2.1. Introduction

The seafloor created by spreading processes and aseismic ridges originating by mantle plumes from the Early Cretaceous to the Present document the tectonic history of break up of eastern Gondwanaland, major plate reorganizations, directions and rates of plate motions; interactions of hotspots with spreading centers, intra plate deformation and collision history of Indian plate with Eurasia and Himalayan orogeny (Krishna et al., 1995). The active tectonics of central eastern Asia exhibits a varied and complicated combination of styles of deformation. Much of this region appears to experience shortening in N-S direction, but both normal faulting associated with E-W or NW-SE crustal extension, and strike-slip faulting on major faults appear to play a key role in the overall deformation of Asia (Deng et al., 1979; Molnar and Tapponnier, 1975, 1978; Tapponnier and Molnar, 1977, 1979). These observations led to the suggestion that Asia deforms in response to the collision and subsequent penetration of India into Eurasia and that much of China is pushed eastward out of the way of the impinging continents (Molnar and Tapponnier, 1975, 1978; Tapponnier and Molnar, 1977, 1979).

The island arcs, trenches and marginal basins associated with Sunda arc form one of the most tectonically active and complex regions of the world (Purdy and Detrick, 1978). Stretching from Burmese arc nearly to Timor, the Sunda Island Arc delineates a subduction zone separating the Indian-Australian plate from the
southward projection of the Eurasian plate. The Sunda Island arc, displays the characteristic relationship of a deep trench, a sedimentary arc, and a gravity minimum inside the trench, earthquake hypocenters along a dipping Benioff zone, and a volcanic arc above the Benioff zone. It continues to be an area of high interest for studies of the complexities created in a zone of plate convergence (Curray et al., 1977).

2.1. Regional geotectonic setting

The island arc extends over some 5600 km and separates the Indo-Australian plate and the Eurasian plate. This sector of the subduction system has been active since middle Tertiary time, as inferred from dating of the Sunda system volcanism by Hamilton (1988). Hamilton suggests that along the arc, the collision system changes from oceanic-continental in Sumatra through transitional in Java to intra-Oceanic in Bali. A morphological map of the study area is shown in Figure 2.1

On the northeastern side of the study area, the slow slipping Red River Fault of Vietnam and Southern China separates the Southeast Asian plate and the Eurasian plate. The Burmese-Andaman arc system forms an important transitional tectonic link between the Himalayas in the north and the Sunda arc in the south (Hamilton, 1979). Towards north, the Burmese arc meets the Himalayan arc at the syntaxis zone along the Mishmi hills block forming a major thrust zone. The Burmese arc is bounded on its west by the tectonically active belts of northeast India wherein, currently uplifting Shillong plateau is the most important tectonic feature. The Burma plate covering the Burmese plains, the Andaman and north Sumatra basins separate the Indian plate and the Eurasian plates. The eastern periphery of this Burma plate lies, the relatively high standing areas that include the Shan plateau, the Malay Peninsula and its western shelf, the Malacca strait and Sumatra. The Shan-Sagaing fault is a major right lateral
fault along the eastern edge of the Burmese arc where the western Burma seems to slide past the rest of Indo-China (LeDain et al., 1984).

![Morphology map of the Andaman-Sumatra-Java trench-arc system.](image)

Figure 2.1. Morphology map of the Andaman-Sumatra-Java trench-arc system.

The Andaman basin is an extensional basin spreading in a NW-SE direction marking the edge between the Eurasia and Burma plates in the north to Indonesia in the south, situated between 6°N and 14°N and 91°E and 94°E. Win Swe (1972) inferred that the Sagaing fault turns southward into the spreading axis of Andaman Sea. This back arc-spreading center in the Andaman Sea is transformed southward
into the Sumatra fault system that cuts the entire length of Sumatra (Curray et al., 1977). The western side of the Burmese and Andaman trench-arc region is bordered by Bay of Bengal and Ninety East Ridge. The Andaman basin comprising of Andaman Sea in the back-arc extends nearly 1200 km from Burma to Sumatra in the N–S and around 650 km from the Malay Peninsula to the Andaman and Nicobar Islands in the E–W. The central Andaman Sea is marked by steep and elongate sea valleys and seamounts such as the Nicobar Deep, Barren–Narcondam volcanic islands, Invisible bank, Alcock and Sewell seamounts (Rodolfo, 1969). Curray et al. (1982) suggested that the Andaman Sea and the central lowlands of Burma are parts of a single structural province.

