Chapter 13

Anatomy of the Andaman–Nicobar subduction system from seismic reflection data

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Abstract: The Andaman–Nicobar subduction system is the northwestern segment of the Sunda subduction system, where the Indian Plate subducts beneath the Sunda Plate in a nearly arc-parallel direction. The entire segment ruptured during the 2004 great Andaman–Sumatra earthquake ($M_w = 9.3$). Using recently acquired high-resolution seismic reflection data, we characterize the shallow structure of the whole Andaman–Nicobar subduction system from west to east, starting from the nature of the subducting plate in the Bay of Bengal to back-arc spreading in the Andaman Sea. We find that the Ninety-East Ridge is overlain by thick continental margin sediments beneath the recent Bengal Fan sediments. The boundary between these two sedimentary units defines the plate interface. We observe evidence of re-activation of fracture zones on the subducting plate beneath the forearc, influencing the morphology of the upper plate. The forearc region, which includes the accretionary wedge, the forearc high and the forearc basin, is exceptionally wide (250 km). We observe an unusually large bathymetric depression within the forearc high. The forearc high is bounded in the east by a normal fault, whereas the forearc basin contains an active backthrust. The forearc basin is floored by the continental crust of Malayan Peninsula origin. The active sliver strike-slip fault lies in a deep basin, created during the rifting of the forearc continental crust and the Malayan Peninsula. The sliver fault connects with the Great Sumatra Fault in the south and with the Sagaing Fault in the north, via the Andaman Sea spreading centre and a large transform fault in the Andaman Sea.

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The Andaman–Nicobar subduction system (at latitude 5°–15° N) is the northernmost segment of the Sunda subduction zone, one of the most seismically active regions on Earth, where the Indian Plate subducts beneath the Sunda Plate in a nearly arc-parallel direction, at a rate of c. 43 mm a$^{-1}$ (McCaffrey 1992, 2009) (Fig. 13.1a). This segment marks the western boundary of the Andaman Sea, which is a complex active back-arc extensional basin (e.g. Curray 2005; Morley & Alvey 2015).

The subduction along the Eurasian margin is thought to have existed since Permian time (Katili 1973). After the separation of India from Australia in the late Cretaceous, the convergence rate increased significantly. By Tertiary time, the subduction margin reached a length of 6000 km (Katili 1975).

The collision of the Indian Plate with Eurasia has played a key role in the tectonic evolution of the region and the present-day configuration of the subduction zone. Around 59 Ma ago, the northern corner of Greater India collided with Eurasia, causing the Indian Plate to rotate anticlockwise up to 55 Ma (Klootwijk et al. 1992). Between 55 and 45 Ma, India was indenting the Eurasian margin and rotating the subduction zone in a clockwise direction, bending the NW Sunda subduction and increasing the obliquity of the subduction (Curray 2005). India fully collided with Eurasia at 44 Ma, leading to the development of the strike-slip sliver fault such as the Sagaing Fault and West Andaman Fault in the east (Peltzer & Tapponnier 1988). The volcanic arc was east of these faults along the Mergui Ridge and on mainland Sumatra. The increasing oblique convergence might have moved the volcanic arc further west and led to extension in the Mergui Basin in the late Oligocene, between the volcanic arc and the Malaya Peninsula.

By the early Miocene c. 23 Ma, the plate convergence was oblique enough that the rifting moved westwards, close to the sliver fault and volcanic arc, leading to coincident seafloor spreading (c. 7 mm a$^{-1}$) and volcanism, forming the Alcock and Sewell rises (Curray 2005). With continuing rotation of the arc, the direction of extension changed from 310° to 335° during 32–15 Ma and stabilized at 335° azimuth (Curray 2005). At around 16–15 Ma, the rifting jumped east of the volcanic arc and the Eastern Basin with east–west extension between the Alcock/Sewell rises and the Malaya continental peninsula.

In the north, the north–south-trending Andaman–Nicobar subduction system joins with its onshore prolongation, the Indo-Burmese arc (17°–27° N). At the corner between the Sumatra–Andaman and the Indian subduction zones, the Indo-Burmese range is structurally complex and seismically active to depths of c. 150 km (Li et al. 2008). In the Indo-Burmese wedge region, the northwards motion of the India Plate with respect to the Sunda Plate is c. 35 mm a$^{-1}$ (Vigny et al. 2003; Nielsen et al. 2004; Maurin et al. 2010) and is assumed to be accommodated through slip partitioning in the Indo-Burmese arc and on the Sagaing Fault (SF) (Fig. 13.1a). While subduction is active along the Andaman–Nicobar system, earthquakes and stress state do not support active subduction across the Indo-Burmese arc at present (Kundu & Gahalaut 2012). Available measurements in the SF region (Vigny et al. 2003; Maurin et al. 2010) and GPS measurements in the Indo-Burmese arc region (Gahalaut et al. 2010) suggest that the SF takes up between half and c. 60% of the relative motion between India and Sunda, the other half being taken up at the trench itself.

