

The west Andaman fault and its influence on the aftershock pattern of the recent megathrust earthquakes in the Andaman-Sumatra region

K. A. Kamesh Raju

National Institute of Oceanography, Goa, India

G. P. S. Murty

National Institute of Oceanography, Regional Centre, Visakhapatnam, India

Dileep Amarnath and M. L. Mohan Kumar

National Institute of Oceanography, Goa, India

[1] Distinctly different rupture patterns of December 2004 and March 2005 megathrust earthquakes occurred in the Andaman-Sumatra region suggest strong influence of tectonic and structural elements. We have analysed the shipboard gravity, bathymetry and seismic data across the West Andaman Fault (WAF), a major tectonic feature in the Andaman Sea, to infer the crustal structure and to examine its influence in controlling the aftershock pattern. Our results support the idea of Singh [2005] that WAF forms a lithospheric scale boundary and together with other tectonic elements modulates the occurrence of large earthquakes and their rupture pattern. The active strike-slip motion along the WAF, presence of backarc spreading coupled with increased obliquity of subduction in the Andaman Sector reduce the probability of occurrence of major or great earthquakes north of 10°N.

1. Introduction

[2] The two megathrust earthquakes of 26 December 2004 ($M_w=9.3$) and the 28 March 2005 ($M_w=8.6$) in the Andaman-Sumatra region exhibited distinct and divergent rupture patterns. As postulated by Singh [2005], these events have demonstrated that the tectonic and structural elements play a critical role in governing the nucleation, growth and arrest of rupture propagation. The 2004 event nucleated off northern Sumatra, propagated unilaterally in the north-northwest direction and ruptured about 1300 km long plate boundary in about 8-10 min [Ammon *et al.*,

2005], the rupture area roughly coinciding with the aftershock distribution (Figure 1b). In contrast, the 2005 event has shown bilateral rupture. While the length of the rupture zone and the source region are well constrained [Lay *et al.*, 2005; Neetu *et al.*, 2005], the factors that controlled the geometry of rupture and the distribution of aftershocks are not well understood. Singh [2005] attributed the differences in the aftershock distribution and pattern of these two events to a lithospheric scale boundary based on bathymetry, and modelling results. The two events are located on either side of West Andaman Fault (WAF) [Curry *et al.*, 1979], indicating that WAF played a critical role in controlling the rupture pattern of both the 2004 and 2005 earthquakes [Singh, 2005]. In the case of 2004 event, the rupture confined to the narrow corridor between the WAF and the trench line, whereas the 2005 event being on the eastern side of the WAF did not result in much aftershock activity across the WAF (Figure 1).

[3] The fault plane motion along the WAF exhibit variability as depicted by the CMT solutions of the events located on or very near to the WAF (Figure 2). The northern portion of the WAF in the Andaman sector represents predominant strike-slip motion, while a mixed response of strike-slip and thrust fault motions are seen toward south in the Sumatra sector. The WAF bifurcates into two branches off Nicobar Island, one branch joins the great Sumatran Fault and the other swerves around the northern tip of Sumatra, continues in the western offshore

