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Structure and Tectonics of the Andaman Subduction Zone from Modeling of Seismological and Gravity Data

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1. Introduction

The Andaman arc is the site of the giant mega-thrust earthquake of 2004 (Mw 9.3), one of the largest earthquakes that ever occurred globally (Lay et al., 2005). The earthquake originated at Bandah Aceh in the south, off the coast of northern Sumatra and ruptured a zone of about 1200 km cutting through the Andaman-Nicobar Islands. The focal mechanism given by the Harvard University indicated a thrust fault mechanism with a NW-SE trending plane. It is generally believed that this earthquake was caused by a sudden slip of the mega-thrust lock-up zone on the interface between the subducting Indo-Australian plate beneath the Burma plate (Sieh, 2005). Detailed marine seismic mapping across the subduction zone in the Sumatra region is, however, suggestive of a possible brittle failure at mantle depths (Singh et al., 2008).

The Indian plate borders the Burmese plate along the Burma and Andaman arcs to the east. While the Indian plate obliquely subducts in the Andaman arc (Fitch, 1972; LeDain, 1984; Curray, 1979), it is believed to have a nearly strike-slip environment in the Burmese arc (LeDain, 1984; Kumar and Rao, 1995; Kumar et al., 1996; Vigny et al., 2003) with a possible cessation of subduction in the recent times (Rao and Kumar, 1999; Rao and Kalpna, 2005). The main tectonic features marking the India-Burma plate boundary are the Indo-Burman ranges in the north and the Andaman-Nicobar ridge to the south. To the east of the ridge lies the Andaman sea which is an active back-arc extensional basin (Curray, 2005) that was initiated about 4 million years ago (Raju et al., 2004), and exhibits transform faulting evidenced by strike-slip and normal fault earthquakes. The Burmese plate adjoins the Sunda plate to the east, along the NS trending Sagaing fault which is known to have a right lateral strike-slip motion. The West Andaman Fault and the Sumatran fault system are the major tectonic features towards southern Andaman, forming the continuity of the Sagaing fault across the Andaman-Nicobar ridge (Figure 1).

On 10 August 2009, at 19:55:39 UTC an earthquake of magnitude 7.5 occurred to the north of the Andaman-Nicobar Islands off the coast of Diglipur Island at latitude 14.013° N and longitude 92.923° E (figure 1). The earthquake was felt not only in the Andaman and Nicobar Islands but also in several cities along the east coast of the Indian peninsula. This earthquake is considered significant due to its large size for a normal fault event in this

region, but more importantly since its location marks the northern limit of the very long (1200 km) rupture zone of the great Sumatra-Andaman earthquake of 26 December 2004 (Mw 9.3) (Ammon et al., 2005; Lay et al., 2005). In the present study, seismic waveform data of the 10 August 2009 earthquake of Mw 7.5 and its aftershocks recorded by a network of five broadband stations in the Andaman and Nicobar Islands, are modeled to obtain moment tensor solutions with accurate focal depths. A joint inversion adopting a Monte-Carlo approach additionally yields a P wave velocity model of the crust-mantle structure along the arc that best fits all the earthquake waveforms. Further, modeling of teleseismic receiver functions and Bouguer gravity anomalies in this region provides, in conjunction with the new velocity model, fresh constraints on the seismicity, crustal structure and tectonics of the northern Andaman subduction zone.

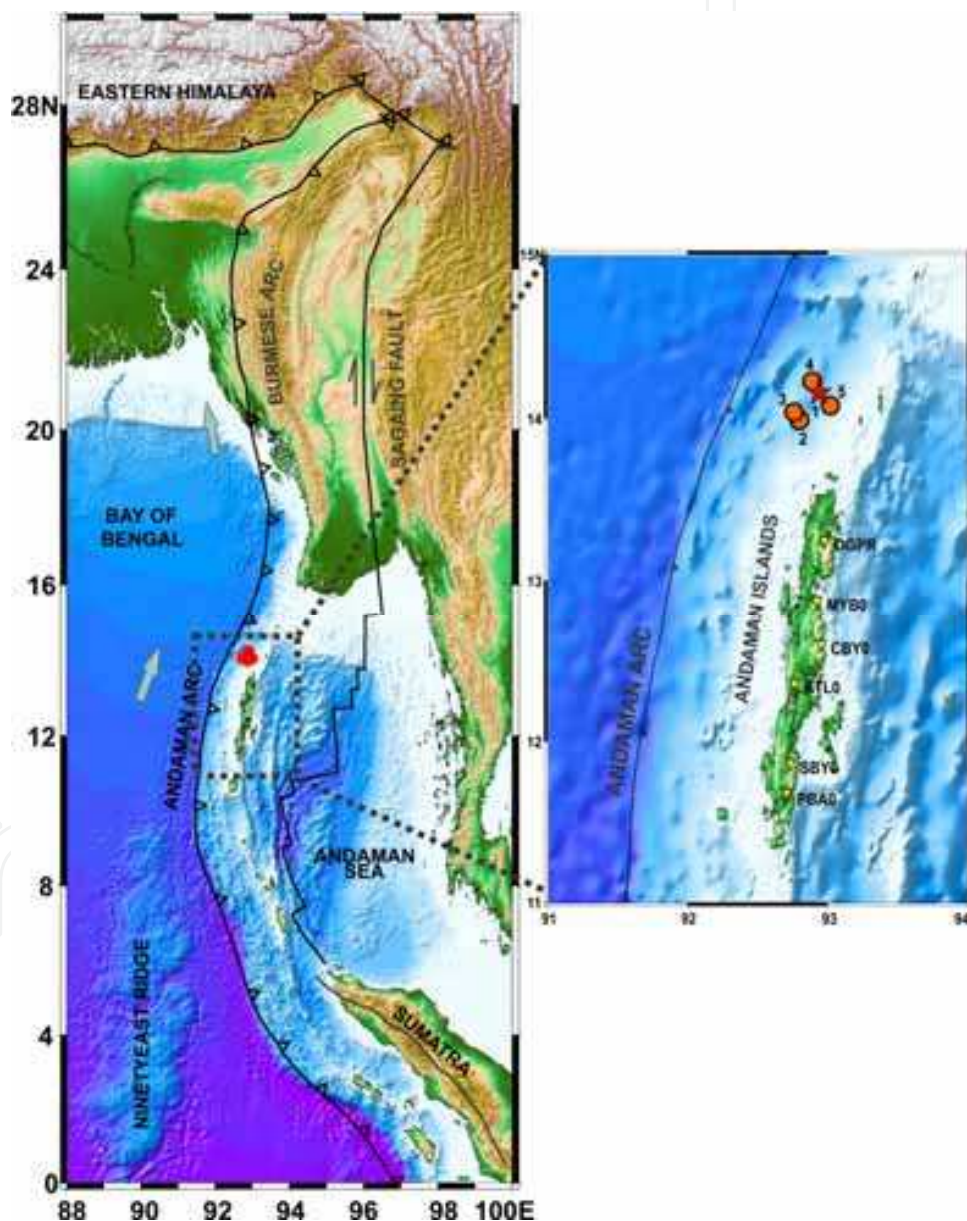


Fig. 1. Tectonic map of the Burma-Andaman arc region indicating locations of the 10 August 2009 earthquake of Mw 7.5 and its aftershocks analyzed in this study. Also indicated in the inset is the ISLANDS seismic network deployed in the Andaman-Nicobar Islands

2. Data and methodology

A seismic network of broadband stations is currently being operated in the Andaman and Nicobar Islands (Figure 1, inset) by the National Geophysical Research Institute, Hyderabad, under a research project funded by the Ministry of Earth Sciences of the Government of India. This project entitled (I)nvestigation of (S)eismicity and (L)ithospheric Structure beneath the (AND)aman and Nicobar Islands (S)ubduction zone (ISLANDS), is complimented by 3 permanent stations of the India Meteorology Department, New Delhi. The seismometers are of the Reftek or CMG-3T make while the data loggers are of the Reftek make equipped with GPS for accurate time keeping. The sampling rate is set at 100 per second. Broadly the stations have a NS disposition from Port Blair in the south to Diglipur in the north.

The 10 August 2009 Andaman earthquake of Mw 7.5 and 4 of its aftershocks of magnitude 4.6 to 5.8 (Table 1) were recorded by the broadband stations. Whole waveforms are modeled using the moment tensor inversion method of Kikuchi and Kanamori (1991) where the Green's functions are obtained using a combination of the Reflection-Transmission coefficient matrix approach (Takeo, 1987) and the discrete wave-number summation method (Bouchon, 1981). The earthquake waveforms are low-pass filtered, resampled, instrument corrected and integrated to obtain the displacement seismograms which are compared with the synthetic seismograms. The normalized cross-correlation function is used as the criterion for assessing the quality of waveform matching. The Andaman-Nicobar region being a subduction zone, it is hard to assume a simple velocity model. However, since the stations are mostly aligned parallel to the arc, a 1-D model approximation is considered to be reasonable, especially while modeling in the low frequency range (< 0.1 Hz). Velocity models of Curray (2005) and Kayal (2004) close to the epicentral region were considered as the starting point and a random search was performed around these model parameters using a Monte-Carlo approach where over 1000 velocity models comprising 5 layers were tested to simultaneously fit waveforms of all the 5 events under consideration. The best model obtained was selected based on the criterion of minimum misfit error between observed and synthetic seismograms of all the events. Table 2 indicates the search limits and the final velocity model obtained.