Towards south, the Sumatra fault system extends for 1900 km along the volcanic chain of western Sumatra from 10°N to 7°S (Sieh and Natawidjaja, 2000). In the southwestern part, there is a 300 km wide strip of lithosphere between the Sumatran fault and the Sumatran deformation front called the Sumatran fore arc sliver plate. The SFZ is also considered as the limit between the Eurasian plate and the fore arc sliver plate. The fore arc ridge (outer arc high) is characterized by islands such as Enggano, Pagai, Siberut, and Nias that provide considerable geological information.

Java (8° S, 110° E) is part of the Sunda Island Arc, which includes Sumatra to the North West and Bali to the East. It is the world's 13th largest island formed mostly as the result of volcanic events. Java Sea and Borneo lies to the north and Indian Ocean to the south of Java. Its southern edge is marked by the presence of the Wharton Basin and the north Australian Basin. (Figure 2.2).

Since this area is associated with strong earthquake activity and volcanism, it is important to understand the tectonics, geological history as well as the ongoing geodynamic processes in order to assess the future hazards.
2.3. Geotectonic Framework and evolution of the Andaman-Sumatra-Java trench-arc system in the Eastern Indian Ocean

The zone of active convergent margin along the Andaman – Sumatra-Java arc in the eastern Indian Ocean is geodynamically quite complex and interesting in view

Figure 2.2. Generalised tectonic map of the Andaman-Sumatra-Java trench-arc and adjacent regions.
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of wide variation in subduction geometry, morphology and stress field in both along and across the arc and the presence of active back-arc spreading in the Andaman Sea.

Major tectonic features in the eastern Indian Ocean were inherited from the break-up of the eastern Gondwanaland and subsequent spreading of the Indian Ocean floor. Some of these features which are important in the evolutionary history of the region (see Fig. 1.3- generalized tectonic map) are: (1) the large sediment filled basin called the Bengal fan in the Bay of Bengal, 2) the Ninety East ridge, a 4500 km long aseismic ridge trending N–S along the 90° E meridian (3) The fold mountain belt of Andaman and Indo-Burman ranges formed by eastward subduction and motion along the Shan-Sagaing transform and the Neogene back-arc spreading in the Andaman Sea (4) the Sumatran Fault Zone (SFZ), a northwest trending active strike-slip fault that cuts the entire length of Sumatra and Indonesia (5) Java onshore region termed as Java Fault Zone (JFZ) (6) Sumatran fore arc sliver plate consisting of Mentawai fault zone (MFZ) (7) The offshore Java fore arc region, which is characterized by typical fore arc basins and (8) The Sunda strait, which is considered as a transition zone between the normal subduction in front of Java to the east and oblique subduction to the west. Most of these features came into existence during the northward flight of India since the late Cretaceous. McKenzie and Sclater (1971) studied the evolution of the Indian Ocean since the Late Cretaceous based on magnetic anomaly identifications and concluded that during 75–35 m.y., the movement of the Indian plate was very rapid (18 cm/yr) mostly in northward direction. They infer that this movement was taken up by the Chagos-Laccadive transform fault on the West and by the Ninety East Ridge on the East. Johnson et al. (1976) have studied the spreading history of the eastern Indian Ocean, where the oldest magnetic anomalies are aligned sub-parallel to the East Coast of India corresponding to about 2 km isobath. A schematic illustration of age and history of oceanic crust in the eastern Indian Ocean (Figure 2.3) is given by Hamilton (1979).
The details on various prominent stages of geological evolution and resultant formation of major tectonic/structural elements are discussed here for better understanding of present day geodynamics of the region.

