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STRUCTURAL STYLE AND EVOLUTION OF THE SUMATRAN FOREARC BASINS

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ABSTRACT

In the last few years, there has been significant interest in hydrocarbon exploration in the Sumatran fore arc basins. Over ten thousand kilometers of seismic reflection data were acquired from Aceh Basin in NW to Enggano Basin in SE by TGS in 2008-2009, covering the full length of the Sumatran fore arc basins. These data were complemented by earthquake and tsunami studies funded by Western Geco, CGGVeritas and various academic institutions acquiring data (including deep seismic reflection, refraction, bathymetry, heat-flow) covering the whole subduction system, from the oceanic crust to the fore arc basin margins. While refraction data provide insight for large-scale crustal velocity structures, deep seismic reflection data of Western Geco and CGGVeritas provide precise positioning of the plate boundary and continental Moho, which is extremely important for understanding the basin evolution. Densely spaced TGS seismic profiles allow us to map the basement and important sedimentary horizons on a basin scale. The crust beneath the fore arc basin is thin (~20 km) and thickens towards Sumatra mainland. Fore arc basement architecture exhibits extensional structures and deposition of probably Late Eocene - Early Oligocene syn-rift sediments. Post-rift sediments may have been deposited in grabens and slopes during Late Oligocene - Early Miocene. These grabens exhibit transtensional structures. The inversion of old structures could be related to the transpressional strike-slip fault zone. This episode is followed by marked subsidence during Middle - Late Miocene, overprinting older depocenters. Traces of local tectonics are observed, indicating other factors contribute to deformation within the fore arc basins. For example, compression due to strike-slip faults can be observed within the Simeulue and Aceh Basins. Similar features can also be observed in the southern part of Mentawai Basin. Mud diapirism seems to be present in the fore arc basin and involve sedimentary units of Pliocene - Recent deposits. The deformation zone, previously interpreted as Mentawai strike-slip fault, may also be interpreted as backthrust development along re-activated old structures with minor strike-slip component and associated mud diapirism.

INTRODUCTION

The Sumatran fore arc basins are located offshore West Sumatra, bounded to the west by outer arc islands such as Simeulue Island in the northwest and Enggano Island to the southeast (Figure 1). The long axis of the basins extends over 1700 km NW-SE, with width of 140 km SW-NE. The basins contain up to 6 sec TWT of Cenozoic sediments. In the last few years, there have been significant increases in hydrocarbon exploration in the fore arc basins of West Sumatra. Studying the structural styles developed in the fore arc region is important to aid understanding of the evolution of the area. This study is also important considering the development of active faults and large earthquakes activities within this region. The structural styles and evolution of the Sumatran fore arc basins are based on geological interpretation of seismic reflection data.

DATA AND METHODS

Seismic reflection datasets were acquired from Aceh Basin in the northwest to Enggano Basin in the southeast covering the entire length of the Sumatra fore arc basins. These data were provided by TGS, and also from earthquake and tsunami studies funded by WesternGeco, CGGVeritas and various academic institutions acquiring data

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(including deep seismic reflection, refraction, bathymetry, heat-flow) covering the entire subduction system, from the oceanic crust to the fore arc basin margins.

While refraction data provide large-scale crustal velocity structures, deep seismic reflection data of Western Geco and CGGVeritas provide precise location of the plate boundary and continental Moho, which is extremely important for understanding the basin evolution. Previously published data has also been utilized to assist the calibration and correlation of seismic interpretation in the study area (Karig et al., 1980; Beaudry & Moore 1985; Howles 1986; Hall et al., 1993). Based on correlation of markers from those wells to the study area, ages of key horizons have been estimated and their stratigraphic relationships interpreted.

PREVIOUS TECTONIC MODELS FOR THE SUMATRAN FOREARC AREA

Previous work within the Sumatran fore arc area suggests that the Paleogene inner fore arc basin developed along the Bengkulu Shelf (Hall et al 1993; Howles 1986). During the Paleogene the margin is uplifted and eroded as evidenced by the occurrence of a widespread erosional surface (Izart et al., 1994). Development of a fore arc basin during the Neogene was influenced by local variations along trend in the morphology and rate of accretionary wedge growth and in the geometry of the continental margin (Matson & Moore, 1992). In the northern Sumatra offshore, strike-slip faulting has controlled the fore arc basin evolution since the Late Miocene (Berglar et al., 2010). North-south trending structures traversing the fore-arc basin were also recognized in the Singkel and Pini grabens (Matson and Moore 1992). In the Bengkulu fore-arc, the Pagarjati and Kedurang grabens also developed in N-S trend (Yulihanto et al., 1995). N-S trending grabens also traverse the Mentawai fore arc and formed the Bose and Sipora grabens (Yulihanto & Wijanto 1996). Depocenter of the fore arc basin has oscillated with time, primarily in response to uplift of the outer-arc ridge (Beaudry & Moore 1981).

