seismic reflection profile shows the occurrence of graben-like structures, with the largest one appears as a 25-km-wide half-graben filled with ~2s thick sediments in the northern Sumatra forearc basin (Fig. 8)[68]. These half grabens stretch mainly in the SW trend as observed in the seismic line crossing the axis of the basin. However, there is no indication of the half grabens on the profiles crossing at right angles to the axis of the forearc basin. A pattern of alternating gravity high and low is observed along Simeulue Island, possibly reflecting structural high and low in the basement[69]. This high and low gravity anomaly pattern could represent the continuation of half grabens observed in the forearc basin. Deep-seated north-trending structures have been reported across the forearc basins that play a role in the variation of depocenters in the northern Sumatra forearc basin[38]. Batee Fault has developed in the area between SF and MF in the front of Simeulue Island[34], which was believed to have extended from the SF[21]. The Neogene forearc basin fills appear to have maintained their thickness along the basin (Fig. 8). Indeed several parts of the basin show thicker stratigraphic units suggesting the depocenters' position, but there is no indication of structural control to the formation of these depocenters.

In some parts of the northern Sumatra forearc, the opening of the basins was initiated by the limited E-W extensional phase related to the emerging play of the Sumatra and Mentawai faults during the growth of the Miocene forearc basin[68]. Based on the occurrence of an unconformity that divides the Paleogene and basement rocks with the relatively uninterrupted Neogene sedimentary units, Beaudry and Moore (1985) suggest that a regional-scale tectonic event took place preceding the subsidence and deposition of the Neogene basin fills [66]. During Pliocene-Quaternary, the north Sumatra forearc basin is separated into Aceh and Simeulue basins by a compressional structure in a strike-slip fault zone[9,32].

Based on several exploration wells, the oldest Paleogene sediments in the northern part consist of dolomitic limestone, calcareous mudstone, and pyritic shale of Late Eocene to Early Oligocene[41,66]. Lower Miocene shelf sediments unconformably overlie this Paleogene sequence. A widespread carbonate platform has developed in the shelf area during the middle-late Miocene[67]. The upper Miocene deep marine shale with occasional thin sandstone or limestone bed deposited over the carbonates. In the upward portion of the basin, regressive clastic unit of sandstone, shale and limestone filled the basin during Pliocene-Pleistocene.

Apart from offshore forearc basin investigations, several field mappings have been conducted in Nias Island[e.g., 16,35,70]. Samuel et al. (1997) suggested the Oligocene-earliest Miocene extensional phase occurred based paleobathymetry data from the deep marine sequence[16]. The extensional structures formed several NW-trending half grabens along the axis of the forearc high. An important Early Miocene unconformity occurred in the western area of Nias Island that formed as a response of basin inversion. The Early and Middle Miocene periods of differential uplift and subsidence had terminated in the Late Miocene. A subsequent unconformity is observed in the whole island, indicating the beginning of a major uplift during Pliocene.

3.6.2. Southern Sumatra

The southern Sumatra forearc basins subsided and became depocenters sedimentary deposition since at least Late Eocene[40] contained more than 4 km of Miocene to recent sediments (Fig. 9). Previous studies refer to these forearc basins as Bengkulu Basin[20,40] or Mentawai and Bengkulu basins[41]. Horst and graben structures appear to have formed in the basement and controlled deposition of the Paleogene strata. Hence, the Paleogene basin seems to be localized within the grabens. In the upper section, the Neogene sediments formed almost in similar thickness along the basin with no indication of structural interference on the Neogene basin's formation. The deepest part of the Neogene basin appears to have formed longitudinally along the center of the basin and parallel to the trench. This trench-parallel trend of basin depocenters suggests that the subduction system has played a major control in forming the basin. North-south structures appear to have controlled the Paleogene Bose and Sipora Grabens in the Mentawai Basin[42]. Similar north-trending structures were also interpreted from onshore gravity and seismic data set within Kedurang and Pagarjati Grabens offshore Bengkulu[71]. In the Bengkulu shelf, northeast-trending basement high structures area the prominent structural features[40,72]. The north–south structures developed within the basement of the southern Sumatra forearc may represent a regional E–W extension, which have been suggested due to a N–S compression during Middle Eocene[73]. The NE–SW trend of graben system during the Late Eocene to earliest Miocene in the South Sumatra forearc may also reflect the rotation of Sumatra that changed the direction of compression in the trench, supporting the previous hypothesis of an anti-clockwise rotation of southern Sundaland[74].

The oldest rocks are of Pre-Tertiary that found as metamorphic rocks, metasediments, and igneous rocks. These rocks may represent the basement of the basin. The Paleogene sediments are exposed in the onshore south Sumatra forearc basin, which shows unconformable contact with the underlying pre-Tertiary rocks[75,76]. The Lower Oligocene sediments cropped out as volcanics with fluvial to shallow marine sandstone intercalations. The Upper Oligocene–Lower Miocene sediments are of shallow- to deep-marine siliciclastic sediments. In the Bengkulu shelf, the coeval Paleogene stratigraphy is represented by the Eocene-Oligocene to lower Miocene siliciclastic deposited in local depocenters, possibly pull-apart basins[40,41]. The lower to upper Miocene sequences consist of backstepping carbonates interfingered with carbonaceous-tuffaceous fine clastics, overlain by regressive clastics. These deposits were subsequently covered by middle to upper Miocene deposits of marine transgressive-regressive fine clastics. The early Pliocene to recent strata consists of a succession of fine-grained marine sediments[77].

