

Source Characteristics of the 2012 Earthquake Swarm Activity in the Andaman Spreading Ridge

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ABSTRACT

Earthquake swarms are a sequence of events clustered in space and time, with no single earthquake dominating in size. Such swarms were observed in the Andaman sea region during the years 1983-1984, 1994, 2005 and 2012. The recent one in 2012 occurred to the north of the Nicobar Islands (9° N, 94° E) within the Andaman spreading ridge, starting on 16 April, 2012. Interestingly, the swarm followed the M_w 8.6 Indian Ocean earthquake of 11 April, 2012, the largest strike-slip earthquake ever. This activity lasted for nine days and comprised about 27 earthquakes in the local magnitude (M_L) range of 2.2 to 4.4, whose focal depth varied from 4 to 51 km. In the present study, we first analysed the phase data of these earthquakes recorded by a nine station broadband seismological network established by the CSIR-National Geophysical Research Institute (CSIR-NGRI), together with the data from three stations of the India Meteorological Department (IMD), to constrain the hypocentre locations of the swarm events using the double difference method. Further, we determined the moment tensor solutions of the three largest events using the full waveform inversion technique, to understand their source characteristics. Interestingly, all the three mechanisms showed a high non-double-couple component of over 70%, comprising both isotropic and CLVD components. Therefore, it is inferred from the present study that the mechanism of swarm earthquakes can be explained by ascension of magma at the spreading ridge coupled with inflation or deflation of magma chambers in the volcanic source region. In contrast, moment tensor solutions of four tectonic earthquakes that occurred to the north of the Andaman Islands away from the spreading center and the swarm, show a very high double couple percentage as expected for a normal tectonic earthquake, validating our interpretation.

Key words: Andaman Nicobar, Swarm earthquakes, Earthquake relocation and Moment tensor solutions.

INTRODUCTION

The Andaman arc along with the Burma arc to its north forms the eastern margin of the Indian plate. The Andaman Sea adjoining the Andaman subduction complex falls in the back arc region (Figure 1). However, it is categorized as a rip-off or pull-apart basin rather than a typical back arc basin and is considered as an active extensional margin (Curry, 1989). Evidence for active extension comes from a synthesis of the results from many geophysical studies including bathymetry, magnetic, gravity and heat flow (Rodolfo, 1969; Curry et al., 1979). The structure of the Andaman back arc mapped by Kamesh Raju et al., (2004) identified three major SW-NE spreading segments offset by several kilometers having a step like structure. The spreading in this region was initially attributed to leaky transform or trench roll back, similar to the back arc basins in the Pacific (Uyeda and Kanamori, 1979). However, the most important reason for the active extension or spreading is the oblique subduction of the Indo-Australian plate beneath the Sunda plate. The complex accommodation of the strain along this oblique subduction is evidenced in the form of arc-parallel strike-slip faulting along the Western Andaman Fault and also formation of a sliver plate moving northward (Fitch, 1972; McCaffrey, 1992; 2009). The boundary between the Burma plate (Sliver), and

the Sunda plate is inferred from a system of arc-parallel transform faults and arc-normal ridges (Alock and Sewell ridges) in the back arc of the Andaman Sea.

The NW-SE extension of the Andaman Sea corresponding to the pull-apart basin along the plate boundary is due to the northward drag of the Burma Plate with respect to the Sunda plate by the underthrusting Indo-Australian plate (Curry, 2005; McCaffrey, 2009). Studies of magnetic anomalies indicate that the sea floor spreading was initiated ~4 Ma ago, much younger than in the Sunda arc, with the initial spreading rate increasing from 1.6 cm/yr to 3.8 cm/yr from ~2-2.5 Ma to the present (Kamesh Raju et al., 2004). The spreading ridge falls under the category of slow-spreading ridges. The neotectonic extension in this region is manifested in terms of normal faulting mechanisms in the northern part of the Andaman Sea whose extension is along the NW direction (Fitch, 1972). The dominance of normal earthquakes at latitudes 10° N and 14° N indicates the presence of two spreading centres, separated by N-S transform faults experiencing right-lateral strike-slip as revealed by the source mechanisms of earthquakes (Eguchi et al., 1979).