The fore-arc basin has subsided slowly since the Miocene (Izart et al., 1994; Matson & Moore, 1992). Sedimentation within the fore arc basin suggests that Sumatran sediment sources began eroding in the late Mid Miocene (Karig et al., 1979). The N-S trending Batee fault possibly was active during the Late Miocene - Pleistocene and thereby controls the sedimentary fill of the fore arc basin (Matson & Moore, 1992). Subsequently, the subsidence accelerates from the Pliocene to Quaternary (Izart et al., 1994).

STRUCTURAL STYLES

2D seismic profiles acquired by TGS with line spacing of 10-25 km permitted mapping the basement and important internal sedimentary horizons. Four seismic units have been recognised, identified here as Megasequences within the fore arc basin. The top of acoustic basement was correlated from wells located out of our area of interest and integrated with the deepest coherent reflection in the available seismic lines.

Normal faults are recognised beneath the deepest horizon that can be mapped (Figure 2, 3). These faults mark the Late Eocene-Early Oligocene extensional events, creating half grabens which permit deposition of Megasequence-1. Similar extensional events are also responsible for the development of NE-SW half grabens offshore Bengkulu (Hall et al., 1993).

N-S trending structural provide the boundaries of Megasequence-2 sediment packages. These sediments were deposited in Late Oligocene - Early Miocene grabens and slopes. The N-S trending structures were then segmented by NW-SE lineaments thereby overprinting earlier depocenters.

In contrast, NW-SE compressional - transpressional features characterise the deformation of the western edge of the fore arc basins. En echelon domes and anticlinal ridges are visible on the seafloor. These features suggest mud diapirism was active within the fore arc basin. Traces of localised tectonics are also observed, indicating other factors also contribute to the deformation of the fore arc basins. For example, compression due to strike-slip faults can be observed in Simeulue and Aceh Basins.

EVOLUTION OF SUMATRAN FOREARC BASINS

The crust beneath the fore arc basin is thin (~20 km) and thickens eastwards towards the Sumatran mainland. Basement architecture of the Mentawai fore arc exhibits NE-SW extensional structures (Figure 2, 3). Origin of the basement is difficult to differentiate, but fragments of the Bentaro-Saling Arc and the associated Woyla Terranes could well be present beneath the fore arc basin (Barber, 2000).

The Paleogene basins developed as extensional half grabens from at least the Late Eocene (Hall et al., 1993) (Figure 3a). Hypothetically, the extension in both fore arc and backarc areas is initiated by convergence rate reduction along the entire Sunda subduction system. This also may have induced subduction roll-back (Morley, 2002), due to the slow-down of the Indian Ocean spreading centre, coeval with the India-Eurasia collision between 50-43.5 Ma (Longley, 1997). The Paleogene basin developed in the present forearc setting might have formed in the same manner as the one in the present backarc setting. The NE-SW or N-S trending depocenters are possibly segmented by NW-SE and WNW-ESE faults in the northwest and southeast of Mentawai fore arc basin, respectively. Offshore Bengkulu, the Eocene sediments of Megasequence-1 consist of a series of high amplitude events, which has been interpreted as interbeds of volcanogenic and argillaceous sediments (Hall et al., 1993). Offshore Padang, the equivalent series has been interpreted as interbedded shallow marine shales, sandstones and limestones. Blocks of nummulitic limestone have been discovered on Sipora and Pagai islands (Yulihanto & Wiyanto, 1999).

The fore arc basin underwent uplift and subaerial erosion in the Early Oligocene to create a regional unconformity. This uplift could be due to an increase in the rate of movement of the Indian Ocean Plate (Karig et al 1979). The fore arc basin underwent subsidence possibly due to the development of transtensional basin accommodating the deposition of Megasequence-2 which overprinted the Paleogene depocenters (Figure 3b). Early Miocene carbonates and clastics were deposited in the shallow marine environment offshore Padang and Bengkulu (Howles, 1986; Hall et al, 1993; Yulihanto & Wijanto 1999).