The entire Andaman–Nicobar segment ruptured during the 2004 great Andaman–Sumatra earthquake but, prior to this event, this segment had not experienced many large earthquakes ($M_w > 7$). During the December 2004 event however, the Andaman–Nicobar segment experienced the second-largest slip of the rupture area (c. 20 m; Ammon et al. 2005) and a significant near-trench slip. Known historical events along the Andaman–Nicobar segment are the 1881 thrust event ($M_w = 7.9$), located off Car Nicobar Island (Ortiz & Bilham 2003) and the 1941 event ($M_w = 7.7$), which was a thrust event located off Port Blair (Jhingran 1953) (Fig. 13.1b). Two events of $M_w > 7$ have occurred on the Andaman–Nicobar segment since the December 2004 (Fig. 13.1b). An event with a left-lateral...
A focal mechanism occurred on 24 July 2005 ($M_w$ 7.2). Another event with a similar focal mechanism, the 12 June 2010 ($M_w$ 7.5) earthquake, is the most recent large earthquake along the Andaman–Nicobar segment. These earthquakes occurred in the subducting plate and were generated by left-lateral strike-slip faulting on NNE–SSW-oriented near-vertical faults (Rajendran et al. 2011).

Until very recently, most of our knowledge of the Andaman–Nicobar segment of the Andaman–Sumatra subduction system was based on marine data acquired in the early 1970s (Curray et al. 1979; Curray 2005). High-resolution seismic reflection data have recently become available (Singh et al. 2013; Moeremans et al. 2014; Moeremans & Singh 2014, 2015), providing insight into the detailed crustal structure of the Andaman–Nicobar subduction zone. The goal of this chapter is therefore to characterize the geometry of the subduction front, accretionary prism and forearc area of the Andaman–Nicobar subduction, based on the interpretation of these seismic reflection data. Only aspects of the subduction zone that can be directly resolved from our seismic reflection data will be covered in this chapter, that is, the shallow morphology and present-day structure of this segment. While most of the features discussed here extend further north and south, the focus of this chapter is strictly the Andaman–Nicobar segment of subduction.

In the following sections, we summarize our findings and characterize the major features of the Andaman–Nicobar system from west to east, starting from the nature and role of the subducting plate, the forearc system, the sliver plate boundary and the back-arc Andaman Sea. To the west of the trench on the oceanic plate, the Ninety-East Ridge (NER), a long linear feature in the Indian Ocean, indents the Andaman–Nicobar segment up to the northern Nicobar Islands. The NER is visible on bathymetric data up to 10$^\circ$N, but is covered by the Bengal Fan sediments further north (Fig. 13.1). The trench in this area is filled with thick Bengal and Nicobar fan sediments (Moeremans et al. 2014). The age of the subducting oceanic crust along the Andaman–Nicobar segment varies from 60 Ma in the south to 80 Ma in the north (Jacob et al. 2014). The forearc is very wide (200–250 km) and is composed of a seawards...

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**Fig. 13.1.** (a) Bathymetry map (based on Sandwell and Smith (2009)) of the study area showing the Andaman–Sumatra subduction zone and (b) Andaman–Nicobar subduction system. Convergence direction and rate are shown with white arrows. Beach balls represent earthquake locations with hypocentre depth <20 km (red), 20–40 km (orange), 40–60 km (green) and >60 km (blue). The black rectangle marks the area shown in Figure 13.1b. CIB, Central Indian Basin; WV, Wharton Basin; GSF, Great Sumatra Fault; WAF, West Andaman Fault; ASSC, Andaman Sea spreading centre; ANF, Andaman–Nicobar Fault; EMF, Eastern Margin Fault; DF, Diligent Fault; AL, Alcock Rise; SW, Sewell Rise; MB, Megui Basin; EB, Eastern Basin; F6–G9, fracture zones.

**Fig. 13.2.** A 2D schematic diagram showing cross-section of the Andaman–Nicobar subduction system from the oceanic plate to the Andaman Sea spreading centre. Acronyms as for Figure 13.1.
accretionary wedge and nearly flat forearc high dotted with the Andaman and Nicobar islands (Fig. 13.2). The presence of ophiolites on the Andaman Islands suggests that these islands could be as old as 100 Ma (late Cretaceous) (Rodolfo 1969). The forearc high is bounded in the east by the Eastern Margin Fault (EMF) (Cochran 2010; Singh et al. 2013; Moeremans & Singh 2015) (Fig. 13.2). Further east, the Diligent Fault (DF) seems to be active within the Andaman–Nicobar forearc basin (Singh et al. 2013). The Andaman–Nicobar forearc basin is dammed in the east by a north–south-aligned ridge, the Invisible Bank (IB). The sliver strike-slip fault, the Andaman–Nicobar Fault (ANF), separates the Burmese sliver plate from the Eurasian Plate. The ANF is connected with the Great Sumatra Fault in the south, on the mainland Sumatra, and with the Sagaing Fault in Myanmar with a series of spreading centres and transform faults (Curray 2005; Singh et al. 2013).

Although some volcano-like features are present, there is no clear evidence for a volcanic arc east of the ANF. Inner-arc volcanic activity from the Andaman and Nicobar islands has been reported from Quaternary-aged volcanoes (Pal et al. 2003).