The Andaman Sea region hosted several earthquake clusters or swarms in the past, during the years 1983-1984, 1993 and 2005 (Figure 1), with an interesting periodicity of about 10 years. An earthquake swarm can

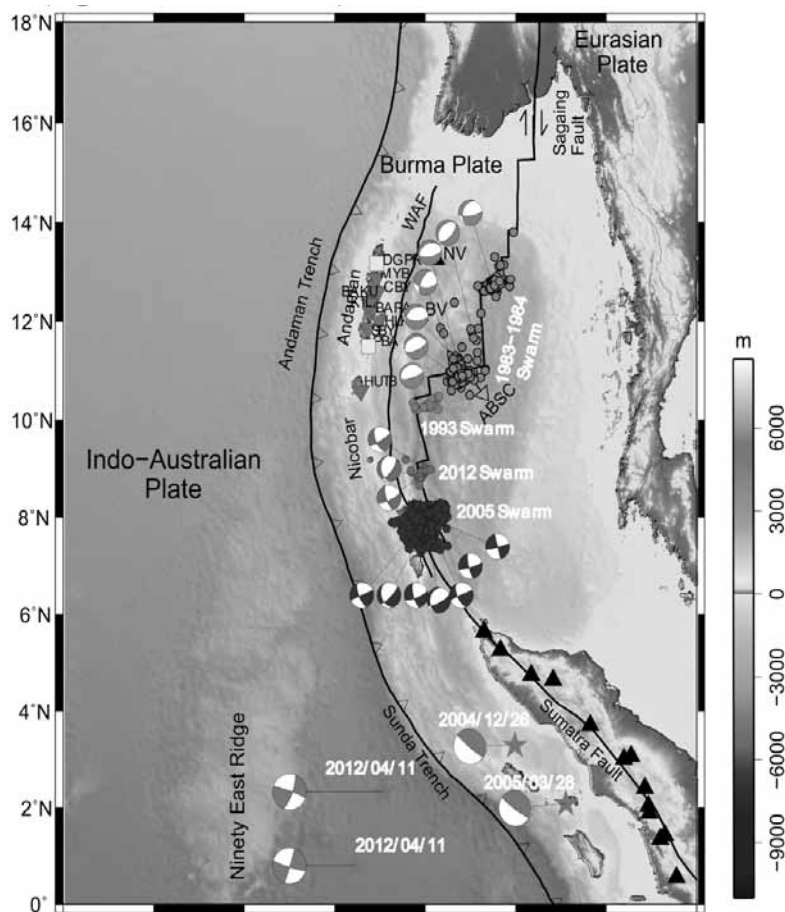


Figure 1. Tectonic map of the Sumatra-Andaman region with active faults indicated by solid lines and inactive faults marked as dashed black lines. Triangles correspond to volcanic arc, BV: Barren Volcano, NV: Narcondam Volcano. AB: Aceh Basin, ABSC: Andaman Back-Arc Spreading Centre, AR: Alcock Rise, SR: Sewell Rise, SFS: Sumatra fault system, SEU: Seulimeum strand of the SFS, WAF: West Andaman fault.

be defined as a sequence of earthquakes clustered in space and time with no distinct main shock (Mukhopadhyay and Dasgupta, 2008; Roland and McGuire, 2009). Among known swarms in the Andaman region, the 2005 swarm is globally considered as the most energetic one that occurred exactly a month after the M_w 9.2 December 2004 Sumatra earthquake. Kundu et al., (2012) suggested that the 2005 swarm is due to a combination of both tectonic and volcanic sources. Recently, in the year 2012, after the great twin strike-slip earthquakes of M_w 8.6 and 8.2 in the Indian Ocean, an earthquake swarm occurred in the Andaman Spreading region. The occurrence of swarm earthquakes not only indicates episodes of rifting, but also seems to be associated with a major or great earthquake in the proximity. Thus, understanding the source characteristics of these earthquakes would shed light on resolving the enigma associated with the complex history of swarm seismicity. In the present study, we attempt to decipher the source processes of earthquakes in the 2012 swarm using the moment tensor inversion approach. The results are