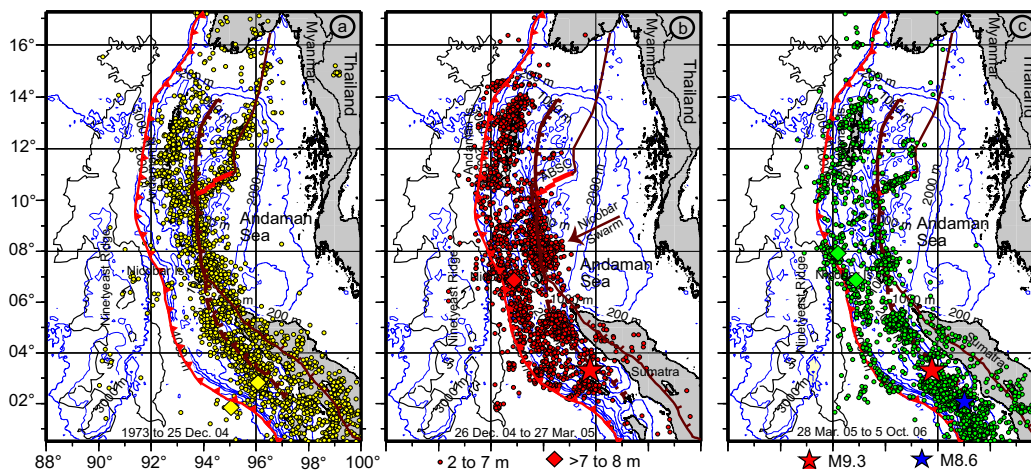


Figure 1. Earthquake epicenters from NEIC. a) Events from 1973 to 25 December 2004. b) 2004 event and the aftershocks till 27 March 2005. c) Aftershocks of 28 March 2005 event, till October 2006. Note the change in the aftershock pattern in b) and c)

of Sumatra and eventually joins the Mentawai fault zone [Diament *et al.*, 1992]. While the Sumatran fault and the Mentawai faults in the Sumatra sector are well studied [Sieh and Natawidjaja, 2000], the nature and characteristics of the WAF in the Andaman sector between 4°N to 12°N remained poorly known due to scanty information. Here we provide crustal structure and new insights into the tectonic characteristics of the WAF in the Andaman sector by using shipboard gravity, swath bathymetry, single channel seismics and seismological data. We also examine the influence of WAF in modulating the after shocks of the two megathrust events.

2. Geodynamic Setting

[4] The subduction zone in the northeastern Indian Ocean and the Andaman island arc system together with the Andaman backarc basin is a part of major trench-arc system. The tectonic framework of the Andaman Sea is well documented [Rudolfo, 1969; Curray *et al.*, 1979; Kamesh Raju *et al.*, 2004; Curray, 2005]. Prominent morphological features such as Barren Island (BI), Narcondam Island (NI), Invisible Bank (IB), Andaman Backarc Spreading Center (ABSC) and the Alcock and Sewell seamount complexes, mark the backarc basin (Figure 2).

[5] The subduction, presumed to have started in the early Cretaceous [Scotese *et al.*, 1988], occurs all along the Sunda arc and extends from the eastern Himalayan syntaxis to Banda arc with major variations in speed and direction resulting in oblique convergence. The strike-slip faulting parallel to the trench axis, formation of a sliver plate, backarc extension and basin formation are some of the effects of oblique plate convergence. Analysis of high resolution swath bathymetry and other geophysical data [Kamesh Raju *et al.*, 2004] suggest that true seafloor spreading in the Andaman Sea commenced at about 4 Ma instead of the 11 Ma proposed earlier. The opening rate

based on the revised seafloor spreading estimates is 26 mm/yr. The ABSC is connected to the Sagaing fault system in the north and abuts the WAF in the SW; and the WAF in turn connects to the Sumatran fault and the Mentawai fault systems off Sumatra (Figure 2).

3. Data

[6] Multibeam bathymetry data acquired during the 168th cruise of ORV Sagar Kanya and the earlier data [Kamesh Raju *et al.*, 2004] are presented. Single channel seismic reflection and gravity data acquired onboard AA Sidorenko (April, 1995) are used to generate the crustal models. Seismological data and focal mechanism solutions are obtained from the National Earthquake Information Center (NEIC), USGS and the Harvard-CMT solution catalogue respectively.

4. Crustal structure across the West Andaman Fault

[7] Three profiles along $9^{\circ}20'\text{N}$, $10^{\circ}12'\text{N}$ and 13°N latitudes across the WAF are used to generate the crustal models with the constraints of single channel seismics, bathymetry, and seismotectonic setting of the region (Figure 2).