A complimentary approach to ascertain the discontinuities in the layered velocity model is the Receiver function approach using an independent data set comprising the teleseismic earthquake waveforms in the epicentral distance range of $30\text{--}100^\circ$. The method we follow to obtain the P-receiver functions involves rotation of the Z, N and E components into a ray coordinate system to essentially decompose the wave field into its P, SV and SH components (Vinnik, 1977). The converted phases are then isolated from the P-coda by deconvolving the P from the SV component by simple spectral division in the frequency domain using a water level stabilization. In addition, low pass filtering with a Gauss function limits the frequency band to enhance the scattered wavefield, especially from deeper interfaces. In order to make receiver functions at different slowness values (corresponding to different epicentral distances) comparable, and to distinguish multiples from converted phases, a moveout correction is applied separately for the converted phases and multiples. Additional stations further south in the Nicobar region have also been used in comparison to the waveform modeling study.

To further constrain the velocity model obtained from seismic waveform modelling and Receiver function approach, satellite gravity data over the Andaman region was analysed. The satellite gravity data are often used to study lithospheric structure underneath the oceans, due to their better accuracy in the deep ocean (Sandwell and Smith, 1997). Free-air gravity anomalies are primarily dominated by bathymetry of the subduction zones;

nevertheless they also reveal the fore arc sediment infill and deep lithospheric structure of the converging plate (Well et al., 2003; Gravemeyer and Tiwari, 2006). To remove the effect of bathymetry and sediments, 3D effect of bathymetry (GEBCO) and sediment thickness (NOAA-NGDC) was computed from the free-air gravity anomalies (Sandwell and Smith, 1997). The gravity anomalies corrected for sediments (SCGA) are utilised to determine the north-south gradient along the Andaman subduction zone to obtain an insight into the along-strike segmentation. To reconfirm the nature of gradients, we also computed the gradient of Bouguer gravity anomalies by applying only bathymetry correction.

S.No	Y/M/D	Hr: Min: S	Lat	Lon	Depth	Mw	Strike	Dip	Rake
1	2009/ 8/ 10	19:55:35	14.10	92.91	18	7.5	39	48	-110
2	2009/ 8/ 11	6:10:02	13.99	92.88	25	4.6	338	53	-163
3	2009/ 8/ 13	9:21:35	14.05	92.74	26	5.8	345	77	-169
4	2009/ 8/ 13	20:49:25.7	14.23	92.89	18	4.7	187	54	-91
5	2009/ 8/ 14	19:39:49.9	14.04	92.99	11	5.3	196	49	-71

Table 1. List of the earthquakes modeled in the present study, comprising location parameters and fault plane solutions of the 10 August 2009 Mw 7.5 Andaman earthquake and its aftershocks

3. Results

The significant results in this study comprise focal mechanism solutions from moment tensor inversion, accurate focal depths from waveform matching, and velocity structure from joint waveform inversion, Receiver function approach and gravity anomalies over the seismic zone under investigation. These results are very much comparable and in conjunction provide us new constraints on the structure and tectonic controls on seismogenesis in northern Andaman arc region.

3.1 Moment tensor solutions

The best fitting moment tensor solutions for the main shock and the aftershocks assuming a double couple mechanism, are obtained based on the criterion of minimum mismatch error between observed and synthetic displacement seismograms derived using the best model (figures 2 a-b). The obtained solutions are listed in Table 1 and plotted in a map view (figure 3). A normal fault mechanism with NNE to NS oriented fault planes is obtained for the 10 August 2009 mainshock and two of its aftershocks respectively. The focal mechanism of the main shock event is comparable to that reported by the Harvard CMT or the USGS. With the available data, it is not possible to constrain the east or west dipping fault plane. However, considering the geometry of the accretionary wedge in the forearc region of the overriding plate, the east dipping fault plane may be more acceptable. For the other two aftershock events, a strike slip mechanism is obtained with the two fault planes oriented NE and NW respectively. Strike slip mechanisms with this kind of fault plane orientation were reported earlier for the Andaman arc region close to the arc or in the outer rise zone to the west, but not in this region north of the Andaman Islands. The only other region with exactly the same kind of mechanism is the Sumatran Fault system further south and much eastward from the trench. The other types of strike slip mechanisms are those with a more NS trending fault planes associated with the transform faults in the Andaman sea and the Sagaing fault zone further east, where an inter-plate right lateral strike slip motion is understood to be occurring

between the Burma and the Sunda plates. In order to interpret these earthquake mechanisms in a relatively aseismic zone, we attempt to obtain better constraints on their focal depths together with a reliable 1-D velocity model through joint waveform modeling.

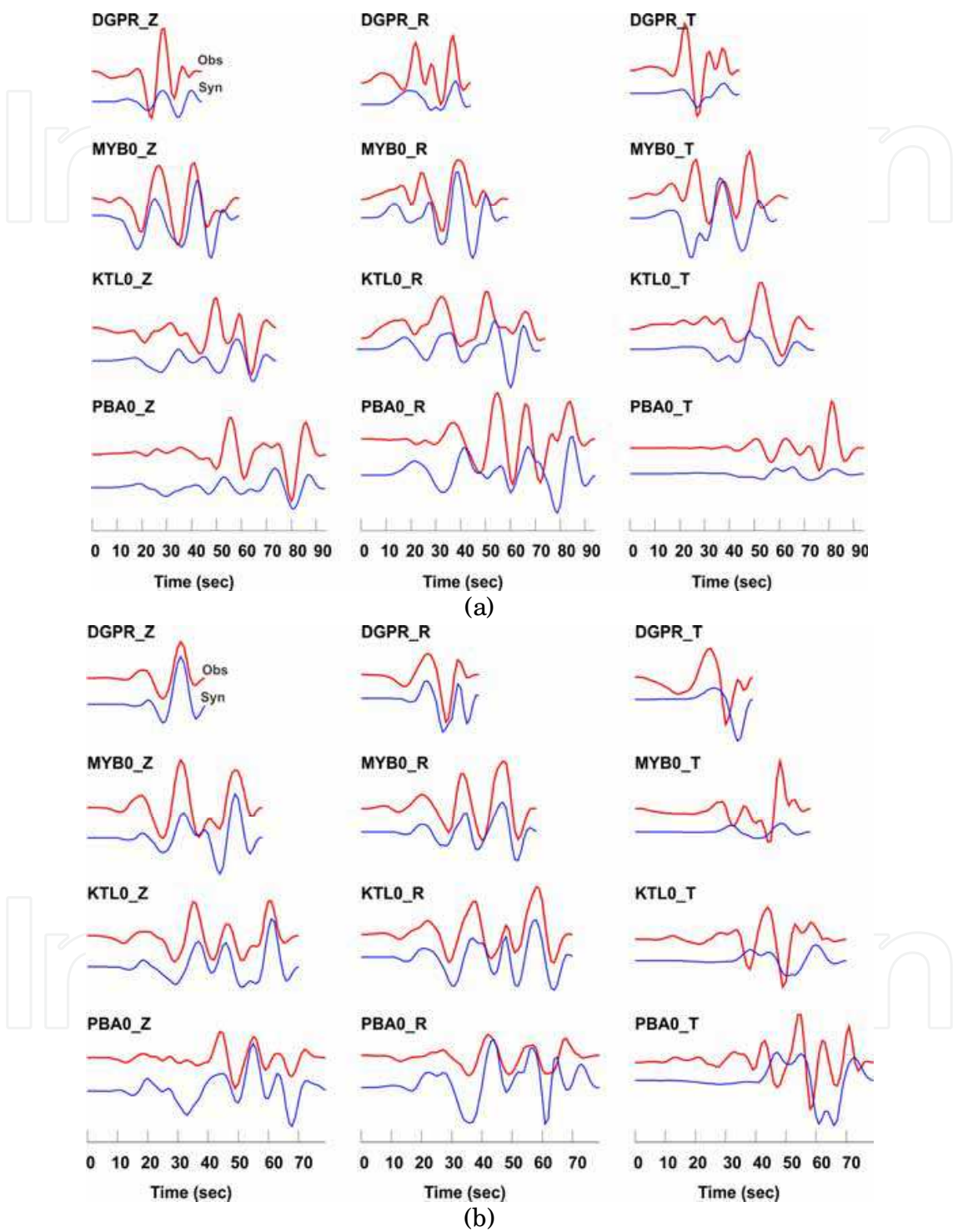


Fig. 2. Waveform matching between the observed and synthetic seismograms of the a) 10 August 2009 Mw 7.5 Andaman earthquake and b) 13 August 2009 Mw 5.8 aftershock. Red curves are the observed displacement seismograms while the blue ones are the synthetic seismograms of the three components