The ensuing subsidence may be recognised in the deepening of the basin, evidenced by deposition and preservation of deeper marine sediments (Figure 3c). This subsidence was induced by steady mass addition to the accretionary wedge (Matson & Moore, 1992). Deposition of Megasequence-3 is initiated by a regional transgression. Limestone was deposited in the offshore Bengkulu area, together with siliciclastics in offshore Padang during Middle Miocene (Hall et al., 1993; Yulihanto & Wiyanto 1999). The Barisan Mountains were uplifted during the Late Miocene, providing the source of sediment subsequently deposited in the subsiding fore arc basins. Transgressive deposits of clastics and carbonates can be recognized offshore Bengkulu. In offshore Padang, clastics dominate the Late Miocene sediments.

Since the Pliocene, these basins rapidly subsided contemporaneously with the rapid uplift of the Barisan Mountains and the outer arc highs (Figure 3d). Deposition of prograding deltaic sediments in the shallow water together with turbidites in the deeper water can be observed in the fore arc basins, assuming the Sumatra mainland as the source of the sediments. Simultaneously, rapid uplift of the outer arc High Mentawai fault system took place. The deformation zone which developed along the western edge of the fore arc basin is likely related to a combination of regional and local factors. These may have included the reactivation of old structures, together with backthrusts and mud diapirism.

CONCLUSIONS

Basement architecture of the fore arc exhibits extensional structures and indicates deposition of probable Late Eocene - Early Oligocene syn-rift sediments. Post-rift sediments were deposited in grabens and slopes during Late Oligocene - Early Miocene, and exhibit transtensional structures. Subsequently, the basins subsided during the Middle - Late Miocene, thereby overprinting older depocenters. Rapid subsidence combined with uplift of the outer arc highs took place during the Pliocene. A deformation zone developed along the western margin of the fore arc basins, with evidence for other factors also contributing to the deformation process.

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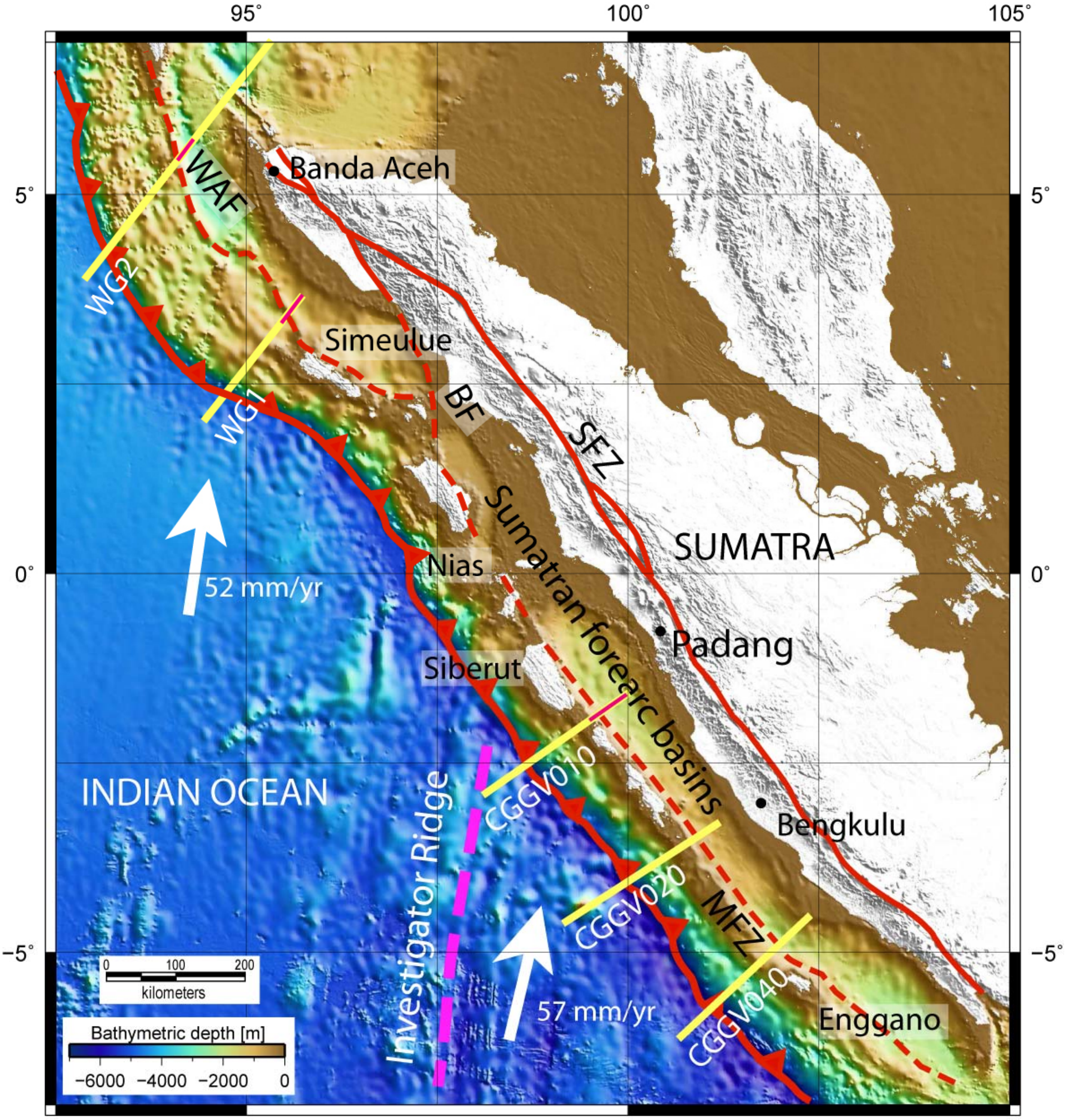