4.1 Free-air gravity and seismics

[8] The free-air gravity mimics the seabed topography along the profiles AN1, AN2 and AN3 (Figure 3). A prominent free-air gravity low of 100 to 150 mGals is noticed towards the west of WAF. This gravity low corresponds to the effects of subducting plate and the formation of forearc basin east of the Andaman Islands. The other prominent gravity anomaly corresponds to the WAF. The gravity, bathymetry and seismic character of the WAF change from north to the south and is controlled by the regional tectonic and structural fabric of the Andaman basin. The profile AN1 does not show a strong bathymetric step and is covered with sediments as it lies on the inactive part of the WAF. In contrast, along the profiles AN2 and AN3, the bathymetric step resulting from WAF is prominent with no sediment cover on the fault plane and thick sediments at the base of the fault and further east. Thin or no sediment cover along the fault plane and the seismic reflection signature over the profile AN2 suggests active faulting and the fault plane solutions indicate prominent strike-slip motion (Figure 2). Towards east of the WAF, the presence of Alcock and Sewell seamount complexes are seen along the profiles AN1 and AN3 respectively. Thick sediments are noticed in the seismic section along the profile AN2 as it traverses the backarc basin (Figure 3).

4.2 Forward modeling of free-air gravity

[9] Long-wavelength gravity effect due to the Indian Ocean lithosphere subducting below the Andaman arc was computed following the method of Furuse and Kono [2003], assuming the subducting plate geometry of Dasgupta *et al.* [2003]. The slab residual anomalies are modeled (Figure 4) to infer the crustal structure.

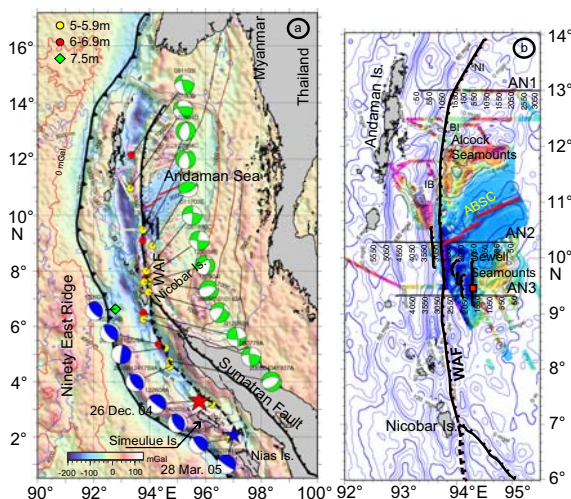


Figure 2. a) CMT solutions of selected events on or near to the west Andaman fault plotted on satellite derived gravity image. b) Multibeam bathymetry image of the Andaman backarc basin covering a part of WAF, over satellite derived free-air gravity contour map. AN1, AN2, and AN3 represent the profiles across WAF used for modelling. Red square denotes location of Andesites.

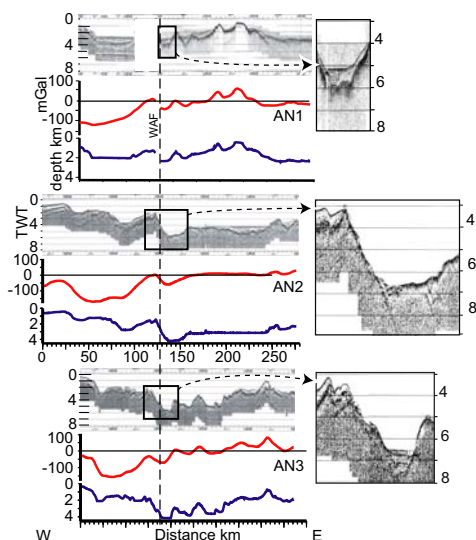


Figure 3. Bathymetry, free-air gravity and single channel seismics along the profiles AN1, AN2 and AN3.