The Ninety-East Ridge and the subducting plate

The nature of the subducting plate has a significant effect on the seismogenic behaviour of the subduction zone. Several factors control its seismogenic behaviour: (1) the age of the subducting lithosphere; (2) the thickness of the sediments over the subducting plate; and (3) the morphology and nature of the subducting plate.

As mentioned above, the age of the oceanic lithosphere along the Andaman–Nicobar segment varies over the range 60–80 Ma. The thermal structure of oceanic lithosphere did not change much during 80–60 Ma however, so the age and resulting thermal regime of the subducting lithosphere should have little effect on the seismogenic behaviour of the Andaman–Nicobar subduction segment. On the other hand, the presence of a bathymetric feature such as the Ninety-East Ridge should have a significant effect.

The Ninety-East Ridge (NER) is a 6000 km long linear feature in the Indian Ocean extending from 30° S at the Broken Ridge to 18° N, following the 90° E Meridian. It is about 120 km wide and has a crustal thickness that can reach up to 15 km (Grevemeyer et al. 2001). The ridge’s northernmost segment indents the Andaman–Nicobar segment of the Sumatra subduction zone at around 8° N. The age of NER is well constrained up to 9° N (83 Ma at DSDP Site 217), but is poorly constrained further north as it is buried by thick Bengal Fan sediments. Seismic reflection data near 13° N show the presence of thick sediments above the NER (Fig. 13.3). Samajdar et al. (2013) suggested that the high-amplitude reflection at a depth of 5–6 s two-way travel time (TWT) corresponds to an unconformity separating the post-collision Bengal Fan sediments above from 1–2 s thick palaeo-sediments below, overlying the igneous NER crust. Figure 13.4 shows a seismic reflection image from the eastern flank of the NER at 10° N. A strong reflection at c. 6 s TWT separates the more recent Bengal Fan sediments above from the c. 3 s thick subhorizontal reflections beneath. This strong reflection can be imaged for c. 60 km beneath the accretionary prism and lies at the base of deformed accretionary prism sediments, suggesting that the décollement lies at the boundary between these two sedimentary units. Moeremans & Singh (2014) suggested that the sediments below the décollement correspond to Cretaceous palaeo-sediments deposited during 120–100 Ma in a
that the P-wave velocity of these sediments increases with sediment thickness could be due to the increasing distance the top of the oceanic plate was not imaged. The increasing of the Bengal Fan sediment increases to more than 3–4 s as thickness of sediments is very similar (Moeremans & Singh from 2 to 3 km near the trench. Beneath these sediments, sediment thickness increases from 1.5 to 2 s TWTT, i.e. We have four seismic profiles acquired across the trench along Trench sediment thickness continental margin environment, and that either the NER was emplaced in the vicinity of a continental margin or the NER in this region might consist of a thinned continental crust.

Since the Ninety-East Ridge is buried by thick Bengal Fan sediments, it is difficult to comment on the role of the NER itself on the seismogenic behaviour of the Andaman–Nicobar megathrust. If the imaged palaeo-sediments – extending up to 60 km beneath the forearc – lie over the NER, then 60 km of the NER might have subducted in the Andaman–Nicobar subduction zone. In this case however, the role of the ridge would have been modified by the sediment–sediment interface. Seismicity in the India–Burma–Andaman region suggests that there is a progressive southwards increase in the dip of the subducting slab (Li et al. 2008; Pesicek et al. 2010; Kundu & Gahalaut 2012). Late Mesozoic and early Cenozoic subduction of the Thetayan ocean floor into the mantle at depth has been reconstructed based on seismic tomographic and plate reconstruction studies (e.g. Replumaz et al. 2004). The continental parts of the subducting Indian Plate appear to be detached from the oceanic slab fragments detected deeper in the mantle. Subduction of the Ninety-East Ridge under Andaman and further northwards could control the dip of the subducting slab under the Andaman–Nicobar segment. The thickened and less-dense crust of the Ninety-East Ridge would be buoyant and result in a shallower dip of the slab, and could even inhibit the subduction process. The steep dip of the subducting slab (Shapiro et al. 2008) beneath the Andaman Sea might be due to a tear in the subducted oceanic lithosphere at depth due to buoyant shallow-dipping sedimented crust beneath the forearc.

The presence of thick sediments over the rough Ninety-East Ridge basement topography would have a significant effect on the friction coefficient at the plate interface, and hence the coupling. The presence of low effective friction material due to the sediment–sediment megathrust interface that extends up to 60 km beneath the forearc could explain the updip extent and large northwards propagation of the coseismic rupture of the 2004 Sumatra–Andaman earthquake.

**Trench sediment thickness**

We have four seismic profiles acquired across the trench along the Andaman–Nicobar segment of the subduction zone (Fig. 13.1). On profile PGS08-11 (Fig. 13.4), the Bengal Fan sediment thickness increases from 1.5 to 2 s TWTT, i.e. from 2 to 3 km near the trench. Beneath these sediments, there are 2–3 s thick palaeo-sediments. Further north, the thickness of sediments is very similar (Moeremans & Singh 2014). Further south, west of Nicobar Island, the thickness of the Bengal Fan sediment increases to more than 3–4 s as the top of the oceanic plate was not imaged. The increasing sediment thickness could be due to the increasing distance from the NER to the trench (Moeremans et al. 2014). In the northern Sumatra region, where the top of the oceanic plate can be imaged, the thickness of the trench sediment decreases from 3 s on profile WG2 to 2.5 s on Profile WG1 (see Moeremans et al. 2014), suggesting the diminishing effect of the Nicobar Fan southwards.