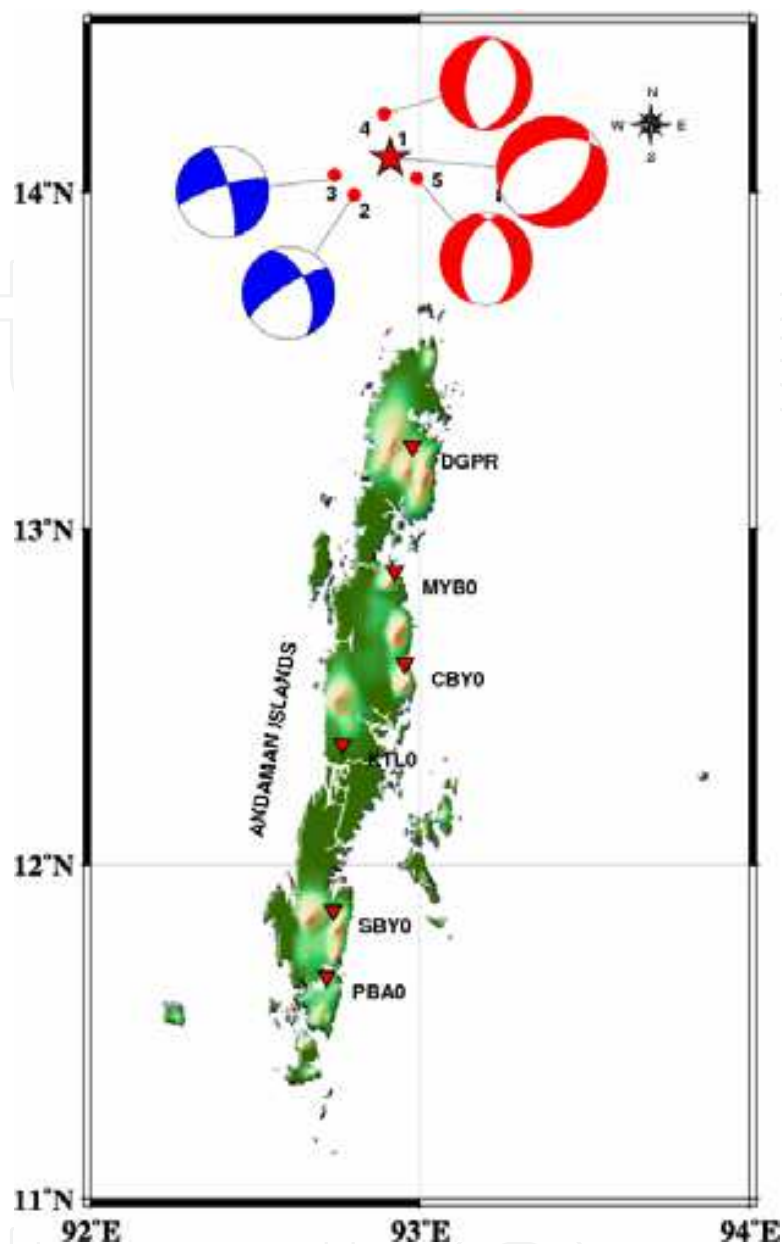


Fig. 3. Plot of moment tensor or focal mechanism solutions of the 10 August 2009 Andaman earthquake of Mw 7.5 and its aftershocks computed in this study. The normal fault solutions including the main shock are shown in red while the strike slip fault solutions are shown in blue. The main shock (star) and aftershocks (circles) are all located north of the Andaman Islands. The seismic broadband stations of the ISLANDS network are shown as inverted triangles

3.2 P wave velocity structure

The joint waveform inversion of 5 events for simultaneous estimation of fault parameters and velocity structure has yielded a 5-layered velocity model along the Andaman and Nicobar Islands in addition to accurate focal mechanism solutions and focal depths. The best model obtained (table 2, figure 4) depicts a Moho at 30 km with a high V_p/V_s ratio of 1.81 indicative of an oceanic crust as suggested by Curray (2005). Waveforms of the farthest station Port Blair (PBA0) were given additional weightage to place better constraints on the

Moho depth and upper mantle velocity in view of its nearly regional distance. The high value of the crustal thickness is interpreted as a double crustal column comprising the overriding Burmese plate having a thickness of about 21 km including a 5 km thick sedimentary layer in the accretionary wedge, and the Indian crust with an apparent thickness of about 9 km. Such a configuration appears quite reasonable considering the location of the Islands at a lateral distance of about 85 km from the trench towards the forearc. While there could be parametric variations in the distance from trench, crustal thickness of each plate and the dip angle, the suggested model seems to provide the least misfit error in the seismic waveform modeling, and is also independently confirmed by Receiver function and gravity modeling as discussed in sections 3.3 and 3.6.

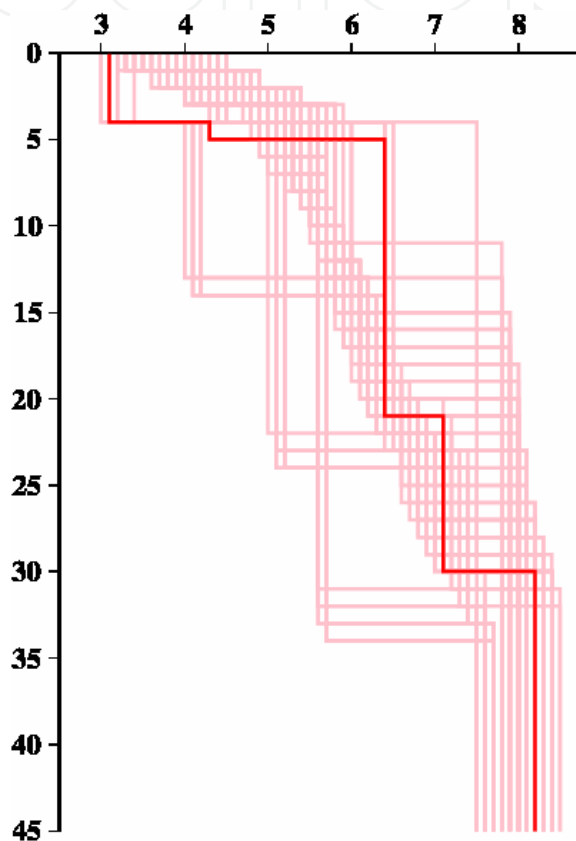


Fig. 4. The best fitting P wave velocity model for the Andaman region obtained by joint inversion of waveforms of 5 earthquakes simultaneously while randomly varying the structural model parameters in a Monte-Carlo approach. The search limits and the model parameters obtained are listed in Table 2

<i>Layers</i>	<i>Vmin- Vmax</i>	<i>Hmin- Hmax</i>	<i>Velocity</i>	<i>Depth to top Layer</i>
1	3-4.5	0-0	3.1	0
2	4.0-6.0	1-5	4.3	4
3	5.0-6.5	5-15	6.4	5
4	5.5-7.5	15-25	7.1	21
5	7.5-8.5	25-35	8.2	30

Table 2. The search limits considered for random selection of 1000 models using a Monte-Carlo approach and the best estimate of the P wave velocity model for the Andaman region based on joint waveform inversion of the 5 earthquakes simultaneously

3.3 Crustal discontinuities from Receiver function analysis

A total of 802 receiver functions are obtained using 372 distant events recorded at 5 stations in the Andaman-Nicobar region since 2009 (Figure 5). These are the first results for this region from Receiver function analysis. A fairly good back-azimuthal coverage can be seen for the events used (Figure 6). The moveout correction is made with reference to a slowness value of 6.4 s° , corresponding to an epicentral distance of 67° . The receiver functions binned in narrow slowness intervals and stacked are shown in Figure 7 for stations DGPR, BART, CTBY, PBA and CMBY. The positive conversions prominently seen close to 2-2.5s at stations DGPR, BART and PBA could correspond to the top of the subducting Indian plate. When converted to depth these times transform to depths in the range of 16-20km. These conversions for stations CTBY and CMBY are not so clear. Also, two stations BART and CTBY that are in close proximity reveal contrasting crustal configurations suggesting a complex structure along the Andaman subduction zone. The Moho conversion, although weak, is traceable at the permanent stations like CMBY and DGPR close to 4s, corresponding to a depth of $\sim 30\text{km}$, very similar to that obtained using waveform modeling.

