Characteristics of the Earthquake Swarms in the Andaman Sea Region, India, from 1960 – 2020

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Abstract

The Andaman Sea region is the highly tectonically and seismically active region in India. This is the perfect site for studying earthquake swarms and how the swarms are reacting with the volcanic activities and tectonic processes. Using the International Seismological Centre (ISC) catalogue and USGS NEIC catalogue, we documented 17 earthquake swarms from 1960 to 2020. The hypocentre of the earthquake swarms was reported at 5 km. to 50 km and most of the incidents occurred below 20 km. depth.

We examined the seismotectonic characteristics of these swarms. The moment tensor solutions of 6 swarms showing these events are controlled by pure normal faults with a significant strike-slip component, few are dominated by strike-slip faults but no thrust mechanisms are recorded. The b value distribution for the Andaman Sea region was calculated from the swarms’ data and the b value significantly varied between 1.4 –2.17. We conclude that the earthquake swarms in the Andaman and Nicobar Island region are probably the result of magma intrusion in the thin and hot oceanic crust. High b values, active volcanoes and cratered seamount support the volcanic background of these swarms.

Keywords: Earthquake swarm, Andaman & Nicobar Island, Faults, Volcano, Magma.

Introduction

Earthquake swarms are a series of the small earthquake that occur over space and time without any identifiable mainshock. The swarms occurred due to stress changes, pressurization of fluid-field reservoirs, anthropogenic or natural hydro fractures and slow slip events. Earthquake swarms may be triggered due to high-stress release in a short period by crustal deformation along with magma intrusion.

Earthquake swarms could be a pure tectonic origin and pure volcanic origin or a combination of both. Examples of such types of earthquake swarms were documented worldwide. But most of the time, earthquake swarms are common in the area of an active volcano. They are mostly involved with magma intrusion and fluid transport in the crust. Volcanic earthquake swarms are categorized by high b values which are associated with a highly fractured crust and a heterogeneous stress field.

Tectonic earthquake swarms are another type of swarm directly linked with active tectonic regions. The Andaman and Nicobar Islands region, one of the most seismically active regions of India comes under seismic zone V characterized by swarm sequences. In this study, we tried to identify all the earthquake swarms in the Andaman and Nicobar Island region from 1960 to 2020 and analysed the characteristic of these earthquake swarms.

Tectonic Setting of Andaman Sea Region

The Andaman and Nicobar Islands are situated in between Andaman- Sumatra trench (west) and the active back-arc rift systems (east). The Andaman-Sumatra subduction zone located on the western side of the Andaman and Nicobar Island covers more than 3000 km as a result of the Indo-Australian Plate subducts under a part of the Eurasian plate. The Andaman and Sumatra convergence is classified as an oblique convergence. The global plate rebuilding data proposed the northeast movements Indian plate obliquely converging at 53 mm/yr. to the Eurasian plate. The Andaman and Nicobar ridge suggests that it was formed during the Oligocene or late Eocene and it is made of seafloor ophiolites and sediments from the Indian plate.

This region is characterized by anomalously high heat flow, a large-amplitude mercurial gravity field peculiarity of subduction zones. The tectonic formation of the Andaman Sea region is too complex. The Andaman and Nicobar region is made of many visible morphological structures e.g. the Andaman Trench, Fore Arc Basin, Back Arc Basin, Barren and Narcondam volcanic islands, Baratang and Diglipur mud volcano, Nicobar deep, Mergui Terrace. Geomorphology of the Andaman and Nicobar Islands fore-arc is 85 to 150 km wide and placed at 300 to 1500m of depth. The major faulting structures within the Andaman and Nicobar fore-arc area are consisting of the West Andaman Fault (WAF), Andaman and Nicobar Fault (ANF), the Eastern Margin Fault (EMF) and the Diligent Fault (DF). Barren island is the single active volcano in the Andaman and Nicobar Island region recently erupted on 23rd October 2019 called Narcondam volcano.

The Andaman Sea region is an extremely active seismic zone that lies in seismic zone V. The Andaman Sea region offers a perfect tectonic setting for the occurrence of megathrust earthquakes. Several major to moderate
earthquakes and earthquake swarms were triggered along the Andaman trench, ANF, WAF, back-arc and fore-arc. Due to the active subduction zone (Sumatra-Andaman trench), the seismic activities are very common for this region\(^2\). Nearly 200 km. deep an east-dipping Benioff zone is present in the study area\(^3\). Shallow focus volcano-tectonic origin earthquakes are common in this region.\(^4\)

**Data**

Earthquake data of the Andaman Sea region from 1960 to 2020 are taken from ISC Catalogue. 11,168 events were recorded and the majority of the earthquake’s magnitude was <4.5. To evaluate the precise details of earthquake swarms occurrence in the Andaman Sea region from 1960 to 2020, we used hypocentre determinations from the ISC Catalogue ([http://isc.ac.uk/iscbulletin/search/catalogue/](http://isc.ac.uk/iscbulletin/search/catalogue/)) for the 1960 to 2020 swarms. The ISC catalogue reports standard error in position and standard error in depth.