Based on a tomographic study, Ghosal et al. (2014) showed that the P-wave velocity of these sediments increases with depth reaching c. 5 km s⁻¹ at the top of oceanic crust. Such a high velocity requires a high compaction due to burial depth. Geersen et al. (2013) suggested that the large thickness of the sediments also increases the temperature at the sediment–basement interface and triggers mineral transformation and dehydration (smectite to illite) prior to the subduction, increasing the updip limit of seismogenic zone, therefore allowing the 2004 Sumatra–Andaman rupture to propagate to the subduction front and hence enhancing the tsunami produced by the earthquake.

**Fracture zones and the Andaman–Nicobar subduction**

It has been known for a while that the Wharton Basin (WB), east of the NER, is deforming actively. The deformation is taken up along re-activated north–south-trending fracture zones (FZ) (Deplus et al. 1998) which are believed to have accommodated c. 100 km of shearing during the last 7.5–8 Ma (DeMets et al. 1988; Delescluse & Chamot-Rooke 2007). Delescluse et al. (2012) observed a recent enhancement of intra-plate earthquake activity in the WB and suggested it was due to the stress induced by the two great subduction zone earthquakes (\(M_w = 9.3\) in 2004 and \(M_w = 8.7\) in 2005) offshore northern Sumatra. Active deformation in the WB was further confirmed by the twin 11 April 2012 \(M_w = 8.6\) and \(M_w = 8.2\) strike-slip earthquakes and their foreshock of 12 January 2012 with \(M_w = 7.2\) (Meng et al. 2012; Wei et al. 2013; Carton et al. 2014; Qin & Singh 2015). These earthquakes seem to have re-activated the fracture zone F6, in the nomenclature of Singh et al. (2011), over a distance of more than 1000 km (Carton et al. 2014).

Graindorge et al. (2008) observed that the re-activation of fracture zones on the subducting plate offshore Sumatra has an influence on the morphology on the upper plate. Two fracture zones (F8 and F9, Fig. 13.1) subduct beneath the Andaman–Nicobar segment. The two largest strike-slip aftershocks of the December 2004 megathrust event occurred on 24 July 2005 and 12 June 2010 (\(M_w = 7.2\) and 7.5, respectively), with left-lateral focal mechanisms that lie along F8. The 2010 event had 41 aftershocks of \(M_w > 4.0\) and its epicentre was located on the northwards extension of the subducting fracture zone F8 (Rajendran et al. 2011). Past the deformation front along F9, strike-slip events are observed beneath the forearc along its extension at c. 30 km depth. In the upper plate above, we observe a bathymetric low between two accretionary folds. This low is cut by a fault (Figs 13.4 & 13.5a) which slightly offsets the sedimentary reflectors on either side, and is associated with a small relief at the seafloor likely corresponding to a strike-slip fault. This fault seems to be related to the strike-slip earthquakes in the lower plate along re-activated fracture zone F9. Our seismic image suggests that although strike-slip faulting initiates in the lower plate along pre-existing oceanic fabric, strike-slip features propagate through the upper plate up to the seafloor.

**Accretionary wedge**

The accretionary wedge in this area is very wide and can be divided in three parts: (1) accretionary prism (outer wedge); (2) inner wedge; and (3) forearc high.

Around 10° N, the accretionary prism (shown in profile PGS08-11, Fig. 13.4) consists of seawards-verging folds and associated thrusts. The frontal thrust is seawards-vergent and is accompanied by a landwards-vergent conjugate fault, indicating a pop-up structure. The next two folds, around 50 km, are bounded by deep-rooted conjugate faults at depth. The next two folds, around 50 km, are bounded by deep-rooted conjugate faults at depth. The next two folds, around 50 km, are bounded by deep-rooted conjugate faults at depth.
deformation on the subducting plate along the re-activated fracture zones as discussed above. The basin is bounded by a 5 km wide fold. The fifth fold at 80 km seems to have accommodated a significant component of landwards-vergent slip. Further eastwards, six 4–6 km wide folds bounded by seawards-verging faults form the rest of the inner wedge. The tops of the folds have been eroded, decreasing the slope of the inner wedge to c. 2–2.5°.

Profile PGS08-12 (Fig. 13.1b) is 33 km further north of profile PGS08-11 and shows similar features (Moeremans et al. 2014). However, a 15 km wide 4.5 s (c. 5–6 km) thick prominent fold is observed (Fig. 13.5b) just north of the fold observed on PGS08-11, with well-preserved layering until the top of the subducting plate. Further south, west of Nicobar Island (PGS08-06, Fig. 13.5c), the toe of the accretionary wedge consists of a series of three rather steep landwards-verging thrusts (Moeremans et al. 2014). At about 30 km from the trench (Fig. 13.5c) the dominant fault vergence switches to seawards vergence and a broad zone of undeformed sediments is present between the two folds with opposite vergence, defining the boundary between inner and outer wedge. Moeremans et al. (2014) suggested that dominance of the landwards-vergent faults in the outer wedge is due to the presence of thick sediments.