4. Discussion

4.1. Strain partitioning in the Sumatran forearc

Strain partitioning in the oblique Sumatra subduction system has been proposed to significantly influence the formation of sliver-plates in the between the arc and accretionary wedge that bounded by major strike-slip faults[8,10,31] (Fig. 1). However, there was a disagreement on the suggestion of the motion within the MF because the GPS data from the northern third of the Mentawai islands showed no indications of any large transverse movement[78,79]. Furthermore, a recent work using the updated geological slip rates for the SF and the latest GPS data covering Sumatra and the forearc high islands revealed that an enduring deformation within the Sumatra forearc sliver plates is minor[80]. Hence, this observation shows no evidence for the strike-slip activity along the MF and WAF zones. Moreover, we do not observe any moderate-major earthquakes with strike-slip motions in the boundary between the forearc high and forearc basins (Fig. 10), suggesting that the major strike-slip faults do not exist or the strike-slip motions are inactive.

Reexamination of published high-resolution bathymetry data[11,55] shows that a strike-slip fault zone is observed in the eastern side of the landward-margin of the accretionary wedge in the northern Sumatra forearc basin. However, this fault zone extends farther up north to the WAF in the Andaman Sea within the forearc basin[14,43,44]. In the Andaman Sea, the boundary between the accretionary wedge and forearc basin is marked by the Diligent Fault[14,43,81]. Therefore, strain partitioning occurred in the northern Sumatra and Andaman forearc by developing a major strike-slip fault. However, this fault zone did not become the boundary between the forearc basin and accretionary wedge complex. This major strike-slip fault stretches from the arc, crossing the forearc basin and terminated within the accretionary wedge. Whereas in the southern Sumatra forearc, evidence of major strike slip deforming the eastern edge of the accretionary wedge is less clear. However, the steeper dip of the backthrusts farther landward deforming the Neogene forearc basin fills might represent some of the trench-parallel shear[15]. Nevertheless, en-echelon structures along the MF were not observed on high-resolution bathymetric data.

In the Sumatran forearc, the trench-parallel strain in this oblique subduction system is also possibly distributed as transpressional folding and thrusting in the accretionary wedge as indicated by the strike of the fold-thrust belt in the trenchward part of the Sumatran accretionary wedge that formed at a low angle to the direction of the trench[12,83]. Furthermore, the trench-parallel motion may have been largely taken up by networks of strike-slip faulting that deformed the accretionary wedge as shown in Nias Island[16], which is also observed in other forearc high islands along the Sumatran forearc[56–58].

In the Ryuku accretionary wedge that form in oblique subduction of the Philippine Sea Plate beneath the Ryuku margin, the Yaeyama Fault dissected some parts of the Ryuku accretionary wedge. It continued farther northwestward, deforming the forearc basin with a strike-slip motion[6]. However, doubly vergent backthrusts and forethrusts are still observed in the arcward margin of the accretionary wedge. A major strike-slip is observed to have developed in the forearc basin that continued farther northwestward toward the Kuril Arc along the oblique subduction of the Pacific Plate at the Kuril Trench[84]. Therefore, similar to what was observed in northern Sumatra, these observations suggest that a major strike-slip fault developed in the forearc due to strain partitioning in the oblique subduction system and deforming both the accretionary wedge complex and forearc basin sediments. This strike-slip fault does not necessarily play as the boundary between the accretionary wedge beneath the forearc high and forearc basin farther arcward.

4.2. Uplift forearc high

The highest part of the elevated accretionary wedge complex is located in the forearc high, which have been interpreted to have bounded by strike-slip faults in the MF-WAF zones[8–11,31,32]. However, field observation in one of the forearc high islands suggested that strike-slip motion does not play as major structural style along with the MF [16]. Furthermore, seismicity records since the early 60's show there was no single strike-slip earthquake event along this fault zone, suggesting there is no active strike-slip faulting in this area. Recent seismic refraction tomographic models show no indication of any large vertical structures that may accommodate transverse motion between the accretionary wedge complex and its backstop[51,85–87].

Based on recently acquired seismic reflection data in the Sumatran forearc[13–15,50], we observed no evidence of inverted structures (e.g. harpoon structures) beneath the forearc high that indicate a structural inversion. Therefore, we argued that the suggestion of basin inversion is responsible for uplifting the forearc high is not yet proven. Furthermore, the previous observations on thrusts beneath the homoclinal flexure in the arcward margin of the forearc high in Nias[34,35] is the first-time recognition of backthrusts in the Sumatran accretionary wedge margin. As for the uplift of the older accretionary wedge in the forearc high due to the activity of a trenchward-vergence detachment or splay fault between the inner and outer wedge, we could not observe similar features in the recent published seismic reflection data set[13–15,50]. However, a splay fault in a similar direction is observed to the west of the northern Sumatra forearc high on 3.5 kHz mud-penetrator profiles[88]. Even though the penetration of these profiles is very shallow, these authors argued that the splay fault might be originated at the plate interface.

Recent seismic tomographic models revealed a geometry of trenchward-dipping continental backstop against the accretionary wedge complex[51,85,86,89]. This trenchward-dipping continental backstop became the place where the arcward-vergent backthrusts developed and bounded the accretionary wedge, as shown by the recently acquired seismic reflection data set along the Andaman and Sumatran forearc[12–15,50,55,90]. The relocation of the 1976 M7 earthquake and its aftershock in the north Sumatran forearc indicates the activity of this deep backthrust fault[82,91]. Furthermore, the forearc backthrust is also suggested to have ruptured at the same time as the 2004 great Sumatra earthquake[12,90]. Landward tilting of the Sumatran forearc high, indicated by the records in the uplifted corals for more than seven centuries, verifies slip on the Sunda megathrust[92]. However, a significant uplift episode in 1685 has an unclear indication of tilting that might have resulted from a motion on the backthrust[27]. This deep-rooted structure extends upward near the seafloor and induced arcward-vergent folding and thrusting within the forearc basin sediments that younging farther landward[13,15]. The arcward-vergent backthrusts in the Sumatran forearc basins appear to coeval with trenchward-vergent imbricated thrust in the forearc high, forming doubly-vergent thrusts in the core of the Sumatran accretionary wedge complex[13,15,18,50].