Figure 2.3. Schematic illustration of age and history of oceanic crust in the eastern Indian Ocean as given by Hamilton (1979).
2.3.1. Geologic Evolution of the Eastern Indian Ocean

Break up of eastern Gondwanaland during the Early Cretaceous resulted in the evolution of the Indian Ocean. The plate tectonic theory has been used for the eastern Gondwana reconstruction to unravel the evolutionary history of the Indian Ocean (McKenzie and Sclater, 1971; Sclater and Fisher, 1974; Johnson et al., 1976; Duncan, 1978; Norton and Sclater, 1979; Powell et al., 1988; Royer and Sandwell, 1989; among many others). Magnetic data constrained by DSDP and ODP drilling results revealed that the seafloor spreading between India, Australia and Antarctica occurred in three main phases with two major plate reorganizations from late Jurassic to present (Royer and Sandwell, 1989). The reorganizations are evidenced by ridge jumps, changes in direction and varied rates of spreading. Geological evidences reveal that an overall compressive tectonic regime along the convergent margin in the eastern Indian Ocean prevailed since Late Cretaceous.

Figure 2.4 describes the evolutionary history of the Indian Ocean in general. The first phase of spreading started in northwest-southeast direction and resulted in India’s movement away from Antarctica-Australia during early Cretaceous. This resulted in the formation of the Mesozoic basins along the western Australian margin (Markl 1974a,b, 1978; Larson et al., 1979; Veevers et al., 1985), and the eastern Indian margin (Ramana et al., 1974a,b, 1997a) as evidenced by the Mesozoic anomaly sequences M11 through M0. During Middle Cretaceous, the Indian plate rotated from its early NW-SE to N-S direction and moved at a slow spreading rate. During this period, the Cretaceous quiet/smooth zone (118-84 m.y) crust evolved in the distal Bengal Fan. Northward movement of Indian plate away from Antarctica took place during Middle Cretaceous to Middle Eocene. The first major reorganization of the plates took place during Middle Cretaceous time, evidenced by the change in India’s motion from NW-SE to N-S (McKenzie and Sclater, 1971; Norton and Sclater, 1979;
Figure 2.4. Sketch model of the evolution of the northeastern Indian Ocean (after Ramana et al., 2001).
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Powell et al., 1988; Cande and Mutter, 1982; Veevers et al., 1986; Scotese et al., 1988). The second phase of spreading started in the N-S direction and continued up to formation of anomaly 19 (about 24 m.y) in the central Indian Ocean. During this period, India drifted in the N-S direction from Antarctica with a rapid speed of 11 to 7 cm/yr. The magnetic lineations 34 through 19 have evolved in the east-west direction with large lateral offsets, giving rise to the major fracture zones. During this phase of drifting, major parts of the central Indian and Crozet basins have evolved (McKenzie and Sclater, 1971; Schlich, 1975, 1982). The initiation of seafloor spreading between Australia and Antarctica (Cande and Mutter, 1982) and the opening of Wharton basin (Sclater and Fisher, 1974; Liu et al., 1983) also took place during this period. The second major plate reorganization occurred in the middle Eocene time when Indian and Australian plates merged and formed as a Single Indo-Australian plate (magnetic anomaly 20 to 18) (Liu et al., 1983; Royer et al., 1989a; Krishna et al., 1995). The third phase of spreading initiated in northeast-southwest direction in the middle Eocene and appears to continue since then. The Australian and Antarctica basins (Weissel and Hayes, 1972) were formed along the SE Indian ridge (SEIR) in the third phase.

2.3.2. Tectonics

The 2004 and 2005 witnessed two mega earthquakes that have ruptured the boundary between the Indo-Australian plate, which moves generally northward at 40-50 mm/yr, and the southeastern portion of Eurasian plate, which is segmented into the Burma and Sunda sub plates. East of Himalayas, the plate boundary trends southward through Myanmar, continuing offshore as a subduction zone along the Andaman-Nicobar islands and further south to Sumatra, where it turns eastward along the Java trench. This zone of convergence is characterized by the occurrence of numerous earthquakes, both shallow and deep (Figure 2.5). The area is a classical example of a
subduction system, composed of the down going Indo-Australian slab along the Sumatra-Java trench, an accretionary wedge, the outer arc ridge forming the backstop (Pubellier et al., 1992; Samuel and Harbury, 1996), the Bengkulu - Mentawai fore arc

Figure 2.5. Seismicity map of the Andaman - Sumatra - Java arc region showing epicenters with magnitude ≥ 5.0. Both shallow upper plate and deeper Benioff zone events have been included in the map.
basin off Sumatra and Java fore arc basin in front of the Volcanic arc (Schluter et al., 2002). The Andaman-Sumatra-Java arc system has evolved through mainly subduction related processes responding kinematically to the plate reorganizations and other tectonic adjustments taking place during the evolution of the Indian Ocean as well as the Philippine Sea region.