Figure 1 - Bathymetric map of showing seismic lines (yellow for the whole line, and thin red line for the ones in figure 2). SFZ: Sumatra Fault Zone (Sieh and Natawidjaja, 2000), BF: Batee Fault, WAF: West Andaman Fault (Malod and Kemal 1996).

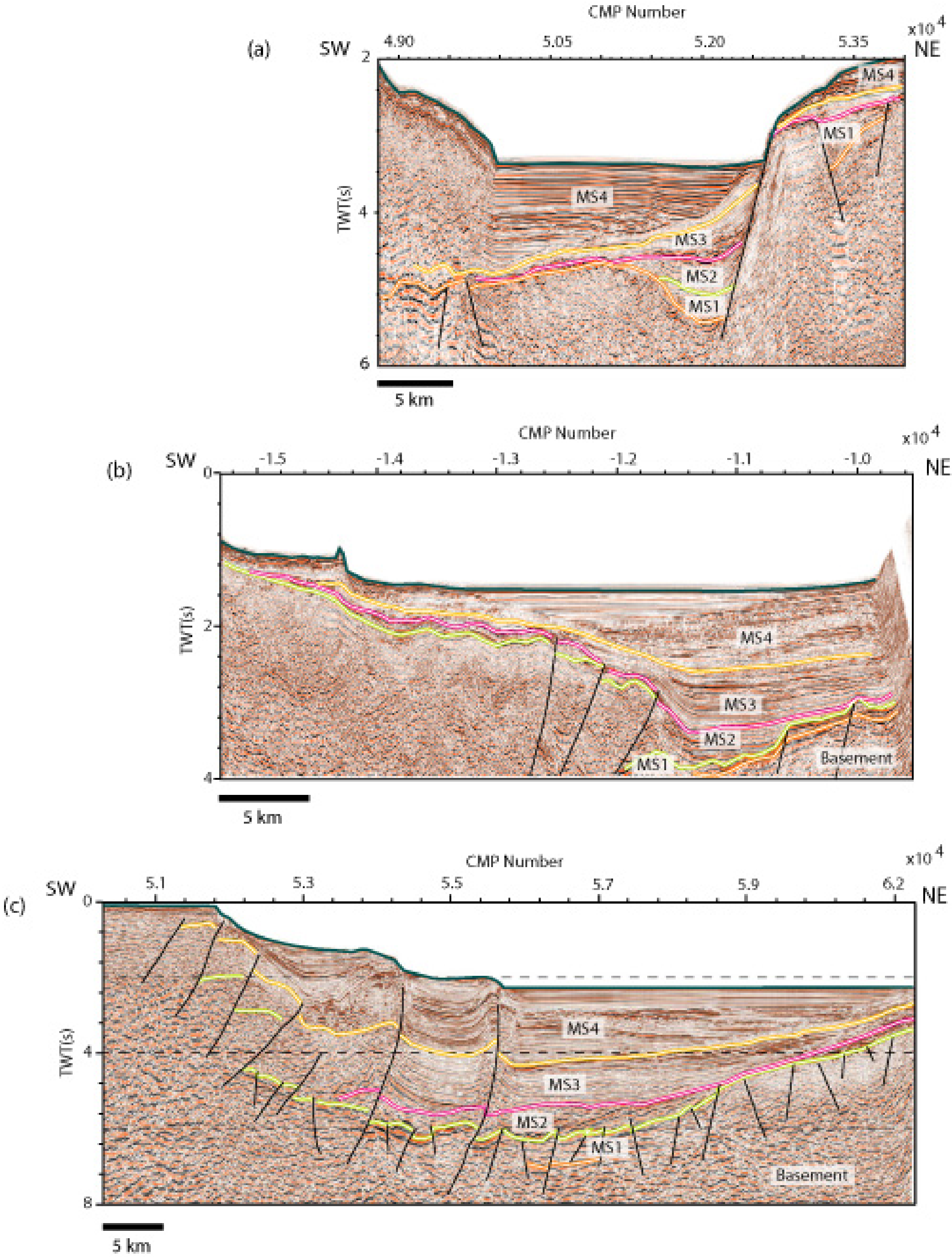