Based on those observations and comparisons, we argued that the development of a doubly-vergent wedge is responsible for the forearc high uplift in the oblique Sumatra subduction system (Fig. 2E). Moeremans and Singh (2015) also observed similar patterns of the growth of the accretionary wedge farther north in the Andaman forearc that exhibit more obliquity of the subduction zone[14], 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 the accretionary wedge[11,31,33]. The strike-slip faults observed along the backthrusts in the north Sumatra forearc basin are the southern extension of a major strike-slip fault, the Andaman-Nicobar fault[81]. Furthermore, thrusting in the forearc high can explain the observation of trench-parallel reverse faults onshore forearc high islands[56–59] that previously have been interpreted as inverted normal faults[16]. The interaction between trenchward-vergent thrusts in the rear part of the accretionary wedge that continuous at depth into the arcward-vergent backthrust in the boundary between accretionary wedge and forearc basin has been observed in other subduction margins: the Hellenic arc[93], Lesser Antilles (Fig.7B)[94], and the Panama Trench[95]. Furthermore, results of analog sandbox modeling show that thrusts and backthrust have uplifted the core of the accretionary wedge and formed the forearc high in the orthogonal to moderately oblique subduction setting[64].

4.3. The growth of forearc basins

Based on observation of seismic reflection data, the Paleogene Sumatran forearc basins developed in localized depocenters related to graben systems[40–42,71,72], which was speculated to have formed as the southwest extension of the South Sumatra graben system in the backarc basin[40,72]. The Sumatran Paleogene basins may also have developed due to northeast-trending rifting that was subsequently overprinted by pull-apart basins system in between major strike-slip faults[40]. However, Paleogene graben observed in one of the seismic reflection profiles parallel to the basins' axis[68] belongs to the deep forearc basin in the front of sub-Neogene shelf edge. Hence, there is a variation along strike of the Paleogene forearc basin where a shallow forearc developed near a deep portion of the basin. This observation supports Matson and Moore (1992) suggestion, where they show variation along with the regional trend for the morphotectonic units and the juxtaposition of a shallow forearc basin near a deep forearc basin[38]. Indeed, this variation of Paleogene depocenters could be controlled by normal faults traversing the basins.

Another suggestion for the origin of these Paleogene grabens is localized depression in pull-apart basins related to SF and MF[40-42]. However, the MF itself is likely to have initiated in the early-middle Miocene[15], whereas the SF may have formed in the middle Miocene[49,96] or Pliocene[21]. A further detailed investigation is needed to verify the onset of these two major fault zone. However, there is no evidence to support the hypothesis that SF and MF have been active during Paleogene.

The deeper portion of the Paleogene Sumatran forearc basin might have been located in the present-day forearc high area that has been uplifted as documented in Nias Island[16]. A similar observation can be inferred from seismic reflection data offshore southern Sumatra, where part of the Paleogene sequences might have been incorporated into accretionary wedge sediments[15,18]. Furthermore, the distal part of the early Neogene forearc basin may have extended up to the present-day forearc high as suggested by the occurrence of continuous Neogene strata from the forearc basin to the forearc high[15,18]. In the northern Sumatra forearc, deformed strata have been observed on top of the accretionary wedge along with the forearc high[13]. These strata are highly folded and faulted, suggesting this area has experienced a compressional phase. The reflectivity of these strata resembles the reflectivity of the Neogene sediments observed in the forearc basin. Hence, this similarity suggests that the sediments on the forearc high might have been formed in a former forearc basin environment. Hence, the forearc basin appears to have shifted eastward. Contrary to the Paleogene forearc depocenters that developed locally, the Neogene forearc basin formed widely along the front of the forearc high islands trending parallel to the trench.

The thick sediments in the Sumatran Paleogene depocenters might generate higher temperatures, which play an important role in maturing hydrocarbon source rocks. In general, sub-commercial quantities of hydrocarbons have been found in these forearc basins suggesting working petroleum systems exist in the area. A further detailed study is needed to clarify the origin of the Paleogene grabens in the Sumatran forearc basins.

5. Conclusions

Based on our review of previous studies in the oblique Sumatra forearc region, several scenarios on the mechanism of uplift of the forearc high have been proposed that include major strike-slip fault zone, flexural uplift, basin inversion, uplift of the older accretionary wedge, and doubly-vergent mechanic wedge in the rear part of the accretionary wedge. Despite the subduction system obliquity, deformation in the Sumatran accretionary wedge is dominated by folding and thrusting due to the orthogonal component of the strain partitioning. Observation of recent seismic reflection data shows that the interplay between trenchward-vergent thrusts and arcward-vergent backthrust has played a major role in the uplift of forearc high. Strike-slip faults appear to have played a minor role in the uplift of forearc high. Part of sediments on the uplifted forearc high have formed in a former deep forearc basin environment. The modern morphology of forearc high and forearc basin is related to rapid uplift of the forearc high and deformation of the accretionary wedge during Pliocene. The Paleogene forearc basin appears to have formed in localized depocenters. In contrast, the Neogene forearc basin depocenters aligned parallel to the trench and developed farther arcward, indicating the important role of the subduction system to the basin formation.