[10] The subducting slab geometry and the trench axis location derived from the satellite derived gravity and topographic maps are considered as the first order constraints. Densities were assigned based on the works of *Mukhopadhyay* [1988] and of *Kopp et al.* [2001] in the Sumatra sector. The forearc basin is modeled by invoking thick sediments forming an accretionary prism with high density of 2.7 g/cm^3 [*Kopp et al.*, 2001]. Along the northern profile AN1, consolidated sedimentary rocks of density 2.7 g/cm^3 with undulating crust-mantle interface was invoked in the model, to compute the effect of part of the Alcock seamount complex, implying local compensation of Alcock seamounts. The crustal models along the profiles AN2 and AN3 (Figure 4) suggest that the WAF is characterized by shallow mantle. It is interesting to note that Andesites were recovered in a dredge haul along the fault planes east of the WAF (Cruise report of AAS-11). The shallow mantle east of the WAF in the Andaman backarc basin is consistent with the presence of ABSC [*Kamesh Raju et al.*, 2004]. The profile AN2 intersects the spreading center (Figure 2) and the shallow mantle in the crustal model coincides with this location.

5. Discussion

[11] Lithospheric boundaries in the upper plate play a key role in the size and nature of the megathrust earthquakes [*Sieh and Natawidjaja*, 2000; *Singh*, 2005]. The WAF swerves around the tip of the northern Sumatra around 6°N and eventually joins the Mentawai fault zone around 2°N . The section of the WAF between 1°S and 2°N is highly segmented and the segmentation is attributed to the transtensional necking of the forearc region during the past 4 m.yr. [*Sieh and Natawidjaja*, 2000].

[12] One of the plausible reasons for the channelling of the 2004 earthquake rupture into a narrow zone towards north could be that the event occurred west of a lithospheric boundary near the Simeulue Island [*Singh*, 2005]. The lithospheric boundary starts near Simeulue Island and continues up to east of Nicobar Islands, where

the Sumatran fault intersects the WAF. It may be noted that the WAF is connected to the ABSC and the Sagaing fault in the north, and Sumatran and Mentawai fault systems in the south. The region east of Nicobar, where these structural features intersect, has witnessed a swarm of events ranging in intensity from 2 to 6 magnitude post 26 December 2004 event (Figure 1). The off Nicobar swarm with more than 150 events with 5 or greater magnitude occurred during 27 to 30 January 2005, is the most energetic swarm ever observed globally. This swarm activity is suggested to be a part of the overall interplate motion partitioning [*Lay et al.*, 2005]. The after shock pattern of the 2004 event and the March 2005 events are distinctly different, and appear to be controlled by the lithospheric scale boundaries. It was also suggested that the subduction of a fossil ridge possibly added some kind of heterogeneity between the ruptures [*Gahalaut et al.*, 2006]. In the south, off Sumatra, the subduction of Investigator fracture zone has resulted in the transtensional necking of the forearc region [*Sieh and Natawidjaja*, 2000].

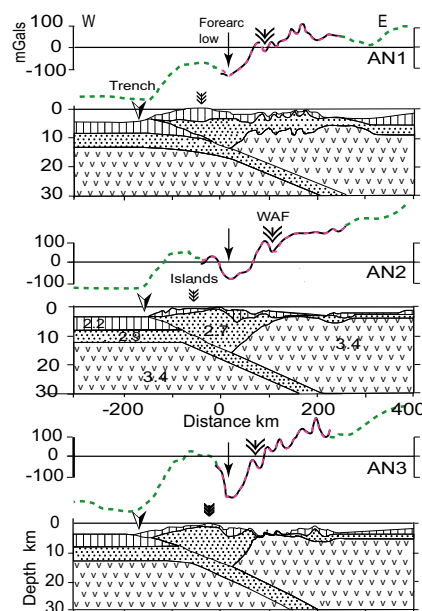


Figure 4. Crustal models based on forward gravity modelling. Slab-residual gravity anomalies are used for modelling. Dashed line represent computed anomaly.