The forearc high is the shallowest part of the accretionary wedge. In places, it rises above the seafloor forming the Andaman–Nicobar Islands, but it also contains a large depression (Figs 13.3 & 13.6). The Andaman Islands expose tectono-stratigraphic units of an accretionary prism in an outer-arc setting and turbidites of a forearc setting (Pal et al. 2003). A number of north–south-trending dismembered ophiolite slices of Cretaceous age and Tertiary trench-slope sediments were uplifted and emplaced by a series of east-dipping thrusts (Pal et al. 2003). A complete sequence from the Moho is exposed in the South Andaman Island. The history of the Andaman Ophiolites, as well as their emplacement mechanism along the outer arc, has been largely debated in literature as upthrust oceanic crust due either to subduction since the late Miocene (e.g. Curray et al. 1979; Pal et al. 2003; Curray 2005) or to the collisional history of the Indo–Burma–Andaman microcontinent during the late Oligocene (Acharyya et al. 1988; Acharyya 2007). Uplift of ophiolites along with sediment...
during late Cretaceous–Eocene times has also been reported for the Sumatra and Java segments of the subduction (e.g. Hall & Blundell 1996; Hall 2002).

On profile PGS08-11 the forearc high lies between 125 and 195 km, and can be divided into two distinct parts at 170 km. The western part is deeper, subsiding and deforming, while the eastern part is shallower and flatter. Reflections are absent within the eastern part of the forearc high, suggesting that it was close to the sea surface and covered in clastics. The western part corresponds to a large (120 × 50 km oval-shaped) bathymetric depression between Little Andaman and Car Nicobar islands. The hinge of the basin lies at the centre of the bathymetric depression, and sediments are tilting towards this centre. Steep faulting features, with some compressive motion, are present around 145 and 160 km (Fig. 13.6).

Offshore southern Sumatra a bathymetric low was observed in the wake of a subducted seamount (Singh et al. 2011), but the bathymetric low observed here and described above is too long and elongated to be associated with a seamount. However, such a bathymetric depression could result from the passage of a wide fracture zone. Indeed, fracture F6 (Carton et al. 2014), for example, is c. 60 km wide and has bathymetric relief of about 1 km. Another possibility is that this bathymetric depression could be due to basal erosion beneath the forearc or a tear in the downgoing plate. Deep seismic reflection data are required to understand the cause of this depression.

The Andaman–Nicobar forearc basin system

Forearc basins are formed due to a variety of subduction zone processes, filling up with sediments in response to a combination of tectonic processes and sediment supply (Dickinson & Seely 1979). Their evolution is therefore recorded in the depositional sequences as a series of subsidence and uplift events, directly associated with subduction processes (Berglar et al. 2010; Ryan et al. 2012), over millions of years. Furthermore, forearc basins are thought to play a role in the seismic cycle as well as during large earthquake ruptures. For example, the maximum slip during large subduction earthquakes has been shown to preferentially occur where sedimentary basins are present to stabilize the wedge (Fuller et al. 2006).

A forearc basin seems to be present all along the Andaman–Nicobar segment, but we only have data up to 11°N. There are four distinct features in the Andaman–Nicobar forearc system: (1) the Eastern Margin Fault; (2) the Diligent Fault; (3) the Forearc Basin; and (4) the Invisible Bank. We discuss each of these features in the next paragraphs.

The Eastern Marin Fault (EMF) defines the eastern margin of the forearc high, and bounds the forearc basin system in the west. The EMF seems to be less active, as no clear fault trace can be identified in the seismic reflection profiles (Fig. 13.7). However, it must have some normal component of motion because it is associated with a narrow V-shaped basin at c. 1.5 km water depth containing 2–3 km thick sediments (Figs 13.7 & 13.8a). The EMF might be associated with large-scale westwards tilting of the forearc basement (Singh et al. 2013) and uplift of the Invisible Bank. The Eastern Margin Fault had also been interpreted as a down-to-the-east normal fault between 8°30′ N and 11°N by Cochran (2010), who suggested that thickening of the sediments towards the centre of the basin is due to continuing subsidence along the EMF. However, the onlapping of the sediments on the western side of the basin (Fig. 13.8a) indicates that the above argument is not valid.

The Diligent Fault (DF) creates a NE-trending structural high, forming a boundary between the basinal plain and the Eastern Margin Fault basin. It is thought to have formed since the pre-Miocene or maybe the middle Eocene (Moeremans & Singh 2015). The Diligent Fault Zone (DFZ), which we define as the folded sequence of ridges bounded by the backthrust faults, is 20–40 km wide. The width of the fault zone increases northwards (Moeremans & Singh 2015). It is narrowest in the south of the study area, east of the Nicobar Islands. It progressively widens and reaches a maximum width along profile PGS08-14 (Fig. 13.7). The width of individual folds is 2–5 km. Fold width and spacing increases northwards. While the thrust faults of the DFZ in the northern part of our study area are dominantly landwards- (eastwards-) verging, the structure of the DFZ becomes more complex towards the south with mixed thrust vergence and a high variability in the fold amplitudes. The Diligent Fault had been previously interpreted as strike-slip fault (Curray 2005; Cochran 2010), but here we observe mainly thrusting. Based on these observations of the backthrust system, the Diligent Fault Zone evolution in the Andaman forearc basin seems to be very similar to that of the West Andaman Fault (WAF) (Chauhan et al. 2009; Singh et al. 2012) or the Mentawai Fault Zone (MFZ) (Singh et al. 2010; Mukti et al. 2012).