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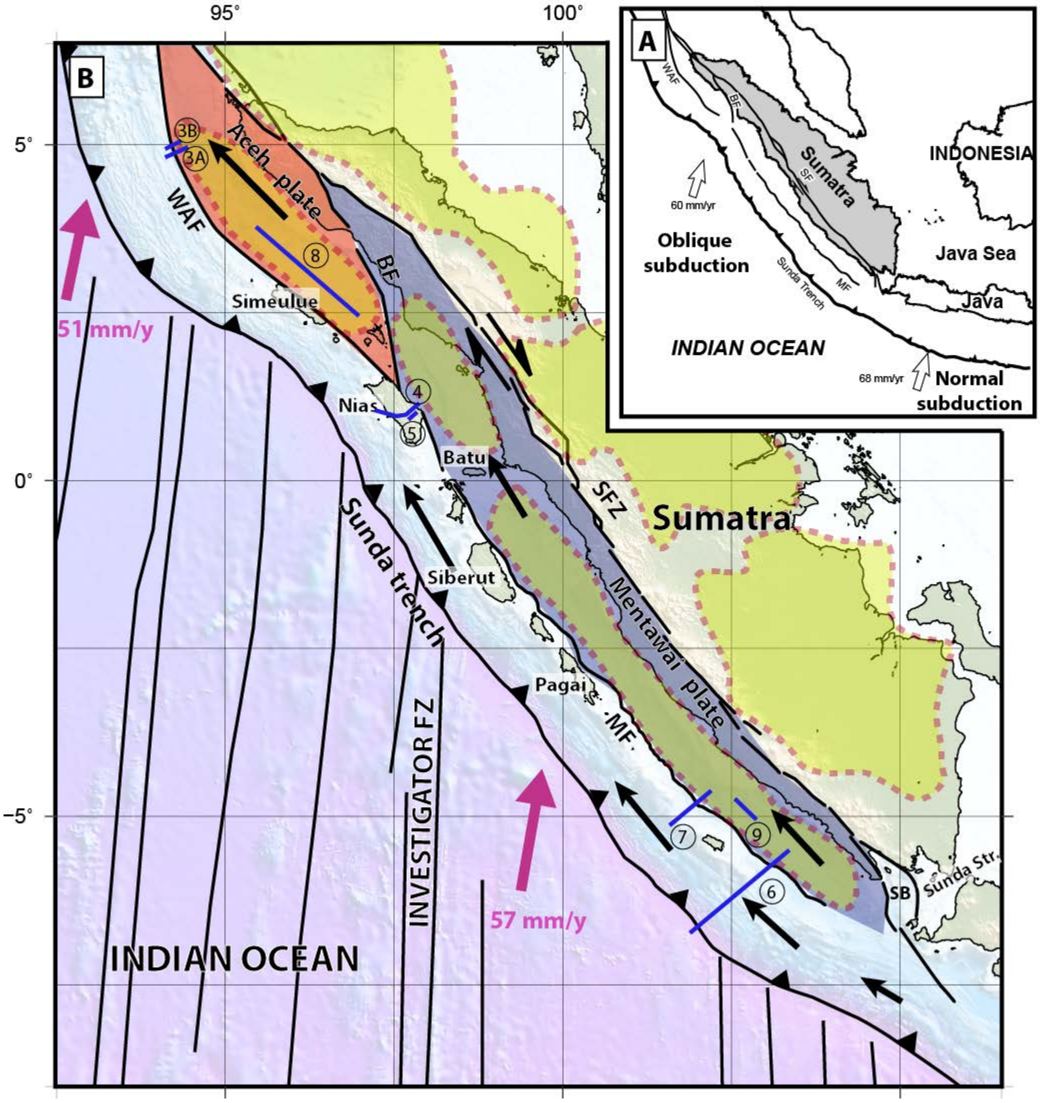

Fig. 1. A) the western Sunda subduction zone with oblique subduction in the front of Sumatra and normal subduction in the south of Java. B) Configuration of the Aceh and Mentawai sliver plates (shaded red and blue areas, respectively) in Sumatran forearc[10]. Purple arrows denote relative plate motion from cGPS[19]. Thick arrows represent motions with respect to Sumatra Island. Blue lines with numbers in the circle are for the profiles shown in this paper. The shaded green area in the dashed-line polygon represents basins in the forearc and backarc regions[20]. SFZ = Sumatran Fault Zone [21]; WAF = West Andaman Fault, BF = Batee Fault [10]; MF = Mentawai Fault[15]. Structures on the Indian Ocean are from Jacob et al. (2014)[22]. SB = Semangko pull-apart basin.