also compared with those of the 2005 swarm using the moment tensor elements of earthquakes from the global CMT catalog (Figure 2). A full moment tensor includes all mechanisms of the source process namely the Double Couple (DC), Compensated Linear Vector Dipole (CLVD) and Isotropic (ISO) (Frohlich and Apperson, 1992). The ISO component is generally associated with an explosive or implosive source where the energy is equally radiated in all directions. On the other hand, earthquakes in general tend to exhibit a combination of all these three types, with a general predominance of DC. The DC component describes equivalent forces acting on a planar fault causing a simple shear whereas the non-DC component including CLVD and ISO-describes more complex processes like landslides (Hasegawa and Kanamori, 1987), inflation or deflation of magma chambers in volcanic areas (Mori and McKee, 1987), tensile faulting caused by high fluid pressure in geothermal and volcanic areas (Ross et al., 1996; Julian et al., 1997, 1998), or shear faulting in an anisotropic medium (Kawasaki and Tanimoto, 1981). A high non-DC

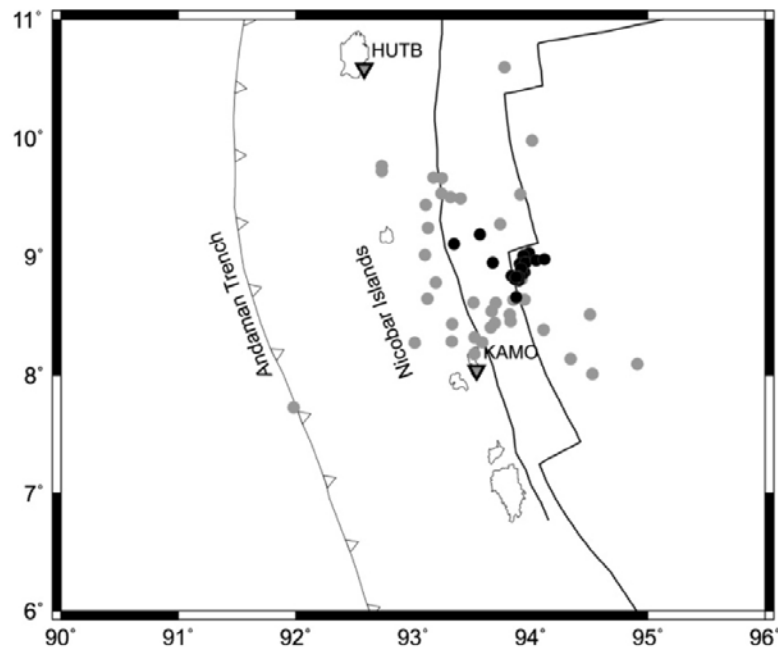


Figure 2. Seismicity in the vicinity of the observed 2012 swarm from 2010 January to March 2012 (ISC catalog (gray circles) and 2012 swarm (black circles)).

component may also be associated with deep earthquakes on slabs in subduction zones. The actual distribution of these components in the moment tensor is used in this study to characterize the complete earthquake source process.

Data and Methodology

The seismic waveform data recorded by the seismic network comprising nine broadband seismological stations established by the CSIR-NGRI and two stations established by the IMD in the Andaman-Nicobar Islands are used in this study (Figure 1). The nine broadband stations are equipped with REFTEK sensors while the other two are equipped with Trillium-240, both connected to data loggers sampling the data at a frequency of 100 Hz. During the routine analysis for earthquake locations, a group of clustered events was observed to the north of Nicobar Islands (9°N, 94°E), within the Andaman spreading ridge, hitherto referred as the 2012 swarm. The background seismicity in the vicinity of the observed 2012 swarm from January 2010 to March 2012 (3 years before the swarm) clearly indicates the absence of clustering of events in the region (Figure 2). This swarm activity consisting of 27 events in the local magnitude (M_L) range of 2.2 to 4.4, started on 16 April 2012, following the M_w 8.6 Indian Ocean earthquake of 11 April 2012 and lasted until 25 April 2012. The vertical component of an event from the 2012 swarm recorded at six stations is shown in Figure 3b. For comparison, the vertical component of a non-swarm

event closer to the arc is also shown in figure 3a. The hypocentral parameters of the swarm events are obtained by an iterative least-squares technique based on the Geiger method (Geiger, 1910; 1912). Even with high precision digital data, it is difficult to precisely locate the earthquakes from the station geometry restricted to a few azimuths due to geographical constraints. Therefore, to get improved locations, events are relocated using the double difference (HypoDD) algorithm of Waldhauser and Ellsworth (2000).