The geometry of the subduction plate varies as it comes from Andaman to Java as the sediment thickness of the subducted plate decreases. Off Java, it is covered by only few hundred meters of sediments, whereas, off Sumatra it exceeds 1 km and at the head of the Bay of Bengal the sediments are thicker by an average of 10 km (Curray et al., 1977). West of the Andaman arc, the Ninety East ridge continues subsurface below the Bay of Bengal sediments up to 17°N (Curray et al., 1982). Geophysical studies indicate that the ridge could be a hot spot trace (Curray et al., 1982; Mukhopadhyay and Krishna, 1995) Refraction data suggests that off Southern Sumatra, in the arc region, the basement is continental whereas, off western Java it changes to oceanic (Kopp et al., 2001,2002). The outer high, which represents the fossil part of the accretionary wedge, is of Eocene-Oligocene age (Pubellier et al., 1992; Samuel and Harbury, 1996). The Andaman–Nicobar ridge is believed to have formed in Oligocene–Miocene times due to E-W compression of sediments derived from the Malayan shelf (Rodolfo, 1969). Lay et al. (2005) observed that age and thickness of the subducted oceanic crust and the convergence rate increase from Andaman towards Java along the arc. The increasing dip and depth of penetration of the Benioff zone reflects this change as well as changes in slab geometry. Oblique, but predominantly thrust motion occurs in the Andaman trench with a convergence rate of about 1.4 cm/yr (Lay et al., 2005). The Andaman back-arc spreading ridge-transform system accommodates the remaining plate motion, joining with the Sumatra fault to the south. The subducting oceanic crust off Sumatra is 46-60 m.y old and has a present convergence rate of 6.81 cm/yr, while the crust off Java with an age ranging
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from 70 to 100 m.y. (Hamilton, 1979, Ghose et al., 1990) converges at a rate of 7.23 cm/yr (DeMets et al., 1994). According to Newcomb and McCann (1987), the slab configuration is ambiguous in the northern Sumatra, where as, in the south the observed dip is 40-50°. West of Sunda strait, seismic activity does not extend below 300 km. But by Java, seismic activity extends from the surface to a depth of 650 km with a gap in seismicity between 300 and 500 km (Fitch and Molnar, 1970; Newcomb and McCann, 1987). As a result of highly oblique motion between the Indo-Australian plate and the Eurasian plate, a plate sliver, referred to as the Burma micro plate, has sheared off parallel to the subduction zone from Myanmar to Sumatra (Lay et al., 2005).

The following sections deal elaborately about the various tectonic features associated with Andaman-Sumatra-Java trench-arc region. As the arc all along contain morpho-tectonic features with widely varying tectonic history and also for clarity, different segments of the arc have been presented separately.