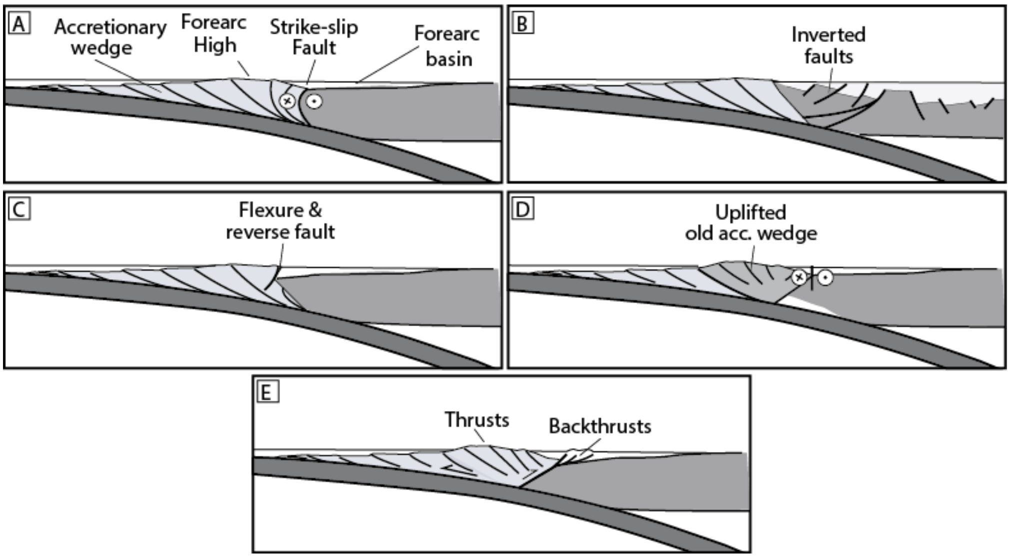

Fig. 2. Simplified uplift mechanisms for the Sumatran forearc high. A) Strike-slip fault[e.g., 10]. B) Inversion-controlled uplift[e.g., 16]. C) Flexure and reverse fault[e.g., 35]. D) Uplift of the Paleogene accretionary wedge[18]. E) doubly-vergent thrusts in the core of accretionary wedge[e.g., 15].

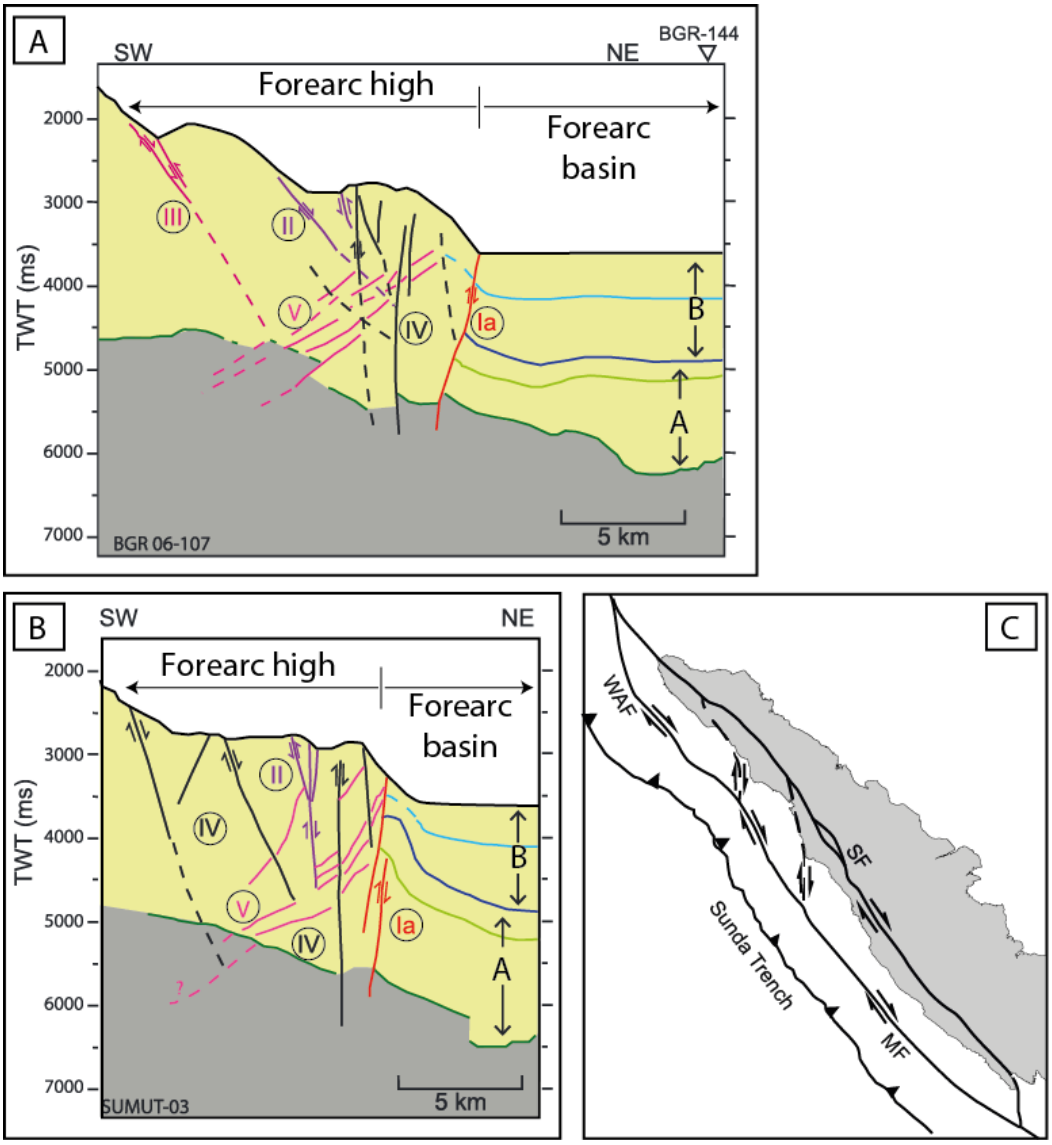

Fig. 3. A) Structural interpretation from seismic profiles line crossing the arcward edge of northern Sumatran forearc high[11,32]. B) Structural variations in the forearc high margin, ~8 km to the north of the line in Fig. 3A[11]. The number in the circle is for the fault group: I to IV are part of strike-slip faults, V is backthrust. Unit A is of Miocene, B for Pliocene-recent, whereas unit below A is pre-Neogene. C) A sketch model for the development of duplexes in the Sumatran forearc[31]. See Figure 1 for the location of the profile.