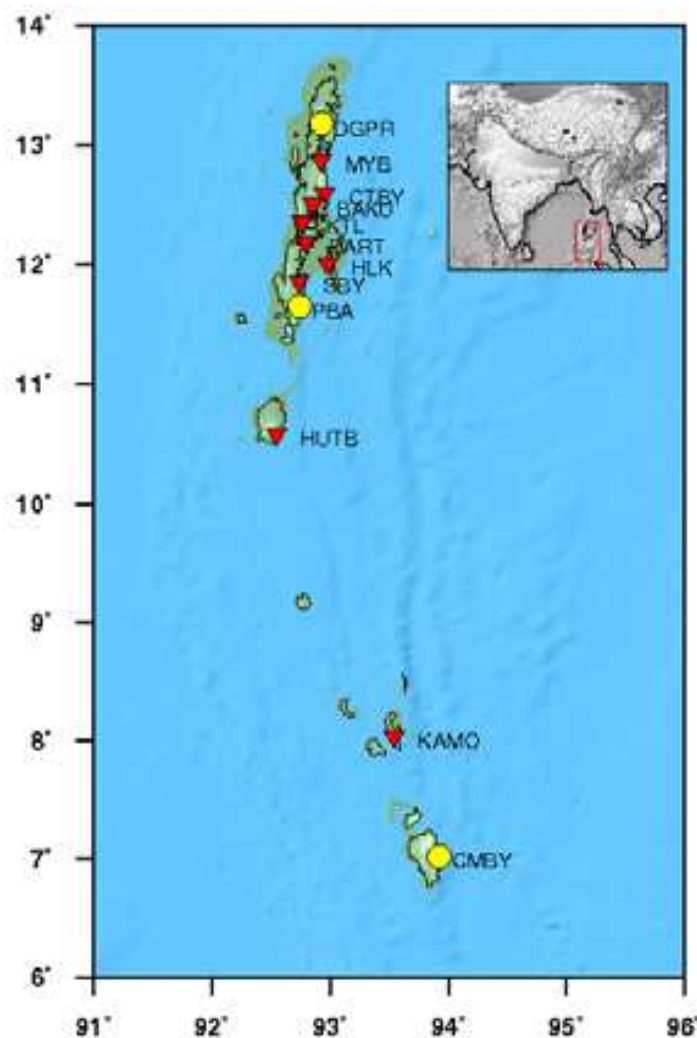


Fig. 5. Location of broadband seismic stations in the Andaman and Nicobar Islands. Yellow circles denote permanent stations operated by the India Meteorological Department. Inset : The Andamnan-Nicobar region is shown as a rectangular box in the Indian subcontinent

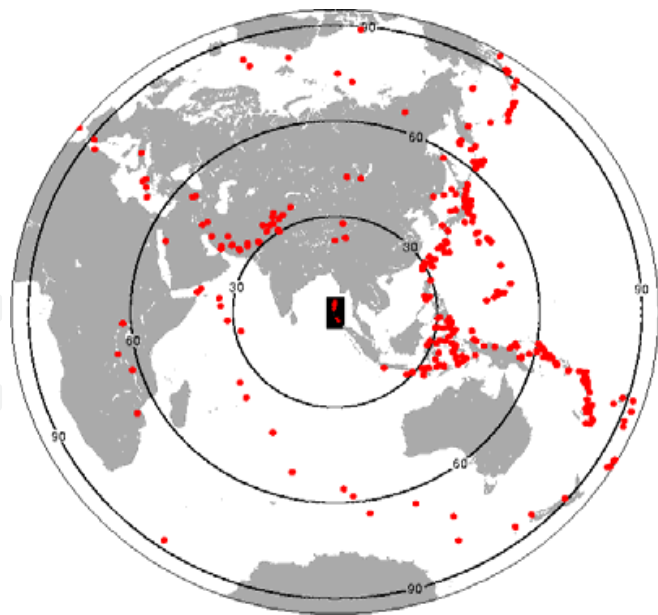


Fig. 6. Teleseismic earthquakes in distance range of 30°–100° used in this study. The study region (Andaman and Nicobar Islands) is indicated by a rectangle

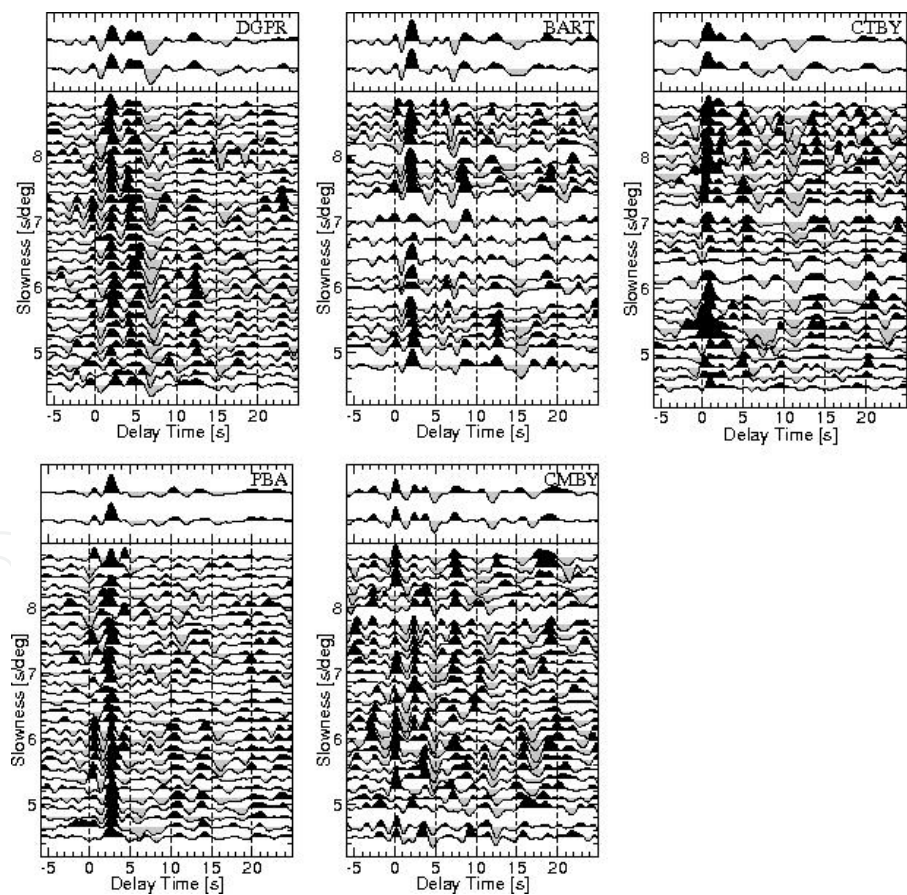


Fig. 7. SV components of P wave receiver functions at stations DGPR, BART, CTBY, PBA and CMBY in the Andaman and Nicobar Islands, stacked in narrow slowness bins. Stations are arranged from north to south. Summation traces moveout corrected for converted (bottom) and multiple (top) phases are shown in the top panel

3.4 Resolution of focal depths

A wide range of focal depths were tested for each event at intervals of 1 km, using the waveform matching criterion. Figures 8 a-d show the normalized misfit error as a function of focal depth for the 10 August 2009 earthquake and 3 of its aftershocks. It can be seen that the focal depth is extremely sensitive to waveform matching since it strongly influences the relative amplitudes of various phases in the seismogram, including the local / regional depth phases. The best estimates of focal depths are obtained on the basis of minimum mismatch error which is generally within 1 or 2 km. It is found that while the main shock and its aftershocks with normal fault mechanism have shallow focal depths within 18 km, the aftershocks with strike-slip mechanism occur at deeper levels of 25 and 26 km respectively. Our centroid depth estimate of 18 km for the mainshock is comparable to the values of 21 km and 22 km reported by the USGS and Harvard respectively. The depth segregation indicates that the normal fault earthquakes are very likely to be confined to the overriding Burmese crust, while the deeper strike slip fault earthquakes need to be accommodated in the lower crust of the subducting Indian plate. In any case, the depth inference would have important implications for understanding earthquake genesis in this seismically quite zone, particularly in the aftermath of the 2004 megathrust earthquake of Mw 9.3.

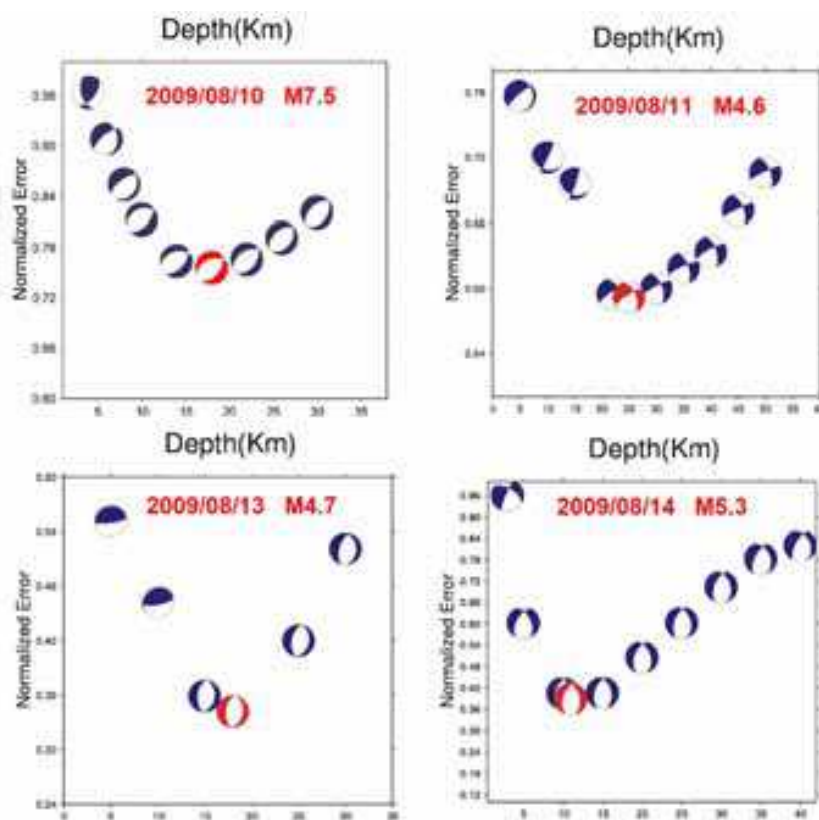


Fig. 8. Normalized waveform mismatch error as a function of focal depth for the 10 August 2009 Mw 7.5 Andaman earthquake and its aftershocks numbered 1, 2, 4 and 5 in Table 1. Note the well resolved focal depth based on the criterion of minimum mismatch error