Relocation: HypoDD technique assumes that the ray paths between the source region and a common station are similar along almost the entire ray path and the difference in travel times for two events observed at one station is attributed to the spatial offset between the events. The residual between the observed and calculated travel-time difference (or double-difference) between two events at a common station is related to the adjustments in the relative position of the hypocenters and origin times through the partial derivatives of the travel times for each event with respect to the unknown. The double-difference residuals for pairs of earthquakes at each station are minimized by weighted least squares using the method of singular value decomposition (SVD) or the conjugate gradient method (LSQR) (Paige and Saunders, 1982). In the present study, a total of 226 P and 120 S travel times are used to relocate the 27 swarm earthquakes using the LSQR method (Figure 4). The following criteria are adopted for relocating earthquakes: (i) the maximum distance between an event pair and the corresponding station is 600 km; (ii) the maximum hypocentral separation between a pair of events

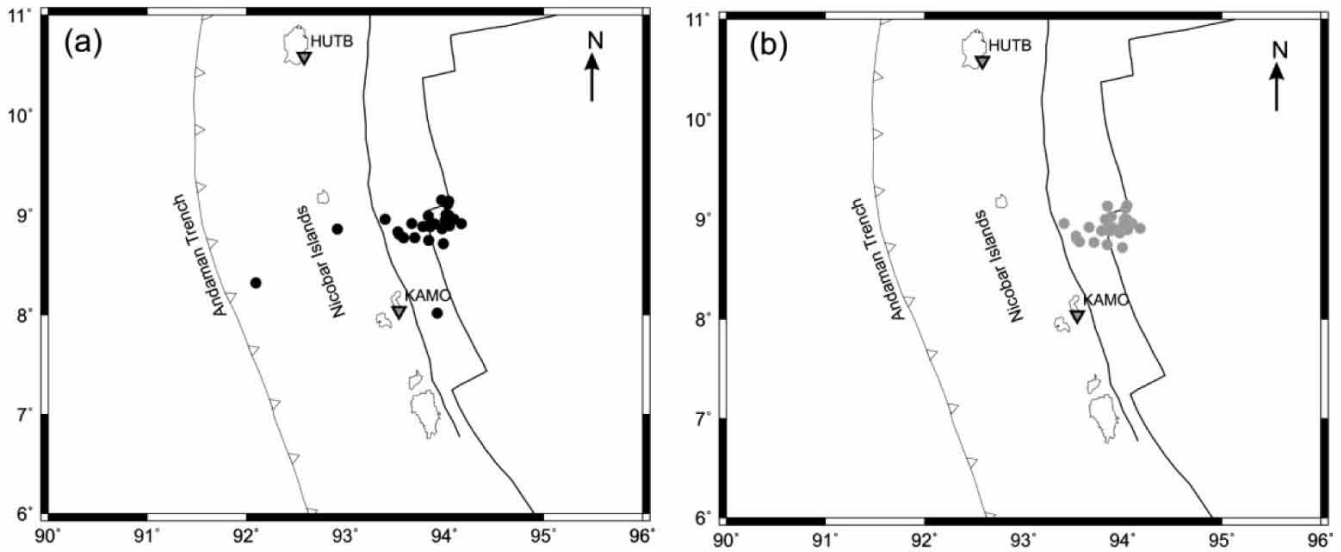


Figure 4. Epicentral map of swarm earthquakes (a) Initial, (b) relocated.

is 60 km; (iii) maximum number of neighbours per event is eight; and (iv) the definition of a neighbour involves a minimum number of three links.

Moment Tensor Inversion: A moment tensor provides a general description of a point source using a pair of couples representing equivalent body forces. A moment tensor solution describes not only the general earthquake faulting or shear mechanisms, but also other models of seismic sources like explosions and implosions or rock falls, landslides, meteorite terminal explosions (e.g. atmospheric), and mixed mode ruptures driven by fluid and gas injections. Thus, the moment tensor inversion is a very important tool in seismic source characterization. In general, a moment tensor is a combination of the three components: (i) Double Couple (DC) which describes equivalent forces acting on a planar fault causing shear faulting, (ii) Compensated Linear Vector Dipole (CLVD) which describes equivalent forces acting on a non-planar fault and (iii) Isotropic (ISO) which represents forces acting radially in all directions. The percentage of each component can be used to distinguish the earthquake process indicating the type of source.