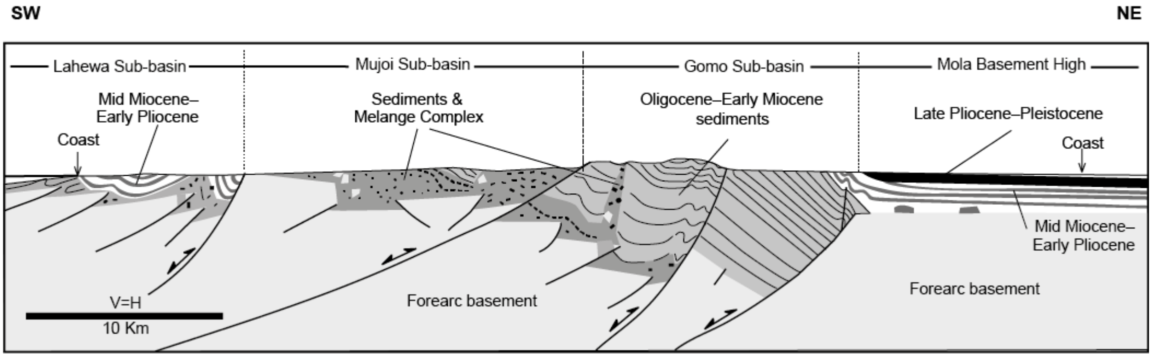

Fig. 4. A geological sketch across Nias Island [16]. Inverted normal faults dominate the structures in the forearc high island. See Fig. 1 for the location of the cross-section.

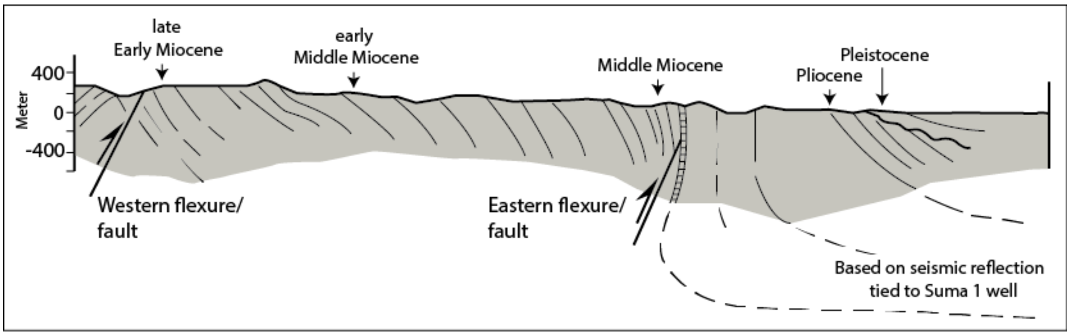

Fig. 5. Section across eastern Nias showing flexures and reverse faults deforming stratigraphic unit of the Nias forearc high [35]. See Fig. 1 for the location of this section.

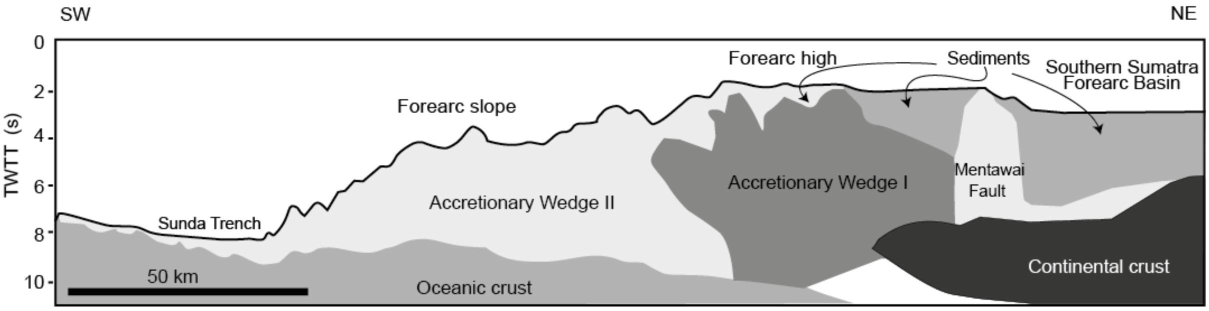

Fig. 6. Interpretation of seismic profile showing division of the Sumatran accretionary wedge [18]. The growth of the accretionary wedge II induced uplift of the accretionary wedge I that formed the forearc high.