The Andaman–Nicobar forearc basin contains a 3–3.5 km thick sediment fill (Fig. 13.7) of Cenozoic age, recording the evolution of the Andaman–Nicobar forearc over the past c. 60 Ma. Previous studies have shown that there are three major sedimentary groups are present in the Andaman–Nicobar forearc (e.g. Rodolfo 1969; Pal et al. 2003; Curray 2005). The oldest group, the Eocene Mithakhari Group, consists of pelagic trench sediments and coarser ophiolite fragments. It is 1.4 km thick and is found in the accretionary prism. Two deposits are found in the forearc basin: the Andaman Flysch Group (AFG) and the Archipelago Group (AG). The AFG is of late Eocene–Oligocene age. It is c. 3 km thick, composed of three different lithofacies and overlies and onlaps the Mithakhari Group. The AFG is unconformably overlain by the AG, which are Miocene–Pliocene-aged sediments thought to have been deposited in an outer-shelf to open-marine environment (Chakraborty & Pal 2001). The AG is composed of two major assemblages of turbidites. In comparison with the AFG and the
AG, the Mithakhari Group shows complex deformation with highly variable bedding orientations (Pal et al. 2003). Forearc sedimentation often occurs around the same time as uplift of the accretionary complex and later-stage deformation in the margin. Sediments in the forearc basin are therefore younger than the accretionary wedge material.

In our seismic reflection data, we identify three major stratigraphic units (P, N and R) in the Andaman–Nicobar forearc basins, based on their seismic characteristics and unconformities between them (Fig. 13.7) (Moeremans & Singh 2015). The top of the basement of the forearc basin is interpreted as high-amplitude reflectors that are dipping westwards. The eastwards end of the forearc basement, the Invisible Bank, can be as shallow as a few metres water depth (Fig. 13.9) at both along-strike extremities of our study area. The high amplitude of these basement reflectors indicates a sharp contrast (increase) in the velocity across this boundary. In certain profiles, the basement presents some reliefs on its top (Moeremans & Singh 2015). Below these high-amplitude reflectors that represent the top of the basement, returned acoustic energy is sparse. Further reflections are visible in some profiles however, which might be due to old sedimentary layering within the crustal material (Singh et al. 2013).

Unit P (Palaeogene) consists of seawards-dipping reflectors characterized by high amplitudes. These reflectors are interpreted as the oldest sedimentary unit of the forearc basin, which was deposited conformably on top of the basement. This unit is westwards dipping and must have been deposited prior to uplift and subsequently tilted and uplifted along with the basement (Fig. 13.9) (Moeremans & Singh 2015). It comprises of two to three depositional sub-units that are separated by reflectors of high amplitude and/or depositional onlap of the top reflections onto the lower reflections. This unit was deposited as flat-lying beds during pre-Miocene times. Some tectonic deformation can be seen in this unit.

Unit N (Neogene) onlaps onto Unit P and is characterized by generally lower-amplitude reflections. It is also seawards-dipping and likely corresponds to Miocene sediments. Onlap and deformation of Unit N indicates that the deformation within the basement resumed for a small time during deposition of Unit N. In contrast to Unit P, which was deposited conformably over the top of the basement prior to uplift and was tilted and uplifted along with it after deposition, Unit N was deposited as some uplift of the basement had already taken place (Moeremans & Singh 2015). Uplift continued throughout the deposition of this unit.

Unit R (recent) is the most recently deposited unit, probably of Plio-Pleistocene age. It is characterized by flat-lying reflectors onlapping Unit N (Neogene) sediments (Fig. 13.9). The sediments of this unit were deposited after the major uplift phase. It shows very little deformation and is found to fill the lows within the basin on either side of the DF. A significant portion of the subsidence along the Eastern Margin Fault had occurred prior to the deposition of this unit, particularly in the north of the study area.

At the eastern edge of the forearc basin, the Invisible Bank (IB) is the shallowest feature in the region apart from forearc islands. It is a cuesta formed by the sliver fault and extends all along the Andaman–Nicobar segment, beyond our study area. The Invisible Bank is approximately 300 km long and 5 km wide. Miocene limestones were dredged on the eastern flank of the IB at 1000 m water depth (Rodolfo 1969). Roy & Chopra (1987) report that drilling near the crest of the IB encountered thick lava flows below 1100 m of middle Miocene sedimentary rocks (e.g. Dredge 12 (c. 11.5° N) with rocks c. 17 Ma uplifted c. 400 m since deposition or Dredge 13 (c. 12° N) with c. 6 Ma rocks uplifted more than 500 m. Curray (2005) suggested that the sliver fault (the Andaman–Nicobar Fault in this paper), which he called the West Andaman Fault, formed the cuesta within the last 6 Ma. The seismic
reflection profiles shown here indicate otherwise because Unit N (Miocene) onlaps onto Unit P, suggesting that most uplift had occurred prior to the deposition of Unit N (unless Unit N is only 6 Ma, but this is unlikely given known sedimentation rates; Moeremans & Singh 2015). Furthermore, the Invisible Bank is cut by a steep fault that could have been the sliver fault prior to the Andaman–Nicobar Fault (Moeremans & Singh 2015).