The focal mechanism solution of an earthquake can be derived from the moment tensor elements. The DC component is described by the fault plane parameters: strike, dip and slip. The moment tensors can be obtained from various inversion schemes: (i) Polarity of P phase, (ii) Amplitude inversion of P, SH and SV waves, (iii) Waveform inversion. In the present study, full waveform inversion is used to obtain the moment tensor solution, including the seismic moment and moment magnitude using ISOLA code (Sokos and Zahradník 2008, 2013). An iterative deconvolution based on the approach of Kikuchi and Kanamori (1991) is used to obtain the moment tensor solutions. Synthetic waveforms are generated by

using the discrete wave number summation method of Bouchon (1981) and Coutant (1989). The core inputs used to calculate the moment tensor solution are the station coordinates, hypocentral parameters, 1D velocity model (Rao et al., 2011), waveform data and the number of iterations.

The best moment tensor solution that yields a good match between the synthetic and observed waveforms is obtained through an iterative process. A good correlation and overall variance reduction indicates the reliability of the fit between the observed and synthetic waveforms. A full moment tensor solution is a combination of DC, CLVD and ISO components which can be isolated as follows:

$$ISO = \frac{1}{3} \frac{\text{Tr}(M)}{|M|_{\max}} (100\%) \quad \text{-----(1)}$$

$$CLVD = -2 \frac{M^*_{\min}}{|M^*_{\max}|} (100 - |ISO|) \quad \text{----- (2)}$$

$$DC = (100 - |ISO| - |CLVD|) \quad \text{----- (3)}$$

where, $\text{Tr}(M)$ represents the trace of the seismic moment tensor M , $M|_{\max}$ denotes the eigenvalue of M that has the maximum absolute value, and $M^*|_{\max}$ and $M^*|_{\min}$ are the eigenvalues of the deviatoric moment tensor with the maximum and minimum absolute values, respectively.

RESULTS AND DISCUSSION

During the year 2012 an interesting phenomenon of earthquake clustering both in time and space, which characterizes a swarm, is observed to the north of the Nicobar Islands. The cluster of 27 earthquakes which is referred as the 2012 swarm started just 5 days after the

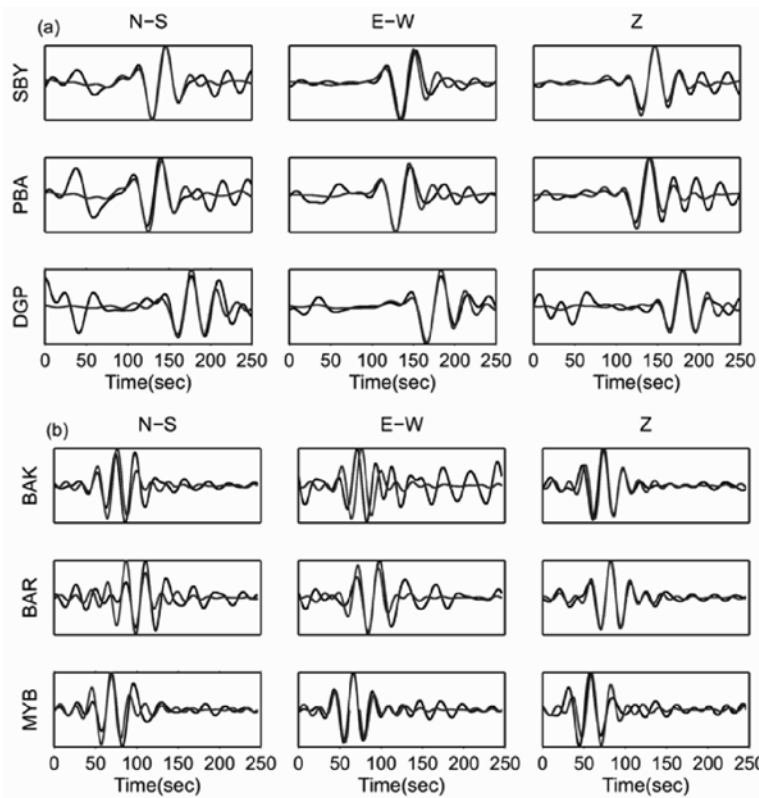


Figure 5. Matching of the observed (black) and synthetic (gray) 3-component displacement seismograms corresponding to (a) swarm (b) non-swarm events.