2.3.2.1. Andaman arc region

The Andaman-Burmese arc system serves as a transitional tectonic link between Himalayan Collision zone to the north and Sunda arc–trench system in the south (Hamilton, 1979). The Andaman–Nicobar Islands, which are sub-aerial expressions of the fore-arc ridge separate the Andaman Sea from the Bay of Bengal. The region is dominated by youthful structures which are either tensional in origin or have resulted from combined tensional and strike-slip movements. The Andaman basin comprising of Andaman Sea in the back-arc extends nearly 1200 km from Burma to Sumatra in the N–S and around 650 km from the Malay Peninsula to the Andaman and Nicobar Islands in the E–W. It is an extensional basin spreading in NW-SE direction marking the edge between the Eurasia and Burma plates in the north and Indonesia in the south, situated between 6° N and 14°N and 91° E to 94°E.
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The Indo-Burman ranges and the Andaman–Nicobar ridges are a northward continuation of the Mentawai ridge of the Sumatran subduction zone. Rodolfo (1969) suggested that the east-west compression of sediments derived from the Malayan shelf resulted in the formation of the Andaman–Nicobar ridge in Oligocene–Miocene age. The central Andaman Sea is marked by steep and elongate sea valleys and seamounts such as the Nicobar Deep, Barren–Narcondam volcanic islands, Invisible bank, Alcock and Sewell seamounts (Rodolfo, 1969). Curray et al. (1982) inferred that the formation of the Andaman Sea has a definite genetic linkage with the evolution of the Bay of Bengal. During this evolution, modifications to the subduction zone geometry have produced considerable mass anomalies at depth. The rock types in the Andaman–Nicobar islands mainly constitute: Cretaceous serpentinites, ophiolites with radiolarian cherts, Cretaceous to Eocene cherty pelagic limestone and a thick section of Eo-Oligocene flysch overlain by Neogene shallow water sediments (Chatterjee, 1967; Eremenko and Sastri, 1977; Roy, 1983). The western base of the Andaman–Nicobar ridge is marked by the trench that is filled with the sediments of the Bay of Bengal (Curray et al., 1979). The structure along the arc in the Andaman–Nicobar ridge region is dominated by east dipping nappes having gentle folding, while tighter folding and intense deformation is observed off Sumatra (Weeks et al., 1967; Moore and Curray, 1980). Eremenko and Sastri (1977) observed that the deformation is more intense in Cretaceous–Oligocene sequences than the younger sequences. Several north–south faults and thrusts have been observed in the Andaman–Nicobar ridge and the adjacent offshore areas, among them, the most significant are the Jarwa thrust developed on the main islands (Roy, 1983) and the West Andaman fault, east of the Andaman–Nicobar ridge (Curray et al., 1979). Mukhopadhyay (1984) observed that some of these faults/thrusts are seismically active. Curray et al. (1982) suggested a relation between thickness of sediments on the subducting plate and height and volume of the outer sedimentary arc or non–volcanic ridge of the arc. Curray et al.
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(1982) inferred that the Andaman Sea and the central lowlands of Burma are parts of a single structural province.

The Andaman Sea is a complex back arc extensional basin that differs from most other such basins in that it is west facing and that it was formed by transtension (Curray, 2005). It lies along a highly oblique convergent margin between the northeastern moving Indo-Australian plate and nearly stationary Eurasian plate. Uyeda and Kanamori (1979) related the back-arc spreading activity in the Andaman Sea to leaky transform tectonics. Eguchi et al. (1979) inferred collision of the Ninety East ridge with the Sunda trench in the middle or late Miocene which transmitted compressional stresses into the back-arc area and at the same time the drag exerted by the collision of India with Eurasia caused opening of the Andaman Sea, whereas, Curray (2005) is of the opinion that as the greater Indian continental mass converged on the SE Asian margin, it caused clockwise rotation of the subduction zone and increase in obliquity to the point that transtension along a sliver plate has resulted in oblique rhombo chasm like opening of the Andaman Sea during the Neogene. General structure in the Mergui north Sumatra basin consists of a series of horsts and grabens. Seismic refraction studies by Kieckhefer (1978) indicate that a thin continental crust underlies the basin. Structures in the basin are suggestive of rotated fault blocks indicating rifting of an older sedimentary section during the opening of this part of the Andaman Sea. The identified magnetic anomalies in the central Andaman Sea indicate a spreading rate of 3.72 cm/yr with opening started about 13 m.y. or in Middle Miocene (Curray et al., 1979). Total opening since that time has been 460 km (Curray et al., 1982). Raju et al. (2004) has arrived at a conclusion that the present full rate spreading in the central Andaman Basin is about 38 mm/yr and that it has opened 118 km in about the last 4 m.y, which agrees with the recent observation of Curray (2005). Win Swe (1972) inferred that this spreading axis is in turn transformed northward onto the Sagaing fault. Curray et al. (1977) proposed that opening of the Andaman
Sea is transformed southward into the Sumatra fault system. In the geologic past, some of the motion of this opening may possibly have been taken up by a southern continuation of the West Andaman Fault.

Curray (2005) excellently synthesized all available geological and geophysical data and proposed different stages of opening of the Andaman Sea region. His reconstruction involves separation of India from Australia and Antarctica in the eastern Gondwanaland and its northward flight since the Cretaceous. Some salient aspects of the reconstruction history (Figure 2.6) have been presented below; as outlined in Curray (2005).