3.5 Vertical distribution of seismicity

The seismicity distribution of the 10 August 2009 earthquake and its aftershocks in depth shows an interesting vertical distribution confined both latitudinally and longitudinally at

about 14° latitude and 93° longitude (figure 9). Such a pipe-like seismicity trend is quite unusual and was absent prior to the 2009 earthquake, as can be seen from the blank zones in figures 10 a and b which depict earthquake hypocenters from the USGS catalog prior to the 2009 event. In fact this zone has been completely aseismic at least for several decades, and also marks the termination of the 2004 mega-thrust earthquake. Such a trend is not seen for other large earthquakes in this region except for the 2008 Little Andaman earthquake (Mw 6.6) also a normal fault earthquake located to the south, closer to the arc at 11° N. The region between these two earthquakes is demarcated by a high gravity gradient whose implications are discussed in section 3.6.

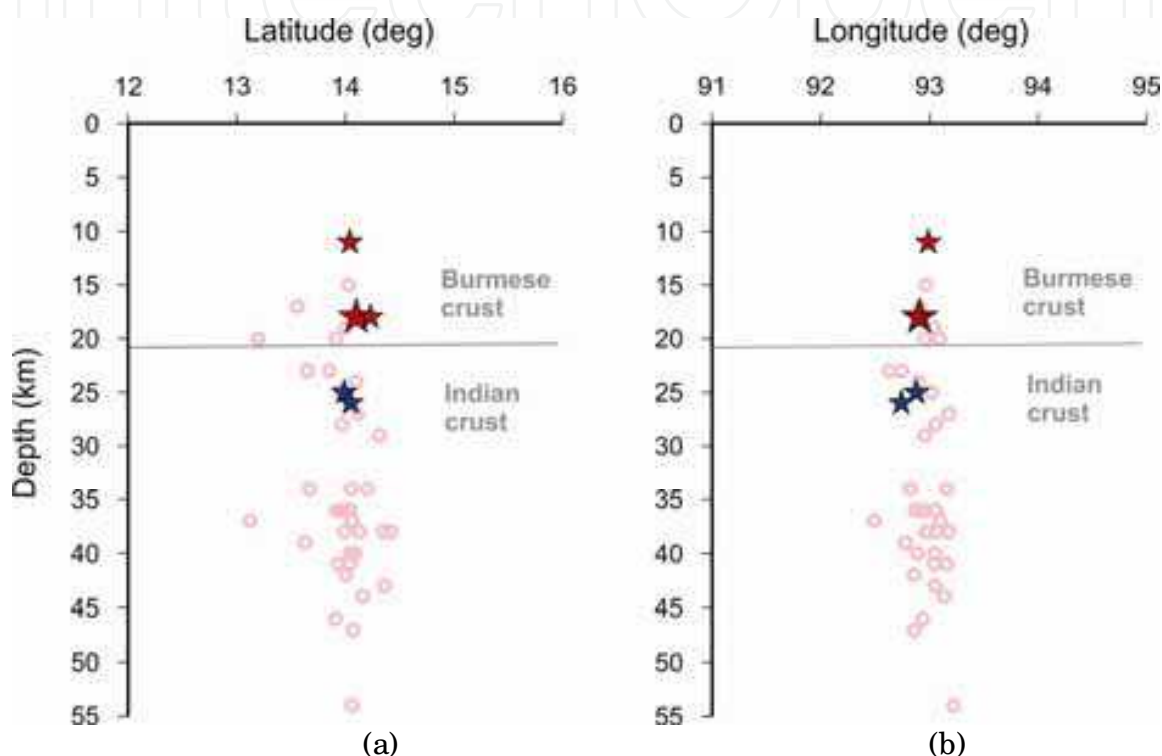


Fig. 9. Hypocentral depth sections of the 10 August 2009 Mw 7.5 Andaman earthquake and its aftershocks along a) East-West and b) North-South profiles across the epicentral region north of Andaman arc, indicating a distinct segregation of events with normal fault mechanism (red stars) and strike slip mechanism (blue stars) above and below the 21 km depth separating the overriding Burmese crust and the underlying Indian crust respectively. Note the peculiar vertical seismicity distribution of aftershocks (source: USGS) at about 14° latitude and 93° longitude

3.6 Modeling of Bouguer gravity anomalies

In the Andaman arc region, the sediments-corrected gravity anomalies (SCGA) are found to be low starting from trench and reach to their minima over the accreted wedge and the forearc basin and again increase towards volcanic arcs (Figure 11). Since gravity anomalies are corrected for sediments and bathymetry, they mainly reflect the geometry of subduction zone and deeper structures. Part of the anomalies might also be originating due to the sediment and bathymetry since the global data that are used for correction have less spatial resolution than the Free air gravity anomalies. However, we filter all the data for 5 minutes wavelength to avoid artifacts due to different resolution of data. The gravity gradients

(Figure 12) also show a similar character, the most striking feature being the reversal from negative to positive values towards north starting from 11° N and culminating in a positive maximum at 14° N coinciding with the epicenter of the 2009 main shock earthquake. The causative of the positive gradient over the fore-arc in the north might be the thinning of the fore arc crust due to stretching of the Sunda plate, eventually leading to normal or strike slip faulting. The figure also suggests that large non thrust earthquakes seem to occur over positive gradients.

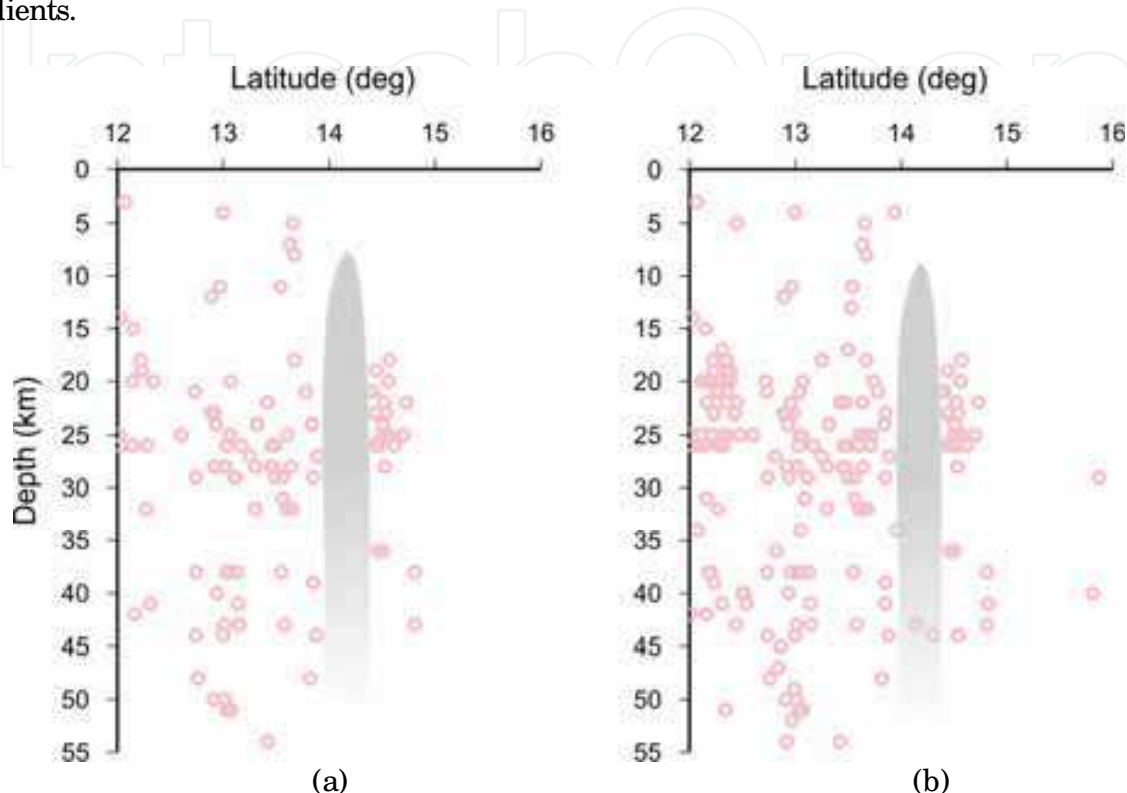


Fig. 10. Hypocentral depth sections in the North-South direction using USGS catalog of earthquake data from a) 2005 to just before the 10 August 2009 Andaman event and b) 1973 to just before the 10 August 2009 Andaman event. Note the clear absence of seismicity in the region below 14° latitude which got activated since the 10 August 2009 Andaman earthquake (figure 6)

It is quite interesting that the highest gravity gradient of 1.5 mgal / km coincides exactly with the location of the 2009 mainshock of Mw 7.5 and its aftershocks vertically distributed beneath. The anomaly has a radius of less than 100 km and adjoins the Andaman basin to the east which is the site of active back arc spreading that was initiated about 4 my ago (Raju et al., 2004). This region is largely aseismic in nature and devoid of evidence for active subduction as suggested by Kumar et al. (1996) based on focal mechanism studies. Richards, et al., (2007) has inferred a near-vertical lithospheric tear in this region between the Burma and Andaman arcs which may be related to this pipe-like seismicity distribution. Further, tomographic images from a recent study by Pesicek et al. (2010) also indicate the lack of a clear subduction in this region which gradually changes to a dipping trend of a subducted slab in the southern Andaman arc and the Sunda arc further south. The positive anomaly is viewed in this perspective to indicate a vertical barrier or a lithospheric tear (also visible in a corresponding depth section numbered 5 in figure 7 of Pesicek et al., 2010) that terminated the rupture of the 2004 megathrust earthquake.