Table 1. Epicentral parameters and focal mechanism solutions of the 2012 swarm events in the Andaman spreading ridge, including the distribution of DC and non-DC components of the moment tensor solutions.

| S. No. | Date | Origin Time | Lat | Lon | Depth (km) | M_w | Centroid Depth (km) | Strike | Dip | Rake | DC | Non-DC | | |
|--------|------------|-------------|------|-------|------------|-------|---------------------|--------|-----|------|------|--------|------|-------|
| | | | | | | | | | | | | CLVD | ISO | Total |
| 1 | 2012/04/24 | 14:57:14 | 8.9 | 93.9 | 23 | 4.4 | 29 | 76 | 60 | 14 | 20.1 | 33.2 | 46.7 | 79.9 |
| 2 | 2012/04/25 | 7:42:24.5 | 9.15 | 93.9 | 12.56 | 4.4 | 7 | 135 | 50 | 150 | 27 | 22.4 | 50.6 | 73 |
| 3 | 2012/04/25 | 12:58:16.6 | 8.9 | 94.07 | 14.7 | 3.8 | 52 | 325 | 44 | -112 | 22.5 | 71.0 | 6.5 | 77.5 |

twin ($M > 8$) earthquakes in the Indian Ocean. The origin of the 2012 swarm was speculative due to its spatial proximity to the Andaman back arc spreading center, the site of the most energetic swarm in 2005 and proximity in time to the Indian Ocean earthquakes. Although the swarm consists of 23 moderate earthquakes (M_L 2.2 to 4.4), focal mechanism solutions could not be obtained for most of them due to poor signal to noise ratios. In the present study, only three focal mechanism solutions that show a good correlation (≥ 0.5) between the synthetic and observed waveforms (Figure 5) could be obtained. Out of these three focal mechanism solutions, two earthquakes have a predominantly strike-slip component with a slight normal component and the third earthquake is dominated by the normal component (Figure 6). The obtained solutions are listed in Table 1.

The combination of normal and strike-slip mechanisms can be attributed to the spreading activity and transform faulting in the Andaman Sea region as evident from the matching fault plane and slip directions. Further, the DC and non-DC components are calculated to distinguish between the tectonic and non-tectonic causes of the earthquake source. Interestingly, a significant percentage of non-DC component ($> 70\%$) is observed for the swarm events which may indicate the role of tensile faulting at high fluid pressure or dyke intrusion (Julian, 1983; Aki, 1984; Julian and Sipkin, 1985). The non-DC component can often be misleading due to improper earthquake source modelling resulting from limited data, inaccurate Greens functions or oversimplified source processes (Vavrycuk, 2002). Therefore, to verify the correctness of the obtained