- **Before the departure of India from Australia and Antarctica,** the South Tibet, Burma and SIBUMASU Blocks had already spun off northward and had docked against Asia. Prior to initiation of the subduction system, this could have been a passive continental margin, the source of some of the older sediments found in Myanmar and the Andaman-Nicobar Ridge.

- The northeastern corner of 'Greater India' hit this subduction zone at about 59 Ma (Klootwijk et al., 1992), the so-called 'soft collision', and India underwent some counter clockwise rotation from about 59 to 55 Ma, at which time the suture was completely closed. During this time and until about 44 Ma, India was indenting the Asian margin and rotating the subduction zone in a clockwise direction. With this rotation the direction of convergence became increasingly more oblique. Finally, probably in the middle to late Eocene, about 44 Ma, a sliver fault formed, the forerunner of the Old West Andaman and Sagaing Fault systems. Right-lateral motion started on the Khlong Marui and Ranong Faults at about this same time (Lee and Lawver, 1995) prior to the opening of the Mergui Basin during the Oligocene. The northern strand of the Mergui fault may have crossed the Mergui
Ridge as a splay of the Sagaing Fault (Figure 2.6a). The Mergui Ridge was probably part of the original volcanic arc.

**Figure 2.6.** Sketch model of the reconstruction history showing different stages of opening of the Andaman Sea region (after Curay, 2005).
By early Miocene, about 23 Ma (Figure 2.6b), the plate convergence was oblique enough that extension and back arc sea floor spreading moved westward to the sliver fault running approximately along the magmatic arc, which had by that time migrated westward. The sea floor spreading and creation of oceanic crust formed the rock masses comprising of Alcock and Sewell Rises. The rocks from Alcock are early Miocene. With abandonment of extension in the Mergui Basin area, rapid subsidence occurred and the shallow water deposits of the late Oligocene were buried by deeper water facies.

At the end of early Miocene, about 15-16 Ma (Figure 2.6c), a major change occurred in the Mergui Basin with an unconformity and deposition of dark gray to black shales of the Baong, Trang and Surin Formations over the carbonate sediments of the Peutu, Tai, Katang and Payang formations. At this time the conjoined Alcock and Sewell Rises started rifting away from the edge of continental crust forming East Basin. And finally at about 4 Ma (Figure 2.6d), the plate edge migrated again to cut Alcock and Sewell apart, and the present plate edge between the Southeast Asian and the Burma Sliver Blocks was formed.

2.3.2.2 Sumatra arc region

Structure of the Sunda arc off central Sumatra was studied by Kieckhefer et al. (1980), using seismic refraction data and interpreted that Sumatra is underlain by older, Paleozoic continental crust (Figure 2.7). Northern Sumatra is also characterized by Paleozoic sedimentary rocks and Mesozoic granites (Katili, 1962). The Sumatran fault Zone (SFZ), a northwest trending fault that cuts the entire length of Sumatra and Indonesia is a major dextral active strike-slip fault zone. In the southwestern part, there is a 300 km wide strip of lithosphere between the Sumatran fault and the
deformation front called the Sumatran fore arc sliver plate. The SFZ is also considered as the limit between the Eurasian plate and the fore arc sliver plate.

Along the Sumatran arc, slip vectors for earthquakes of the under thrusting Indo-Australian plate rotate into north east direction suggesting that convergence is oblique and a large part of the plate motion is taken up by right-lateral shear within the overriding plate in the order of 3.6-4.9 cm/yr (McCaffrey et al., 2000). The trench parallel shear is absorbed by transpressive deformation of the Eurasian plate leading edge and with an assumed northward displacement of continental slivers (Baroux et al., 1998; Simandjuntak and Barber, 1996), indicate the partitioning of oblique plate convergence into thrust and strike-slip motions (Genrich et al., 2000).