The average standard error in position for earthquakes is 8.9 km in the Andaman and Nicobar Islands region and the average standard error in depth is 2.82 km. The U.S. Geological Survey’s NEIC-PDE database has been also used for this study ([http://earthquake.usgs.gov/earthquakes(eqarchives/epic/](http://earthquake.usgs.gov/earthquakes(eqarchives/epic/)).

![Figure 1: Earthquake epicentral map of the Andaman Sea region from 1960 to 2020 (white circles). The size of circles is related to body wave magnitude Mb. Blue stars are indicating epicentres of earthquakes magnitude >6 from 1960 - 2020. Red triangles symbolize active volcanoes and yellow triangles dormant volcanoes. White arrows denote the direction of northward movement of the Ind-Au Plate Image generated using GeoMapApp (www.geomapapp.org).](image-url)
Focal mechanisms of earthquake magnitude > 5 were taken from the Global Centroid-Moment-Tensor (GCMT) Project (http://www.globalcmt.org/) for the period 1976 – 2019 and Seafloor morphology was created using the GeoMapApp tool.

Results

These swarms occurred along the eastern side of the Alcock Rise, the Andaman Spreading Rift System, across the West Andaman Fault and two small swarms occurred along the Andaman trench. CMT solutions of earthquake swarms in these regions are mostly normal faults, some events are normal faulting with a significant strike-slip component.


The identified faults and their beach ball diagrams are shown. For 2005 swarm, 112 focal mechanism solutions are available. The focal mechanism solutions for event 2005 swarm out of 112 are: 8 are strike-slip earthquakes, 20 are pure normal faults while the remaining 84 events indicate normal faulting with a significant strike-slip component (Figure 3). Out of 9 available solutions for the event, March 2006 swarm all are pure normal faults and are located 10.4°N to 10.9°N.

These are shallow focus earthquakes (Figure 3). July 2009 swarm events focal mechanism is showing pure normal faulting and these earthquakes are shallow focus earthquakes (Figure 3). The focal mechanism solutions for the event April 2012 swarm are normal faulting with a significant strike-slip component. These are shallow focus earthquakes (Figure 3).

The b Value of Earthquake Swarms in Andaman And Nicobar Region: The b-values of the seventeen swarms were estimated using the MLE method. The calculated b-value ranges from 1.09 to as high as 2.17. We interpret the anomalously high b-value at the depth of below 25 km along with the Andaman Sea Region as a result of an active shallow magma reservoir beneath the Fore Arc and Back Arc basin of the Andaman Sea.

The presence of a magma chamber gives rise to the main factors linked with the high heterogeneity, high pore pressure and high thermal gradient. High b-value means drops of effective stress by the interface of magma and is also a sign of magma accumulation and injection and an indication of high crustal heterogeneity of local stress regime.

Low b value means high-stress accumulation and the b value calculation suggests a high-stress accumulation west of the Nicobar Islands (b-value 0.62) and the northern part of the Andaman Islands (b-value 0.71). The region is highly vulnerable for future seismic activities especially along with Jarawa thrust and Button thrust. The b-value for 1970 swarm is 2.17 higher than other sequences. Apart from 1970, the higher b-value has been seen in 2000, 2003, 2004, 2005, 2006, 2008, 2009, 2011, 2012 (Sept.), 2014, 2017, 2019 (Nov.) swarms. Based on the literature survey, we are suggesting that these swarms are of volcanic origin, but based on low b-values, we cannot suggest that these are volcanic swarms. The normal faults and the high b-value represented that these swarms are of volcanic origins. The presence of an active volcano, two mud volcanoes and a steep-sided twin dormant submarine volcano near the epicentres of the earthquake swarm is indicating the volcanic nature of the region.

Spatiotemporal Distribution of Earthquake Swarms and their Relation to Tectonic Structures in Andaman Sea Region: Earthquake swarms mostly occurred in the upper part of the Earth’s crust. Depth range of earthquake swarms all over the world is approximately from 2 and 20 km, whereas some deeper earthquake swarms have also been recorded but quite rarely. The majority of earthquake swarm events in the Andaman Sea region are also located around 5-20 km and shallower (Figure 4).

Table 1
The cumulative ‘b’ Value for each Block

<table>
<thead>
<tr>
<th>Number of Swarm</th>
<th>Block</th>
<th>Cumulative ‘b’ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>I (11° N-14° N)</td>
<td>1.35</td>
</tr>
<tr>
<td>7</td>
<td>II (9° N-11° N)</td>
<td>1.30</td>
</tr>
<tr>
<td>8</td>
<td>III (6.4° N-9° N)</td>
<td>1.45</td>
</tr>
</tbody>
</table>
Figure 2: Location map showing seismic events of seventeen swarms and the size of circles is related to body-wave magnitude (Mb). Plotted using GeoMapApp (http://www.geomapapp.org/) and the Topography and Bathymetry SRTM_PLUS.