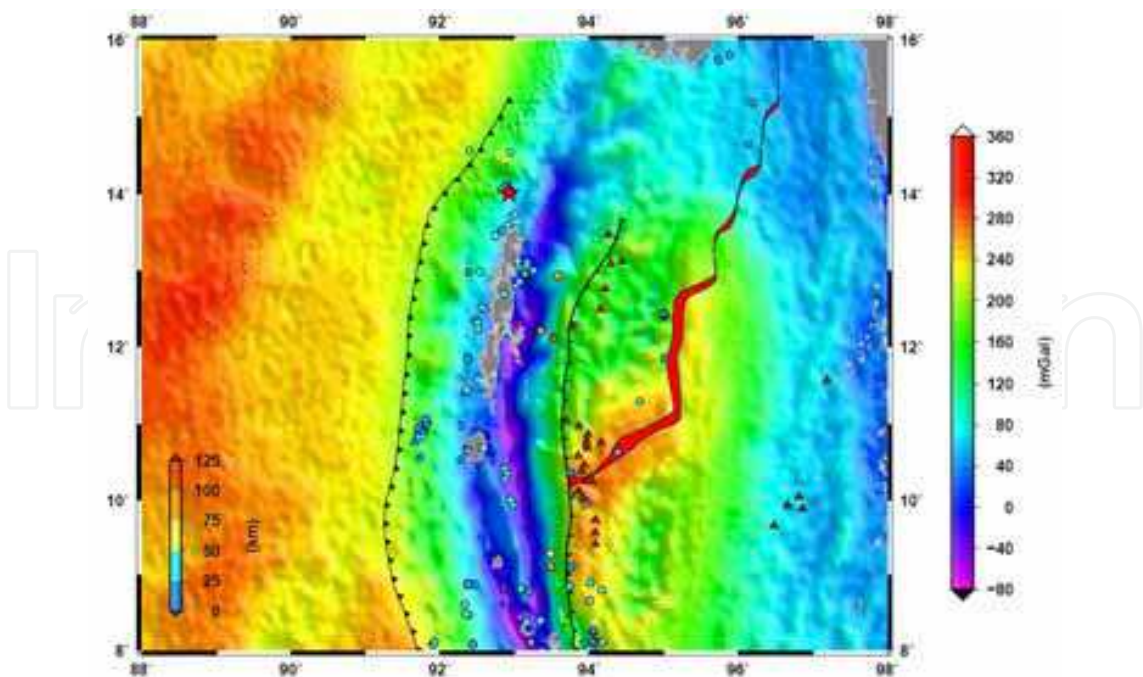


Fig. 11. Satellite derived gravity anomalies (BCGA; Sandwell and Smith, 1997) corrected for bathymetry (GEBCO) and sediment thickness (NOAA-NGDC) over Andaman subduction zone. Locations of earthquakes ($m > 5.5$) are also superimposed in coloured circles (USGS). Red triangles are volcanoes. Star is the epicentre of 2009 earthquake ($M_w 7.5$). Black teetted line is trench axis and west Sumatra fault

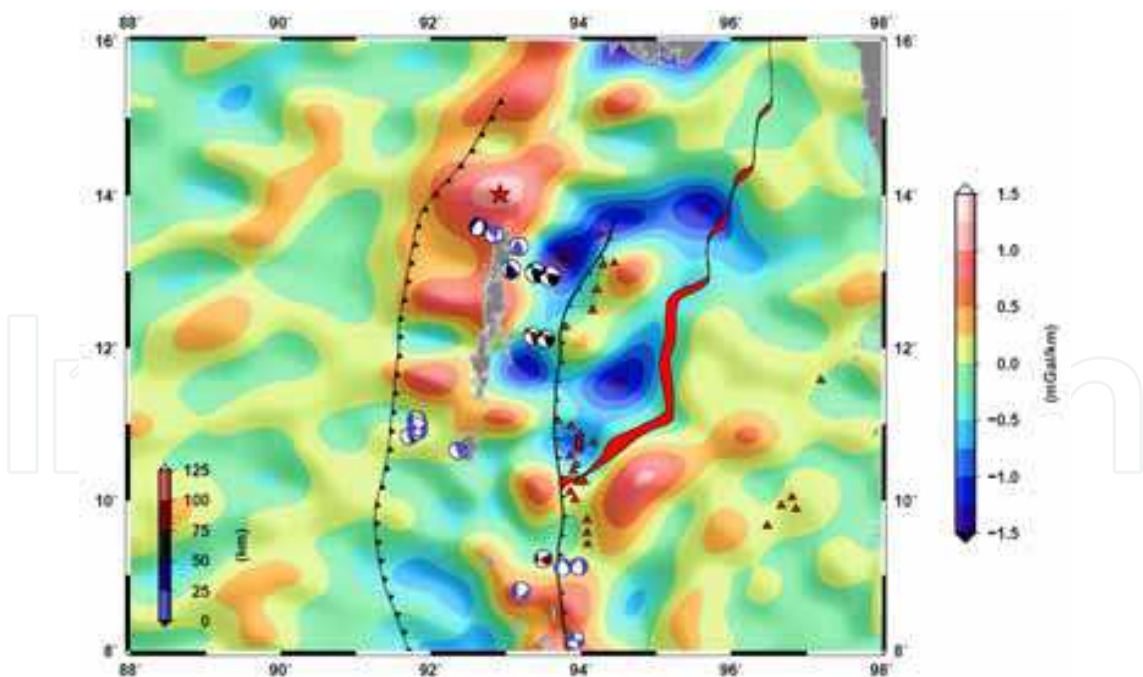


Fig. 12. Gradients of gravity anomalies along axis (N-S) for the Andaman-Nicobar region. Star is the epicenter of 2009 earthquake ($M_w 7.5$), whose epicenter and aftershocks are found to coincide with the location of the maximum horizontal gradient of about 1.5 mgal/km . The positive anomaly has an extension from 11° N to 17° N adjoining the Andaman basin to the east, possibly indicating the absence of a clear lithospheric slab beneath the arc in this region