Based on bathymetry and gravity data from the Andaman–Nicobar forearc basin system and its similarity with Aceh and Mentawai forearc basins, Singh et al. (2013) suggested that the Andaman–Nicobar forearc basin is floored by the Malayan continental crust and belongs to the same regime as the floor of the Mentawai Basin further south, where the oldest sediments could be up to 85 Ma old. The Invisible Bank also seems to be of continental origin, and might have rifted from the Malaya Peninsula at c. 30–23 Ma during the initiation of spreading in the Andaman Sea. Other studies also show that the Andaman–Nicobar forearc basin is floored by continental crust. Forward gravity modelling supports the statement that the Andaman forearc basin is underlain by continental crust (Goli & Pandey 2014). In addition, regional satellite gravity data was inverted to determine crustal type and thickness in different areas of the Andaman Sea (Morley & Alvey 2014); the results indicate that the Central Andaman Basin is oceanic crust, while the adjacent regions of the Alcock and Sewell rises and Eastern Andaman Basin are extended continental crust.

The Andaman–Nicobar Fault

Strain partitioning due to oblique subduction can lead to the formation of a sliver fault, where the arc-orthogonal component of motion is accommodated along the megathrust and arc-parallel motion along the strike-slip sliver fault in the forearc (Fitch 1972). Along the Sunda subduction system the obliquity initiates near the Sunda Strait, increases northwards, and becomes nearly arc-parallel in the Andaman–Nicobar region, extending all the way to Himalayan syntaxes in northern Myanmar. On mainland Sumatra, the strike-slip motion is taken up along the 1900 km long Great Sumatra Fault (GSF) (Sieh & Natawidjaja 2000). As it enters the Andaman Sea near Banda Aceh, the Great Sumatra Fault divides into two strands: the Aceh fault in the west and the Seulimeum fault in the east. Ghosal et al. (2012) have found that the Aceh strand is the most seismically active branch. The strike of these faults is the same as that of the GSF, that is, NW. These two strike-slip faults merge with West Andaman Fault (WAF) (a backthrust, Singh et al. 2012) east of Nicobar Island, creating a triple junction. North of the main Nicobar Island, the Eastern Margin, the Diligent and the strike-slip Andaman–Nicobar (ANF) faults initiate and diverge northwards. The merging of all these fault systems creates a complex deformation pattern in the vicinity of Nicobar Island. After the great Andaman–Sumatra earthquake in 2004 there was a swarm of aftershocks at the triple junction, possibly resulting from the complex interaction between these different faults (Singh et al. 2013).

North of Nicobar Island, the strike of the Andaman–Nicobar Fault is nearly north–south. It lies in a 10–15 km wide 4000 m deep rift basin. Seismic reflection images of the ANF (Fig. 13.10) show that the recent sediments are nearly flat with a vertical fault cutting through the centre of the rift basin, marking the present-day location of the ANF. Singh et al. (2013) showed that the nature of the ANF varies along the margin with a complex deformation pattern. They also found that the distribution of hypocentres is not vertical as one would expect from strike-slip faulting, but exhibits a slight tilt towards the NE. This lithospheric-scale eastwards dip on the sliver strike-slip fault might explain the westwards tilting of the whole forearc basin system and the presence of the Eastern Margin Fault.

The Andaman–Nicobar Fault is extremely active up to 10° N, where it intersects with the Andaman Sea spreading centre (ASSC) (Singh et al. 2013). North of this, there are only a few earthquakes with complex focal mechanism. The seismic reflection image (Fig. 13.7) shows a compressional ridge within the rift valley, which could be due to a complex interaction between the ANF and ASSC. There are no earthquakes further north of 11° N along the strike of the Andaman–Nicobar Fault, suggesting that it terminates at its junction with the ASSC. However, the deep rift valley seems to continue up to 14° N, suggesting that the valley was created prior to the formation of the ANF within the rift valley. Sieh & Natawidjaja (2000) suggested that the Great Sumatra Fault on mainland Sumatra initiated 2 Ma ago; it is therefore possible that the sliver fault in the Andaman Sea moved to its present position.
as the Andaman–Nicobar Fault around the same time. Molnar & Dayem (2010) suggested that the position of intracontinental strike-slip faults is defined by a zone of weakness, or a discontinuity in strength of the lithosphere, where the strain concentrates along the boundary between weak and strong lithosphere. If the rift valley was generated during the separation of Invisible Bank from the Malayan Peninsula, it is an obvious site to host the Andaman–Nicobar sliver fault.