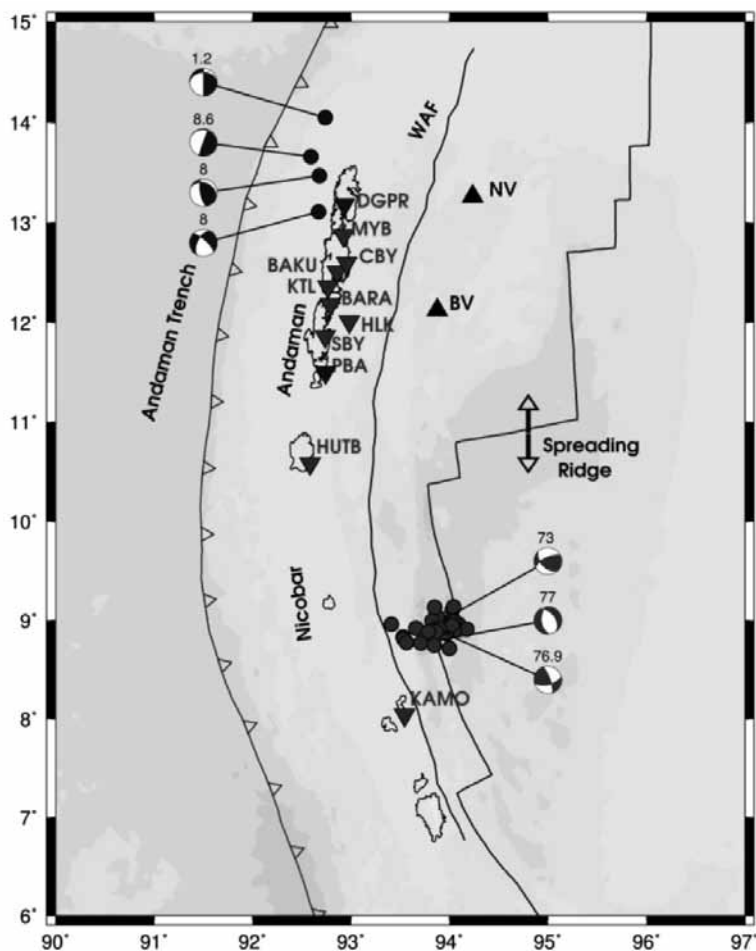


Figure 6. Focal mechanism solutions of swarm (near Nicobar) and non swarm (north Andaman) earthquakes obtained by moment tensor inversion. The black colour lines are the plate boundaries and faults. The numbers above the focal mechanisms indicate the values of the non-DC component.

Table 2. Epicentral parameters and focal mechanism solutions of the non-swarm events north of the 2012 swarm, including the distribution of DC and non-DC components of the moment tensor solutions.

| S. No. | Date | Origin time | Lat | Lon | Depth (km) | M _w | Centroid Depth (km) | Strike | Dip | Rake | DC | Non-DC | | |
|--------|------------|-------------|-------|-------|------------|----------------|---------------------|--------|-----|------|------|--------|------|-------|
| | | | | | | | | | | | | CLVD | ISO | Total |
| 1 | 2009/08/13 | 09:21:35 | 14.05 | 92.74 | 26 | 5.8 | 35 | 180 | 90 | 119 | 98.8 | 0.5 | 0.7 | 1.2 |
| 2 | 2010/05/01 | 21:18:58 | 13.66 | 92.59 | 10 | 4.8 | 7 | 180 | 89 | 100 | 91.4 | 1.7 | 6.9 | 8.6 |
| 3 | 2010/05/02 | 05:53:46 | 13.47 | 92.68 | 29.2 | 4.0 | 61 | 173 | 72 | 113 | 91 | 7.1 | 1.9 | 9 |
| 4 | 2011/03/19 | 12:42:34 | 13.11 | 92.67 | 41.6 | 4.8 | 49 | 209 | 55 | -22 | 79.3 | 0.1 | 20.6 | 20.7 |

non-DC components, a set of four earthquakes far from the 2012 swarm are chosen from the north Andaman region to calculate the moment tensor solutions. A clear match between synthetic and observed waveforms for the non-swarm events is observed, indicating a good correlation. A significantly low non-DC (or a high DC) percentage is observed for these events as expected (Table 2). The high DC (>90%) for the non-swarm events from the North Andaman indicates a pure tectonic origin in contrast to

the swarm events. On the contrary, a significant non-DC component in the 2012 swarm events indicates a non tectonic origin of the source.

For a comparison of swarm characteristics in the Andaman region, the moment tensor components of the 2005 swarm, about 100 km south of the 2012 swarm were computed from the Global CMT catalog data. The focal mechanism solutions of the strongest events of the 2005 swarm vary from a pure strike-slip to pure normal and a