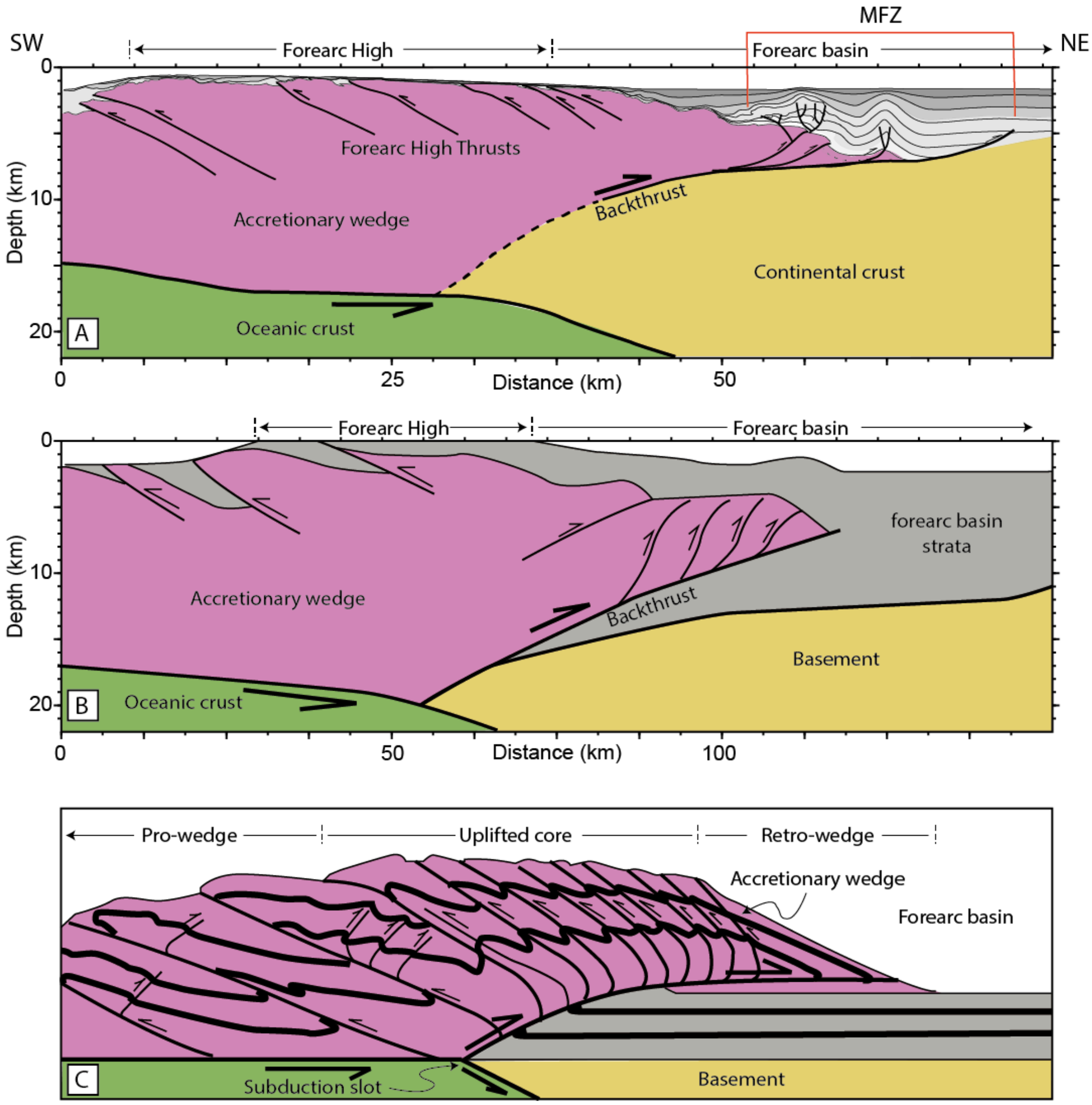

Fig. 7. Structural interpretation of the forearc high-forearc basin. A) Interpreted structures in the southern Sumatra forearc based on seismic reflection data[15]. Forearc high bounded the highest level of the uplifted accretionary wedge, induced by the interplay of trenchward-vergent forearc high thrusts and arcward-vergent backthrust. B) Similar mechanism and geometry of uplift of forearc high in the Lesser Antilles Arc[65]. C) Results of analogue sandbox modeling depicting the role of trenchward-vergent thrusts and backthrust in uplifting the core of the accretionary wedge in the orthogonal to moderately oblique subduction system[64].

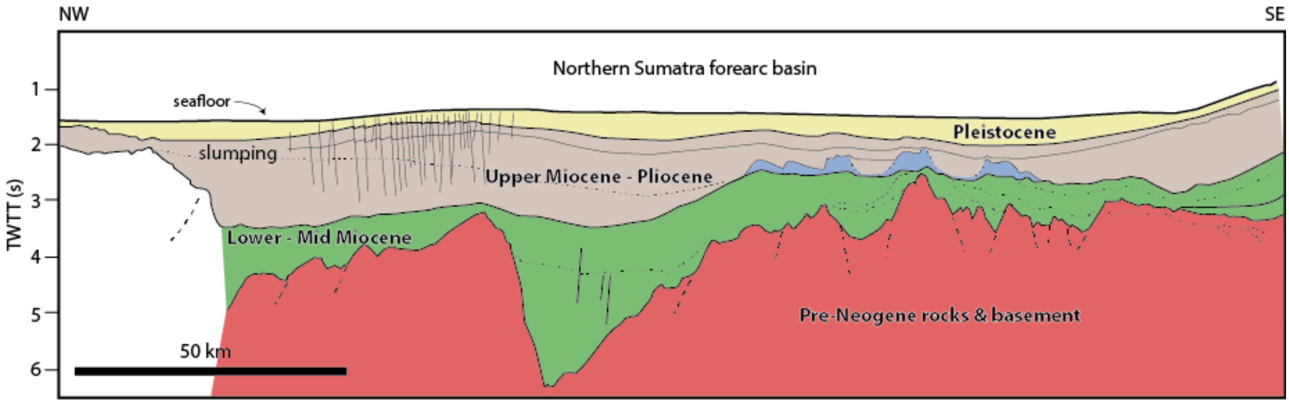

Fig. 8. Interpretation of a seismic line along the axis of the northern Sumatra forearc basin in the front of Simeulue Island[68]. The half-graben represent the Early Miocene structural development. A carbonate platform developed within the Upper Miocene sediments. See Fig. 1 for the location of the section.