The most pronounced shear zone of the overriding Eurasian plate is the Sumatra fault zone (SFZ) within the volcanic arc. The SFZ accommodates most of the right lateral stress of the relative plate motion between the Indo-Australian and Eurasian plates and is seismically active (Schluter et al., 2002). The Sumatran fault system consisting of 20 en echelon segments (Tjia, 1978) is the world’s clearest example of major shear fault system adjacent to a convergent margin (Fitch, 1970a; 1972). The fault extends for 1900 km along the volcanic chain of western Sumatra from 10° N to 7° S (Sieh and Natawidjaja, 2000). It turns into a complex pattern of
extensional faults in the fore arc south of Sumatra. North of Sumatra, the SFZ seen to be continuing into the Andaman Sea and joins with the fracture zones of back arc spreading center (Curry et al., 1978). The oblique subduction beneath Sumatra results in partitioning of the convergent motion. The variation of slip rates along the various segments of SFZ ranging from 1.1cm/yr to 2.8cm/yr (Baroux et al., 1998) was accommodated by fore arc sliver deformation (Diament et al., 1992; McCaffrey, 1992). Slip rates as determined by SPOT images along stream offsets along the fault infer movements of 0.6 cm/yr in the south to 2.3 cm/yr in the north (Bellier and Sebrier, 1995). According to Malod and Kermel (1996), the right lateral slip is not only taken up by SFZ with a rate of 2 cm/yr, but also, by the Mentawai fault zone (MFZ) identified by Diament et al. (1992) in the fore arc basin. The MFZ give rise to a slip rate of up to 1.1 cm/yr off Nias Island. The northern part of the MFZ seems to be connected to SFZ by the Batee fault and terminates within the accretionary wedge, indicating two slivers (Mentawai and Aceh slivers) on top of which the fore arc basin has developed. If this is correct, the accretionary wedge and the outer arc high with the islands of Enggano and Nias must be a separate northward moving feature along the Mentawai fault (Malod et al., 1995; Van der weff, 1996). The shape and location of the Sumatran fault and the active volcanic arc are highly correlated with the shape and character of the underlying subducting lithosphere (Sieh and Natawidjaja, 2000).

Arc-normal extension is known to be an important mechanism in bringing high pressure, low temperature metamorphic rocks to shallow levels in accretionary wedges (Platt, 1986). Arc-parallel extension is also important because the estimated strain parallel to the Sumatran fore arc implies thinning of the fore arc at 1-2 mm/yr, which could result in rapid rise of rocks from deep in the accretionary wedge (McCaffrey, 1991).
A grid of multi-channel seismic profiles and well data from the Sumatra fore-arc basin revealed stratigraphic framework for the northern and central basins (Beaudry and Moore, 1981, 1985; Izart et al., 1994; Malod et al., 1995). According to these data, a widespread uplift and erosion occurred during the Paleogene followed by fore-arc subsidence since the latest Oligocene-earliest Miocene as evidenced by two transgressive-regressive sequences of limestone and shale due to eustatic changes and tectonism. During Pliocene-Paleocene, two more sequences of deltaic, clastic, and clay mineral were shed from the Sumatra margin into the subsiding basin segmented by traverse ridges into several sub-basins (Natawidjaja and Sieh, 1994; Genrich et al., 2000). According to Dickinson (1995), these basins were formed in the Oligocene. However, older basin sediment (Early Eocene) is found on some islands (Pubellier et al., 1992; Schluter et al., 2002).

The fore-arc ridge (outer arc high) is characterized by islands such as Enggano, Pagai, Siberut, and Nias provide considerable geological information. During Eocene and Oligocene an increase in the subduction rate led to the formation of mélangé (Karig et al., 1980), containing ultrabasic oceanic components. Early Miocene sediments were initially deposited in deep water and since the Middle Miocene shallow water clastic and carbonate sequences dominate. On Enggano Island, late Paleogene to Pliocene successions are folded and thrust (Schluter et al., 2002).