**Andaman Sea spreading centre and transform fault**

The Andaman Sea is a complex back-arc extensional basin formed by transtension soon after the collision of India with Eurasia in Palaeogene time (Peltzer & Tapponnier 1988). The Central Andaman Sea basin is c. 118 km wide and is a region of active tectonics, characterized by extensional earthquakes (Kamesh Raju *et al.* 2004; Diehl *et al.* 2013).

The Andaman–Nicobar Fault is connected with the Sagaing Fault in Myanmar through a series of ocean-spreading segments and a large transform fault in the Andaman Sea. Nielsen *et al.* (2004) observed that, because the Burma sliver is buttressed by the Eastern Himalayas, faults accommodating the oblique component of motion of India progressively migrate in space from far-field faults in the south (Andaman–Nicobar and Sagaing faults) to near-trench faults in the north (Arakan Yoma Belt and the trench itself).

The Andaman Sea spreading centre is segmented into three distinct segments (Kamesh Raju *et al.* 2004; Jourdain *et al.*

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**Fig. 13.10.** Blow-up of seismic data across the Andaman–Nicobar Fault (ANF).

**Fig. 13.11.** 3D block diagram of important features in the Andaman–Nicobar subduction system.
Andaman Basin (Kamesh Raju 2016): (1) a western segment; (2) the central segment; and (3) a northern segment. The northern segment seems to be a nascent spreading centre connected to the Sagaing Fault in the north and to the central segment in the south with a 180 km long transform fault. Both the northern and central segments are covered with thick sediments (Fig. 13.7), whereas the western segment is devoid of sediments. Kamesh Raju et al. (2004) suggested that the western segment has been propagating westwards, and hence is younger. Based on bathymetric, shallow-seismic and magnetic data, Kamesh Raju et al. (2004) suggested that the Andaman Sea spreading centre (ASSC) initiated at c. 4.5 Ma, separating the Alcock and Sewell rises. However, Morley & Alvey (2015) recently re-examined the published geophysical data over the eastern part of the Central Andaman Basin (Kamesh Raju et al. 2004; Curray 2005) and suggested that the observed sedimentary geometries are incompatible with continual seafloor spreading since 4 Ma. Instead, these authors suggest that the Central Andaman Basin has formed by episodic seafloor spreading, mostly from the middle to late Miocene, followed by a recent re-activation.

Concluding remarks

Our results are based on seismic reflection data that penetrate down to 10–15 km depth (9 s TWT), and hence we do not have any constraint below this depth. Furthermore, our seismic reflection profiles do not extend over the Ninety-East Ridge, and hence the relationship with palaeo-sediments imaged on our profile and those imaged on the profile of Samajdar et al. (2013) is not direct. We are further constrained by the lack of seismic reflection profiles north of 11° N. Care therefore has to be taken in extending our results beyond our study area. The southern half of the Andaman–Nicobar subduction system is however well constrained, and we draw the following conclusions (Fig. 13.11).

1. To the west of the trench, the Ninety-East Ridge is overlain by thick palaeo-sediments of age 100–120 Ma. The top of the palaeo-sediment unit forms the décollement surface, enlarging the locked part of the plate interface and enhancing the maximum size of megathrust earthquakes in the region.

2. The presence of thick Bengal and Nicobar fan sediments above the palaeo-sediments could increase the temperature of the deeper sediments, leading to mineral transformation and dehydration in these sediments before their arrival at the trench. This could increase the updip limit of a megathrust rupture up to the trench, enhancing the tsunami-genic potential of the margin.

3. Fracture zones present on the subducting plate seem to be re-activated and produce earthquakes below the forearc, thereby influencing the morphology within the upper plate.

4. The accretionary prism consists of bivergent pop-up structures, which can enhance tsunami generation during megathrust ruptures.

5. The forearc high hosts a large (120 km by 50 km) bathymetric depression, which also contains compressive features.

6. The Eastern Margin Fault is interpreted as an inactive normal fault that gave rise to a deep V-shaped basin, marking the western limit of the Andaman–Nicobar forearc basin.

7. The Diligent Fault is predominantly a backthrust and created a NE-trending structural high within the Andaman–Nicobar forearc basin.

8. The Andaman–Nicobar forearc basin is likely floored by continental crust rifted from the Malayan Peninsula, and the Invisible Bank could be a part of this continental block that rifted from the Malayan Peninsula 23–30 Ma ago.

9. The eastern margin of the Invisible Bank is a deep rift basin which hosts the Andaman–Nicobar strike-slip sliver fault.


Although the subduction in the Andaman–Nicobar region is nearly arc-parallel, the main features of the subduction system are similar to those in the Sumatra region. These include a set of bivergent pop-up structures near the subduction front, a wide forearc, forearc high and islands, and a backthrust system within the forearc basin which is floored by continental crust. In the Andaman–Nicobar region, the forearc high is bounded by a normal fault (the Eastern Margin Fault) instead of by a backthrust (the West Andaman and Mentawai faults) offshore Sumatra. The main differences between the Andaman–Nicobar and the Sumatra segments of the subduction zone are due to the presence of spreading in the Andaman Sea. Understanding the dynamics of the Andaman Sea spreading centre would require another chapter.

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References