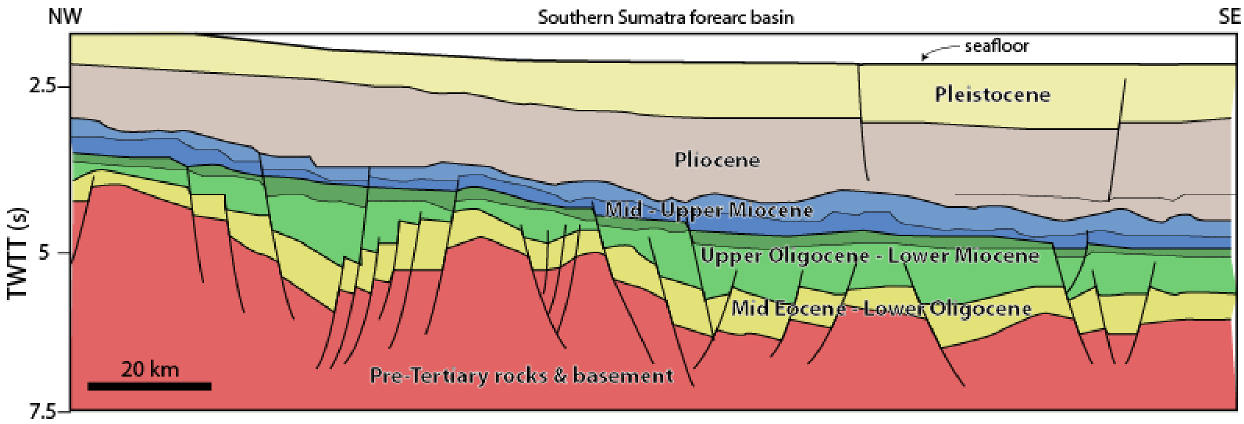

Fig. 9. Stratigraphy and structural interpretation of a seismic profile along the trend of the southern Sumatra forearc basin[41]. The Paleogene grabens are observed beneath the Lower Miocene sequence. See Fig. 1 for the location of the profile.

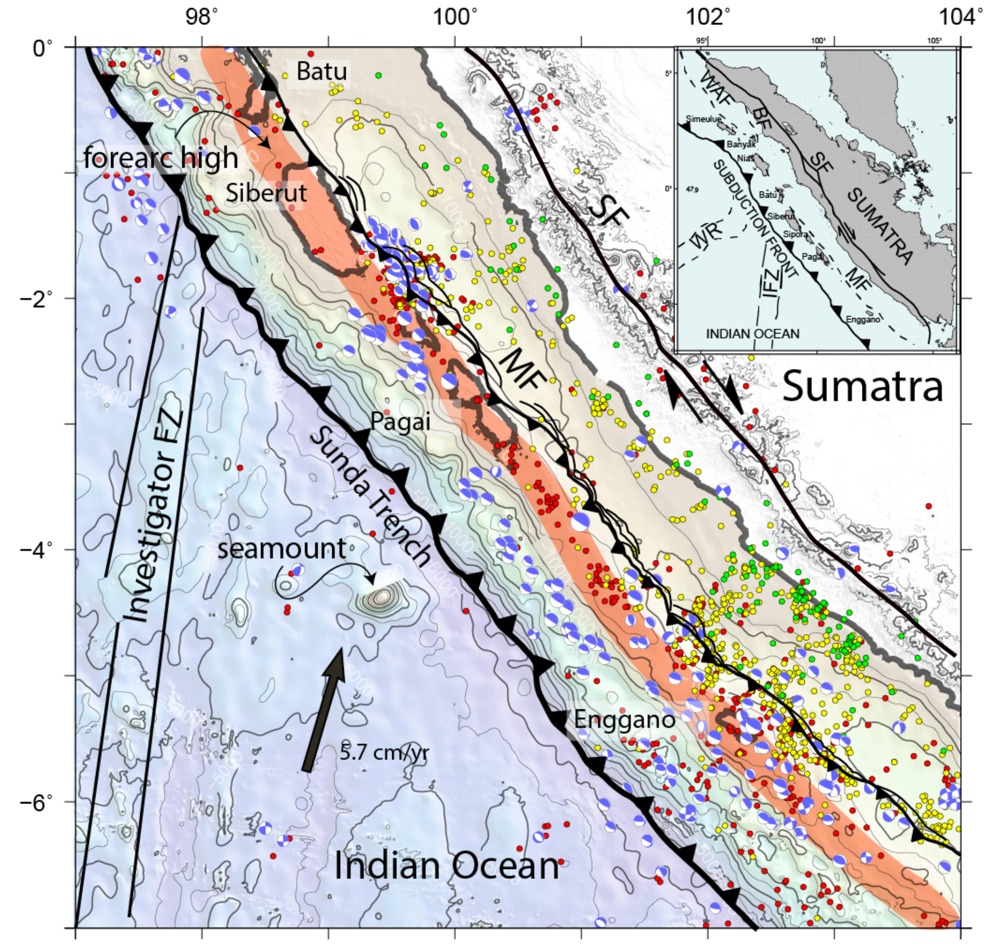

Fig. 10. The alignment of MF along the southern Sumatran forearc[15]. The focal mechanisms for earthquakes <30 km depth were plotted at their centroid locations (1976-2010). Note there are no single strike-slip earthquakes along with the MF. Shaded orange represents the forearc high area that occupied by forearc high thrusts. Red, yellow and green circles are relocated earthquakes[82] with a depth of 0–30, 30–60, and 60–90 km.