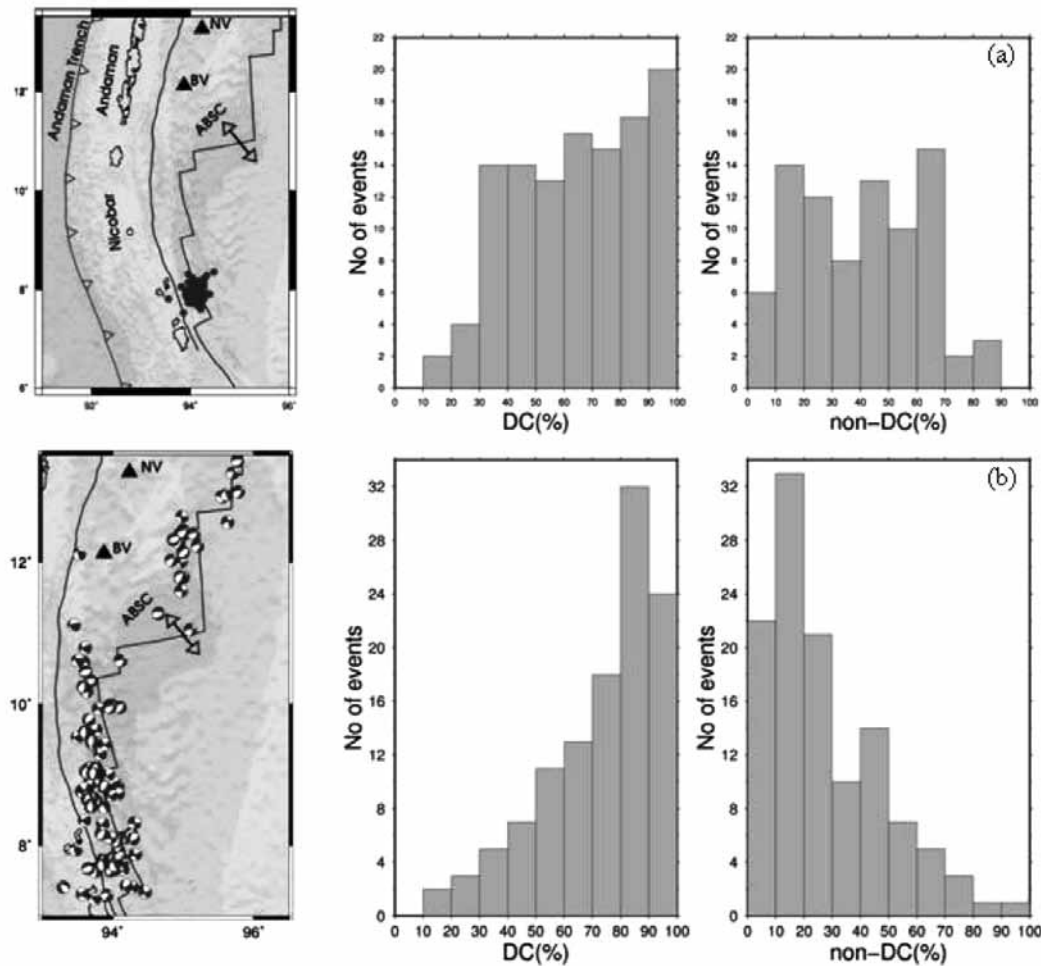


Figure 7(a). DC and non-DC percentages of (a) 2005 earthquake swarm calculated using the solutions from the CMT catalog, (b) earthquakes along the Andaman Back-Arc Spreading Centre calculated from the CMT catalog.

combination of both. Further, the ratio of the DC to non-DC moment tensor components is sometimes high and other times low (Figure 7a). This indicates an overlapping of both tectonic and volcanic source processes for the 2005 swarm, attributable to the mega thrust earthquake of December 2004, as also suggested by Kundu et al., (2012). In other words, the swarms originating in the ABSC seem to have a blend of tectonic and volcanic origin. Further, to understand whether all the non-swarm earthquakes in the ABSC also have a high non-DC component, we examined the moment tensor components of all the earthquakes within ± 10 km along the Andaman spreading centre from 1976 to 2013 (Figure 7b). Though the ABSC is only 300 km away from the Andaman trench, one of the most active subduction zones, interestingly a significant non-DC component is observed. This confirms that the earthquakes in the spreading centre are largely influenced by the magmatic/volcanic activity and not only the tectonic movements.

CONCLUSIONS

The high non-DC component, comprising both CLVD and ISO, in the moment tensor solutions of the 2012 swarm earthquakes in the Andaman spreading ridge is attributed to ascension of magma at the spreading ridge coupled with inflation or deflation of magma chambers in the volcanic source region.

The 2005 swarm earthquakes on the other hand, show a predominance of both DC and non-DC components, indicating a mixture of tectonic as well as non-tectonic origin.

It is concluded that the 2012 swarm activity is linked to the magmatic activity at the Andaman spreading ridge.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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