[13] The crustal structure derived from the gravity modelling suggests that the WAF is deep seated and can act as a lithospheric scale boundary. The reflection signature over the fault plane along the WAF (Figure 3), vouch the ongoing active motion. Recovery of Andesites from the fault planes east of the WAF is indicative of ascending melts. Andesites are the products of re-melted subducted slabs usually recovered in the backarc settings. The WAF has probably provided the pathways for the ascending melts. This evidence also suggests that the WAF is deep seated and may act as lithosphere scale boundary. The distinctly diverse rupture characteristics of 2004 and 2005 events can then be explained by the existence of a combination of complex tectonic structures and their response to the large magnitude subduction zone

earthquakes. It may be noted that besides the widely accepted major factor such as the accumulation of elastic strain due to the subducting plate as the major principal cause of the megathrust events, the structural and tectonic fabric greatly affects the favoured location and the rupture pattern. The WAF, ABSC, Sumatran and Sagaing faults are some of the important interconnected structural elements in the Andaman Sea region that played critical role. The unusually long unilateral rupture zone of 2004 event, the Nicobar swarm, the bilateral rupture of the 2005 event are the manifestation of the influence of these tectonic elements.

[14] Based on the GPS measurements of coseismic displacements in the Andaman sector and convergence direction north of Andaman Islands [Stein and Okal, 2005], Gahalaut et al. [2006] suggested that the probability of occurrence of a great or large earthquake between the north Andaman and Indo-Burmese arc between 14° and 21°N is the least. Sunda strait marks the transition zone between the orthogonal subduction off Java to oblique subduction off Sumatra. The obliquity in the subduction is evidenced by chaotic seismic reflections in the accretionary complex and this is attributed to the strain partitioning due to oblique subduction in the Sumatra sector [Kopp et al., 2001]. The obliquity gradually increases towards north and is more prominent in the Andaman sector and further north in the Indo-Burmese plate boundary it becomes purely strike slip [Rao and Kumar, 1999; Nielsen et al., 2004]. Increase in the age of the subducting lithosphere from 60 m. yr. to 90 m. yr. between Sumatra and Andaman sectors may also influence the mechanical coupling on the thrust plane [Lay et al., 2005]. Subduction of younger lithosphere tend to result in inter-plate faults with shallow dips and broad contact areas and generate great earthquakes, whereas in locations where older crust is subducted and backarc spreading is initiated, great earthquakes are rare [Ruff and Kanmori, 1983; Scholz and Campos, 1995]. The increased component of oblique subduction, active back arc spreading [Kamesh Raju et al., 2004], active strike slip motion along the WAF as evidenced by the fault plane solutions in the Andaman sector are the probable factors that explain the absence of large magnitude earthquakes in the Andaman sector north of 10°N. Further detailed marine geophysical investigations are required to understand the interaction of the WAF and the Sumatran fault.

6. Conclusions

[15] The results support the idea of Singh [2005] that the WAF forms a lithospheric scale boundary and acts as a barrier modulating the occurrence of large earthquakes and their rupture process in the Andaman Sea.

[16] The active strike-slip motion along the WAF, the presence of ongoing backarc spreading activity coupled with increased obliquity of subduction in the Andaman sector reduce the probability of occurrence of major or great earthquakes north of 10°N.

[17] **Acknowledgments.** We thank Dr. S.R. Shetye, Director, N. I. O., Goa, for encouragement and support. We thank Prof. I.V.Radhakrishna Murthy for the valuable suggestions. The study was carried out under CSIR Network program. D.O.D., New Delhi is thanked

for ship time of ORV Sagar Kanya for multibeam survey. This is N.I.O. contribution no. XXXX