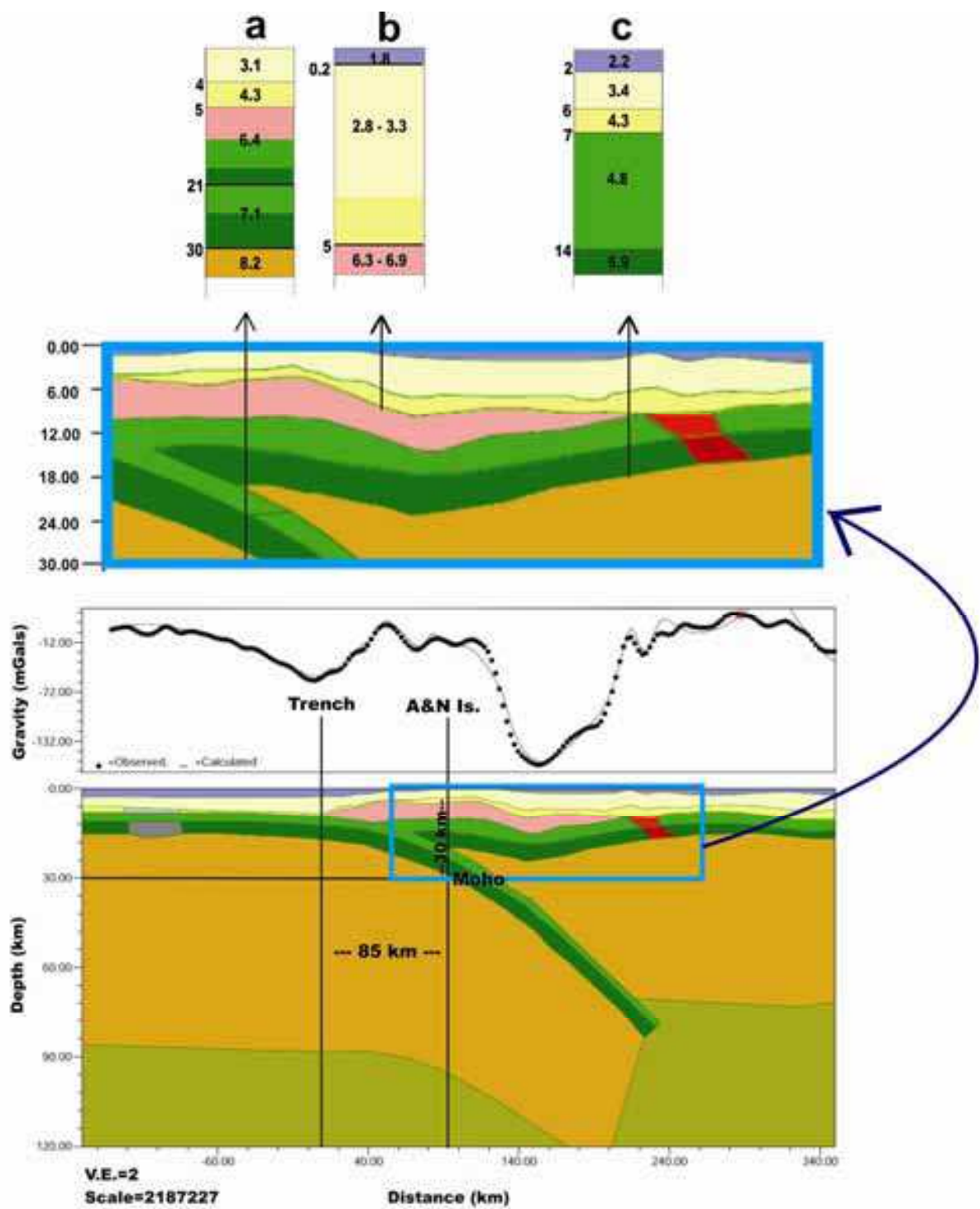


Fig. 13. Modeling of Bouguer gravity anomalies across the Andaman arc near the epicentral region providing a good match between the observed (dark line) and synthetic (dotted line) curves. The obtained model indicates a double crust of 30 km beneath the Andaman Islands including a thin (9 km) Indian crust overlain by a thicker (21 km) Burmese crust including a 5 km thick sedimentary column. The gravity model compares well with other models obtained from (a) seismic waveform modeling in the present study and (b & c) marine seismic sections numbered 1106 and 1109 respectively near the study region (Curry, 2005)

The configuration of the India-Burma plate subduction as inferred from interpretation of gravity anomalies is shown in figure 13. The model shown in the depth section also provides the minimum misfit between the observed and computed gravity anomalies across the subduction zone. The basic configuration proposed corresponds to a coupling of the overriding Burmese crust with that of the subducting Indian crust beneath the Andaman and Nicobar Islands, facilitating an apparently thick oceanic double crust. A good comparison can be seen with the seismic velocity model obtained in this study from waveform modeling and those by Curray (2005) from marine seismic data, plotted at the appropriate locations in figure 13. Teleseismic Receiver function analysis has also provided very similar results in this study.

4. Discussion

The results obtained from seismic waveform modeling, teleseismic receiver function analysis and gravity modeling are consistent, thereby providing a reliable velocity model that can be interpreted in terms of a double-crustal configuration at least beneath the Andaman and Nicobar Islands. This also provides a basis to interpret the 10 August 2009 Andaman earthquake of Mw 7.5 and its aftershocks manifesting as a peculiar vertical distribution. Firstly, it appears that the main shock is an intra-plate normal fault earthquake occurring in the crust of the overriding Burmese plate. The fault planes oriented parallel to the local trend of the Andaman arc, seem to suggest relaxation of the overriding Burmese plate segment in the shallow accretionary wedge zone of the fore-arc basin probably in response to the buckling during the 2004 giant mega-thrust earthquake of Mw 9.3, leading to gravitational sliding of the Burmese crust including the sedimentary column in the eastward dip direction (figure 14). For an Mw 7.5 earthquake, fault dimensions of 80 x 30 km can reasonably be assumed based on empirical relations (Leonard, 2010). A similar dimension was also assumed by Mahesh et al. (2011) based on empirical relations of Wells and Coppersmith (1994). Considering the derived centroid depth of 18 km and a fault plane dip of 48°, a 30 km width of the fault plane can be more or less accommodated in the overriding Burmese crust. However, considering the large magnitude of this event, an extension of the fault into the underlying Indian crust below cannot be ruled out. Catherine et al., (2009) have interpreted this earthquake in terms of reactivation of the strike-slip planes of the Ninetyeast ridge subducting beneath the arc. However, in that case the focal depth would have to be much higher, the fault strike more northward and the fault plane dip angle much steeper. Also, positionally this earthquake appears to be further eastward compared to the probable location of the ridge with respect to the arc. Another possible interpretation of the normal faulting mechanism for the main shock away from the trench could be the upper plate retreat due to divergent absolute plate motions as inferred from magnetic data from the ocean floor of the Indian plate (Whittaker et al., 2007). These results are, however, inferred over a larger geological time frame of several million years, especially towards the southern Andaman and Java-Sumatra region, and a closer examination would be required in order to associate with this specific event north of the Andaman Islands.

The strike slip events with estimated focal depths of 25 and 26 km can hardly be designated as inter-plate events due to (i) the their deep occurrence well within the underlying Indian plate zone, and (ii) because of their nearly vertical fault planes oriented NW and NE respectively, contrasting with the shallow dipping NS trending decollement plane in the India-Burma subduction zone. Earthquakes with a similar mechanism do occur in the Andaman arc region, except that they are associated with the transform faulting in the Andaman sea, the Sumatran fault zone to the east or the NS trending right-lateral strike-slip

faulting along the Sagaing fault zone farther east. Hence, these strike-slip events are distinct from the above mechanisms and are seen to be associated with intra-plate deformation in the subducting Indian plate. An examination of earthquakes west of the arc, in the outer rise zone and the Indian Ocean deformation zone indicates focal mechanism solutions having identical strike-slip mechanism with a left-lateral sense of slip on the NE trending fault plane gradually changing to NS at the ninetyeast ridge and to its southeast (figure 15). This indicates strain accommodation in the Indian crust due to differential motion of the Indian lithospheric plate under the Andaman arc. Previously, a model of wrench fault tectonics comprising extensive left lateral strike-slip motion in the diffuse deformation zone was suggested by Neprechnov (1988) to describe the India-Australia plate kinematics. Rao and Kumar (1996) had proposed a combination of a rigid plate Euler pole rotation model that explained the thrust fault earthquakes in the eastern part of the deformation zone and normal fault mechanism in the western part near the Chagos bank, in conjunction with a non-rigid left-lateral strike-slip faulting all along the deformation zone. It is opined that the strike slip earthquakes obtained in the present study occurred in the Indian crust under the Andaman arc as a part of the wrench fault tectonics of the Indo-Australian subduction, since the Australian plate subducts faster and smoother beneath the Sunda arc as compared to a much slower and stiffer convergence of the Indian plate in the Burma-Andaman arc (Stein and Okal, 1978).