2.3.2.3. Sunda Strait

The Sunda strait is historically famous due to the explosion of the Krakatau volcano in 1883 and is an important area to understand the geodynamic evolution of the western Indonesia. The Sunda strait is interpreted either as related to rotation of Sumatra relative to Java with the rotation axis close to the strait during the late Cenozoic (Zen, 1983; Ninkovich, 1991) or as an extensional feature (Huchon and Le...
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Pichon, 1984; Harjono et al., 1992) resulting from the northwestward displacement of
the southern block along the SFZ as a consequence of oblique subduction in Sumatra.
Schluter et al (2002) suggest that the initial transtension and the formation of pull-
apart basins of the Sunda strait are due to a clockwise rotation of Sumatra with respect
to Java since the lower Miocene. The southeastern part of the SFZ, the Semangko
fault, ends in the Sunda strait in a complex pattern of dominantly normal faults
associated with subsidence, seismicity and volcanism (Huchon and Le Pichon, 1984).
The Sunda strait is mostly covered by quaternary volcanic products (Harjono et al.,
1991; Nishimura et al., 1986). The amount of extension of the Sunda strait is
estimated to 50-70 km (Malod and Kemel, 1996) and presumably occurred during
Pliocene (Diament et al, 1992). The region south of the Sunda strait is a transition
zone between two steady state tectonic regimes: to the east, normal subduction in
front of Java with well developed fore arc basins, and to the west, oblique subduction
with sliver plates and strike slip faults accommodating the lateral component of the
oblique subduction (Malod, 1995). Fitch (1972) proposed the Sunda strait as a
tectonic as well as physiographic break in the arc. Within the Sunda strait, a typical
pull-apart basin, that widens to the south, was initiated during the early Miocene
along the southern part of the Sumatran fault (Diament et al., 1990; Huchon and Le
Pichon, 1984; Lassal et al., 1989). Huchon and Le Pichon (1984) estimated that the
subduction in the Sunda strait started at 13 Ma, whereas, according to Harjono
and Suparka (1992) initiation of subduction is around 7-10 Ma.

2.3.2.4. Java arc region

Formed mostly as the result of volcanic events, Java is the 13th largest island
in the world and the fifth largest island of Indonesia. Curay et al. (1977) examined
the structure of central Java from seismic refraction data and interpreted that the
apparently normal oceanic crust of the Wharton basin is being subducted beneath
central Java. The fore arc basin is underlain by either thickened oceanic crust (Figure
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2.8a and b) or thinned continental crust with slightly anomalous velocities. Java is underlain by a thin young continental crust formed during the Tertiary as the roots of the magmatic arc. The current subduction system, located offshore south of present day Java began in Late Oligocene (Hamilton, 1979). Along the central Java, the oceanic crust converges at a rate of 6-7cm/yr in a direction N11°E and is approximately orthogonal to the trench. At present, 135 m.y old oceanic crust subducts off eastern Java and crustal ages decreases to 96 m.y off western Java.

Figure 2.8. Structure of central Java and Bali from seismic refraction data (after Curray et al., 1977).
Chapter 2

Tectonic stress and extension, resulting from northward movement of the Australian and Indian plates and rotation of Borneo, formed rifts or half graben complexes along much of the southern margin of the Sunda shelf plate (now Sumatra and Java) in Eocene to Oligocene time (Hall, 1977a,b; Longley, 1997; Sudarmono and others, 1977). These complexes are aligned north-south and are separated by faulted plateaus. The normal subduction below Java is characterized by the development of typical fore arc basins. It has been proposed that the transition between the two regimes of subduction zones occurs south west of Java, raising the question of continuation of the Sumatra and Mentawai faults into the accretionary prism and their connection with the structures of western Java, whereas, a survey of the active plate margin south of west Java by Arifin et al. (1987) shows that the fore arc basin is poorly developed. This was interpreted as the effect of continuation of the Sumatra fault within the active margin. A continuous accretionary wedge, outer arc high and fore arc basin are recognized along off Sumatra and western Java, but are not developed further east in off central Java. A large scale uplifts and segmentation of the fore arc due to subduction of oceanic basement relief leads to isolated bathymetric highs reaching water depths of only 1000 m compared to 2000 m in the western part of Java (Wittwer et al., 2006).

On land, a large fault zone known as the Cimandiri fault is interpreted as a large sinistral strike slip fault initiated during the Miocene (Dardji et al., 1994). No shear faulting of regional extent similar to that of SFZ exists in Java (Newcomb and McCann, 1987). The spatial variations in the slip vector azimuths at the Java trench suggest that arc parallel stretching of the fore arc occurs (McCaffrey, 1991).