References

- Ammon, C.J., et al., Rupture process of the 2004 Sumatra-Andaman earthquake, *Science*, 308, 1133-1139, 2005.
- Curry, J.R., Tectonics and history of the Andaman Sea region, *J. Asian Earth Sci.*, 25, 187-232, 2005.
- Curry, J.R., D.G. Moore, L. A. Lawver, F. J. Emmel, R. W. Raitt, M. Henry, and R. Kieckhefer, Tectonics of the Andaman Sea and Burma, *Am. Assoc. Pet. Geol. Memoir*, 29, 189-198, 1979.
- Dasgupta, S., M. Mukhopadhyay, A. Bhattacharya, and T. K. Jana, The geometry of the Burmese-Andaman subducting lithosphere, *J. Seismol.*, 7, 155-174, 2003.
- Diament, M., H. Harjono, K. Karta, C. Deplus, D. Dahrin, M.T. Zen, Jr., M.Gerard, O. Lassal, A. Martin, J. Malod, Mentawai fault zone off Sumatra: A new key to the geodynamics of western Indonesia, *Geology*, 20, 259-262, 1992.
- Furuse, N., and Y. Kono, Slab residual gravity anomaly: gravity reduction due to subducting plates beneath the Japanese Islands, *J. Geodynamics*, 36, 497-514, 2003.
- Gahalaut, V. K., B. Nagarajan, J. K. Catherine, and S. Kumar, Constraints on 2004 Sumatra-Andaman earthquake rupture from GPS measurements in Andaman-Nicobar Islands, *Earth Planet. Sci. Lett.*, 242, 365-374, 2006.
- Kamesh Raju, K. A., T. Ramprasad, P. S. Rao, B. R. Rao, and J. Varghese, New insights into the tectonic evolution of the Andaman basin, northeast Indian Ocean, *Earth Planet. Sci. Lett.*, 221, 145-162, 2004.
- Kopp, H., E. R. Flueh, D. Klaeschen, J. Bialas, and C. Reichert, Crustal structure of the central Sunda margin at the onset of oblique subduction, *Geophys. J. Int.*, 147, 449-474, 2001.
- Lay, T., et al., The great Sumatra-Andaman earthquake of 26 December 2004, *Science*, 308, 1127-1132, 2005.
- Mukhopadhyay, M., Gravity anomalies and deep structure of Andaman arc, *Mar. Geophys. Res.*, 9, 197-210, 1988.
- Neetu, S., I. Suresh, R. Shankar, D. Shankar, S. S. C. Sheno, S. R. Shetye, D. Sundar, and B. Nagarajan, Comment on "The Great Sumatra-Andaman earthquake of 26 December 2004", *Science* 310, 1431a, 2005.
- Nielsen, C., N. Chamot-Rooke, C. Rangin, the ANDAMAN Cruise Team, From partial to full strain partitioning along the Indo-Burmese hyper-oblique subduction, *Mar. Geol.*, 209, 303-327, 2004.
- Rao, N. P., and M. R. Kumar, Evidences for cessation of Indian plate subduction in the Burmese arc region, *Geophys. Res. Lett.*, 26, 3149-3152, 1999.
- Rudolfo, K.S., Bathymetry and marine geology of the Andaman basin and tectonic implications for SE Asia, *Am. Assoc. Pet. Geol. Bull.*, 52, 2422-2437, 1969.
- Ruff, L., and H. Kanamori, Seismic coupling and uncoupling at subduction zones, *Tectonophysics*, 99, 99-117, 1983.
- Scholz, R., and J. Campos, On the mechanism of seismic decoupling and back arc spreading at subduction zones, *J. Geophys. Res.*, 100, 22103-22116, 1995.
- Scotese, C. R., L. M. Gahagan, and R. L. Larson, Plate tectonic reconstruction of the Cretaceous and Cenozoic ocean basins, *Tectonophysics*, 155, 27-48, 1988.
- Sieh, K., and D. Natawidjaja, Neotectonics of the Sumatra fault, Indonesia, *J. Geophys. Res.*, 105[B12], 28295-28326, 2000.
- Singh, S. C., Sumatra earthquake research indicates why rupture propagated northward, *EOS*, 86, 497, 502, 2005.
- Stein, S., and E. A. Okal, Speed and size of the Sumatra earthquake, *Nature*, 434, 581-582, 2005.

Dileep Amarnath, K. A. Kamesh Raju, M. L. Mohan Kumar, National Institute of Oceanography, Dona-Paula, Goa – 403 004, India (kamesh@nio.org)

G. P. S. Murty, National Institute of Oceanography, Regional Centre, 176 Lawsons Bay Colony, Visakhapatnam – 530 017, India (gpsmurty@nio.org)

Revised submitted on 04Dec07

Submitted on 11Nov06 to **Geophys. Res. Lett**

Manuscript #: 2006GL028730