Figure 2 - Seismic line of WG1, WG2 and CGGV010 crossing the fore arc basin

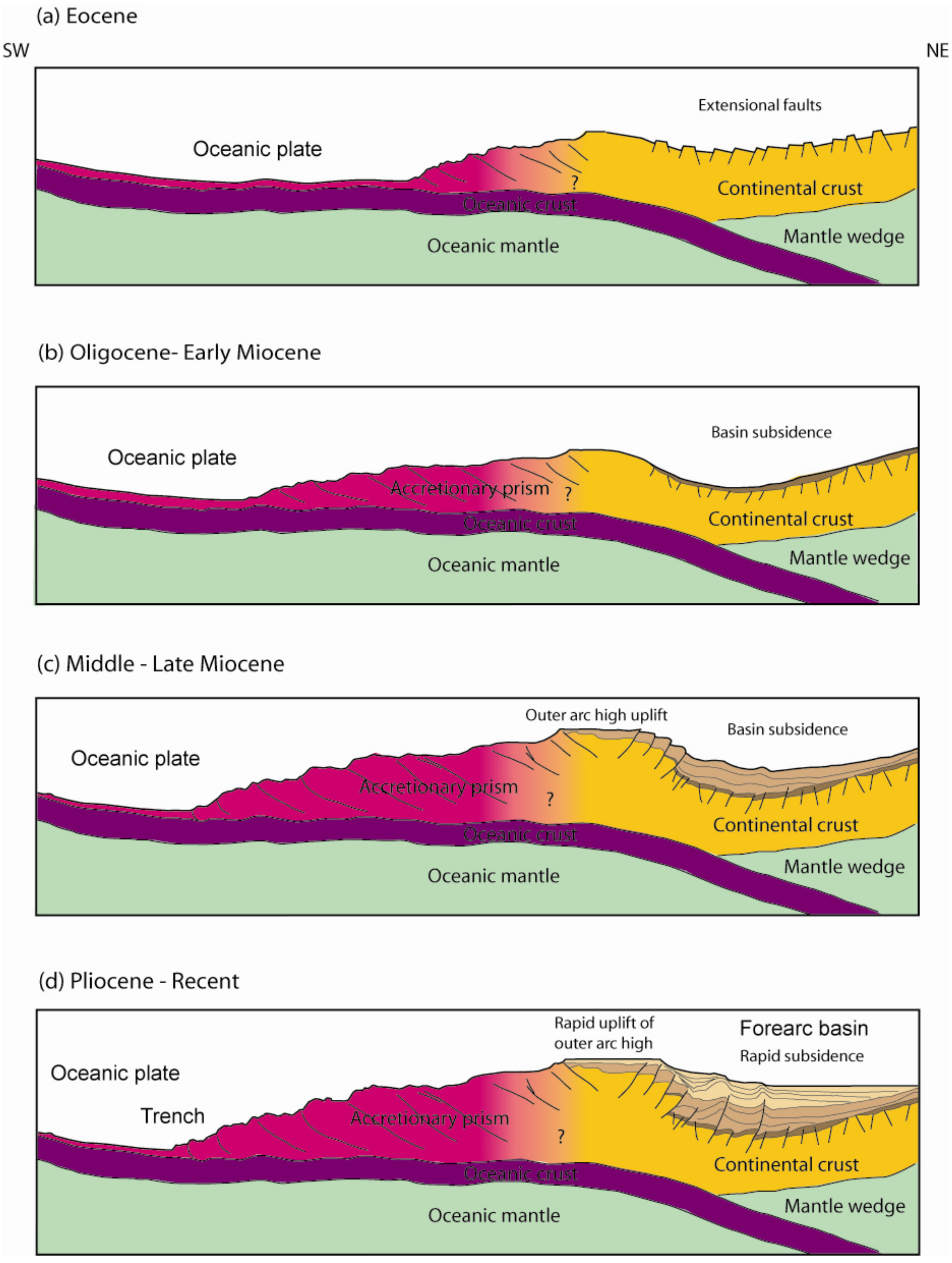

Figure 3 - Schematic diagram showing evolution of the Sumatra fore arc basins. The depth axis is from second two way travel time.