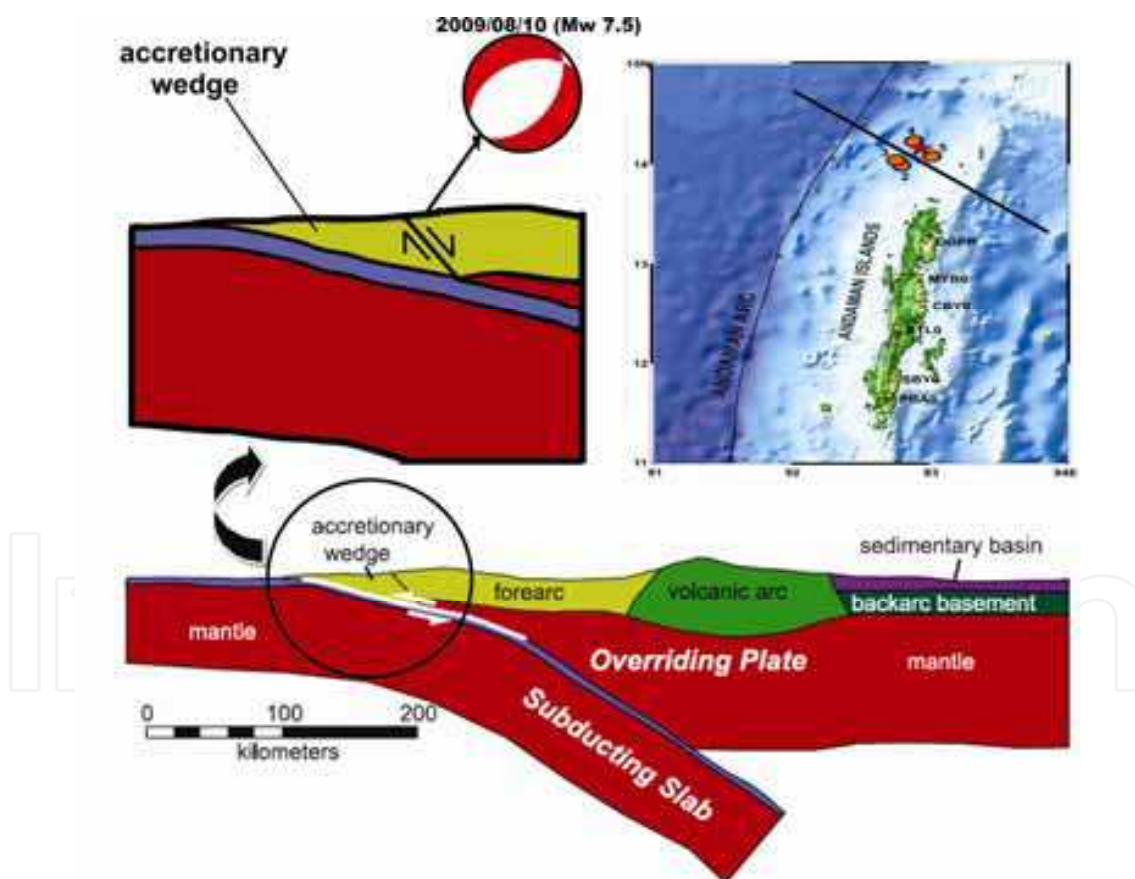


Fig. 14. A cartoon depicting subduction of the Indian plate beneath the Burmese plate along a section cutting across the arc through the epicentral region (modified after Masterlark et al., 2008). Close up of the subduction zone explaining the mechanism of the 2009 Andaman earthquake of Mw 7.5 as a normal fault in the shallow forearc region as a result of intra-plate relaxation of the overriding Burmese plate against the accretionary wedge

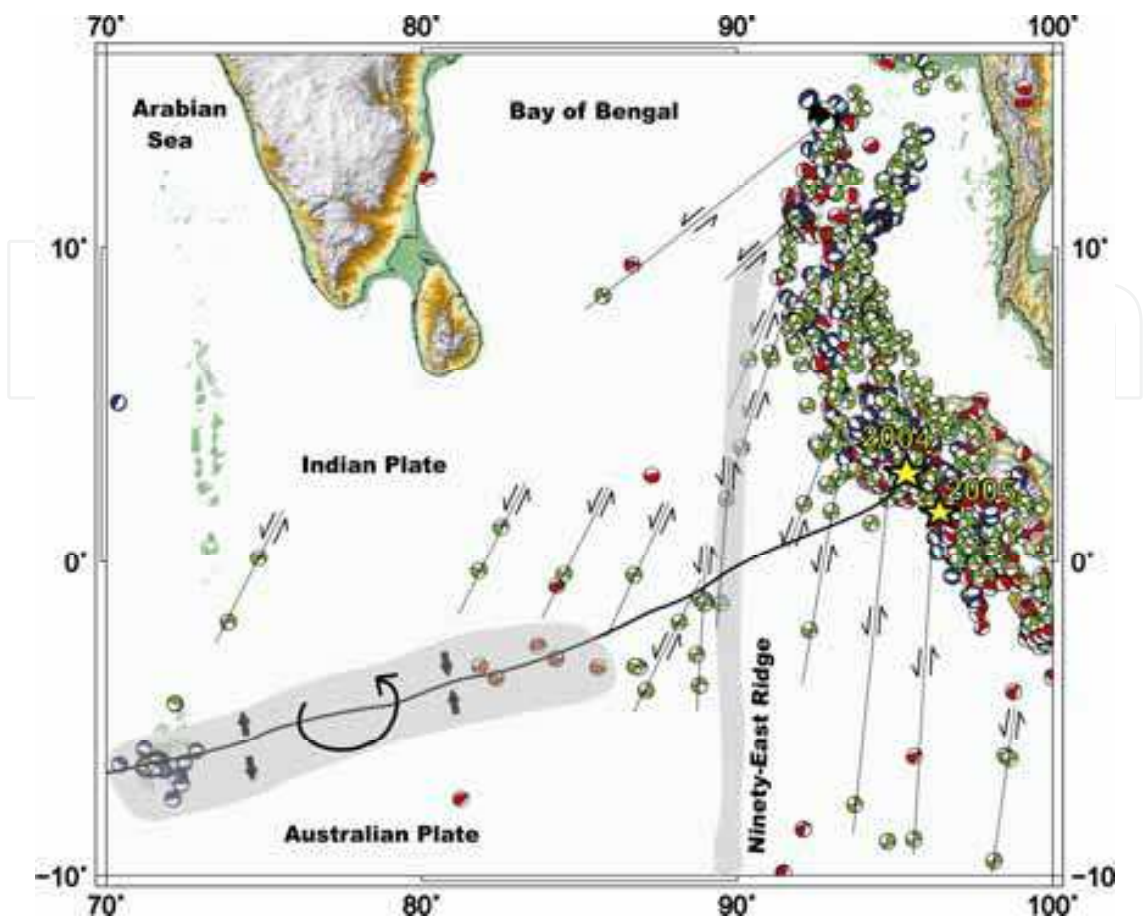


Fig. 15. Focal mechanism solutions of the strike-slip type (green) earthquakes spread over the Indian Ocean deformation zone and the Andaman arc regions depicting a wrench fault tectonic mechanism (Neprechnov, 1988) described by wide spread left-lateral strike-slip motion along NE planes in the west to NS planes in the east near the ninetyeast ridge, that accommodates strains due to uneven convergence of subduction fronts in the Indo-Australian plate with respect to the Andaman-Sumatra arc. This mechanism is invoked to explain the strike-slip events north of Andaman Islands obtained in the present study (black) which occurred at lower crustal depths of the subducting Indian lithospheric plate. Also indicated are the reverse fault earthquakes west of ninetyeast ridge (red) and the normal fault earthquakes near Chagos bank (blue) describing convergence in the east and divergence in the west between the Australia and India plates defined by an anti-clockwise Euler pole rotation model (DeMets, 1990). Stars indicate the giant Sumatran subduction earthquakes of 2004 and 2005. (Data source: Harvard CMT catalog)

The vertical distribution of seismicity north of the Andaman Islands is suggestive of a lithospheric split or tear in this region giving rise to a vertical structure that acted as a barrier during the propagation of the 2004 Sumatra-Andaman earthquake of Mw 9.3. This feature has been interpreted as a near-vertical lithospheric tear by Richards et al. (2007). The absence of a lithospheric slab down to deeper levels and the presence of a vertical barrier is also evidenced by tomographic depth sections of Pisceck et al., (2010). Evidence for such a structure also comes in the present study from the Bouguer gravity anomalies in this region which indicate the steepest gradient of 1.5 mgal / km exactly at this location (figure 12). The focal depths estimated from waveform matching ranging from 11 km to 26 km indicate its

deep-seated nature (figure 8). In any case, this region has been devoid of any seismicity for several years (figure 10), and as shown in this study, the sudden burst of seismic activity starting with the 2009 event can be seen as a trigger releasing the stress accumulated along the lithospheric split zone, subsequent to the disastrous 2004 mega-thrust earthquake of Mw 9.3. Detailed tomographic studies combining land based and ocean bottom seismograph data in the Andaman region in future can resolve this issue in addition to providing accurate 3D images of the subduction zone.

5. Conclusions

1. Joint inversion of broadband data of 5 earthquakes has provided a P wave velocity model of the Andaman region, based on best waveform fits between all the observed and synthetic seismograms. The model depicts a 30 km thick double oceanic crustal column corresponding to a thickness of about 21 km of Burmese crust including a 5 km thick sedimentary column, underlain by a thinner Indian crust with an apparent thickness of about 9 km, which is independently validated by receiver function analysis and gravity modeling.
2. The hypocenters of the 10 August 2009 Andaman earthquake of Mw 7.5 and its aftershocks form a peculiar vertical distribution down to about 50 km depth. This zone is interpreted as a lithospheric split or tear in the Burma-Andaman arc, which incidentally coincides with the northern periphery of the rupture zone of the 2004 mega-thrust earthquake of Mw 9.3.
3. The main shock as well as the aftershocks can be classified into two groups – normal fault mechanism with shallow focal depths within 18 km, and strike slip mechanism at greater depths down to 26 km. The two groups are interpreted as intra-plate events occurring within the Burmese crust and the Indian crust respectively.
4. While the events with normal fault mechanism are attributed to plate relaxation in the fore-arc region subsequent to buckling of the overriding Burmese plate during the 2004 mega-thrust earthquake, the deep seated strike-slip fault events correspond to the crust of the Indian plate and represent a series of left-lateral strike-slip motions that accommodate the Indo-Australian plate convergence under the Burma-Sunda arc.

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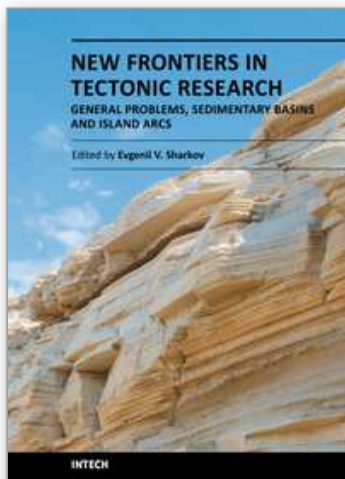
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