We document 11,168 individual earthquakes with an average magnitude (MB) of 4.1 within seventeen (17) separate earthquake swarm clusters recorded in the Andaman Sea region. Individual swarms show pretty different migration patterns though they occur commonly in the same place.

The swarm 1970 started on 25th October ending on 27th December 1970 with 14 events of magnitude 4.7 to 5.5 (ISC). This swarm clusters around Sewell Rise, 9.5ºN and 94ºE with the NE trend (Figure 2). The maximum event 11 was recorded on 25th October 1970 at the southern part of the West Andaman Fault. Most of these seismic events occurred at the depth of around 25 km. The b-value of the swarm is near 2.5.

The 1983-1984 swarms’ activity occurred from 16th December 1983 to 17th August 1984 with a total of 213 seismic events of Mb 3.7 to 5.8 (ISC Catalogue). From December 1983 to March 1984, the swarm occurred along the eastern side of the Alcock Rise around 13ºN on the NE-SW oriented in the Andaman Spreading Rift System (ASR). The first event was recorded on 16th December and its magnitude is 4.7; then 23h later, the main activity started in ASR. The maximum event 39 was recorded on 8th July 1984. From April to August 1984, the swarm migrated to the south and clustered around 11ºN along the central spreading ridge segment between Alcock and Sewell ridges (Figure 2).

Most of the earthquake events originated at depths of 5-26 km. The 1983 cluster occupied approximately 50 km of NE ASR whereas the 1984 swarms occupied around 60 km of the central ASR. The fault plane solution of this swarm results in a NE-SW striking normal fault with a significant strike-slip component (Figure 3). We calculate that the b-value of the swarm is near 1.5. 1983-84 swarm is an oval-shaped.
The 1993 swarm activity starts on 23rd August and ends on 5th October that includes 33 seismic events magnitude of range 3.9 to 5 that clusters around 10°N at the southwest segment of the Andaman Spreading Rift (Figure 2). The maximum events (11) were recorded on 23rd August 1993. The 1993 cluster occupied around 35 km of the SW segment of the central ASR. This swarm started nearly 20 km away from where the 1984 swarm stopped. The majority of events originated at the depths of 10-20 km. The b-value for the swarm cluster is near 1.5. It may be noted that this swarm in the Andaman Spreading Rift System corresponded with March 1991 to May 1995 arc volcanic episode at the barren island.

The 2000 swarm activity starts on 1st October and ends on 29th November along the western side of the Eastern Margin.
Fault which includes 38 seismic events of magnitude 3.9 to 5.3 (ISC Catalogue). Most of the events originated at the depth of around 40 km. The swarm occupied nearly 38 km of the western part of the eastern margin fault. The b-value of this swarm cluster is 1.45. The 2000 swarm started almost 20 km away from where 1993 finished and moved towards the Diligent Fault with SE direction. No CMT solutions are available for this swarm. The upward movement of events might be linked with the diffusion of fluid moving. The shape of this swarm is oval (Figure 2).

The smallest swarm activity occurs in a single day on 30th January 2003 that includes 10 seismic events magnitude range of 3.6 to 4.9 and clusters around 7.5°N and 94.5°E, at the eastern end of the eastern margin fault and near the west Andaman fault with the SE trend (Figure 2). The duration of the 2003 swarm was less than a day. It occupied around 12 km of the western part of the West Andaman fault. The b-value of the 2003 swarm is 1.45.

A minor swarm occurred in 2004 swarm in a very short period from 10th April to 16th April that includes 25 seismic events magnitude range of 3.7 to 5.1 and clusters around 8.8°N where the 1970 swarm started (Figure 2). The 2004 swarm was detected in the Back-arc Basin of Andaman Sea and near West Andaman Fault with the NW-SE trend. The first event was recorded on 10th April and magnitude is 4, then 10h later, the main activity started and no CMT solutions are available for these events. The cluster spread over a distance of about 15km. The b-value of this swarm calculated from the ISC catalogue (MB) is 1.14. The majority of events occur at shallow depths up to 30km and the maximum number of events occur in the focal depth range of 15 to 22 km.

In January 2005, 1 month after the December 2004 Mb= 9.1 event, the largest swarm activity occurred for a very short period from 26th January to 31st January 2005 with 681 events of magnitude 3.8 to 5.7. The swarms were relocated from ISC Catalogue (Figure 2). The 2005 swarm occurred at the West Andaman Fault in the Back-arc Basin of the Andaman Sea. Lay et al.\textsuperscript{13} remarked that the 2005 swarm is the most energetic swarm ever observed globally. This swarm occupied around 90 km across the WAF. Major pulses were noted on 27th and 28th January 2005. The 2005 swarm cluster is an oval shape\textsuperscript{17} and its b-value is 1.09. The epicentral location of the 2005 swarm is showing the NE-SW trend. The majority of events occur at shallow depths up to 30 km whereas the maximum number of events occurs in the focal depth of 10 to 25 km. The CMT solutions of this swarm screening out of 112 8 are strike-slip, 20 pure normal faults while the remaining 84 events indicate normal faulting with a significant strike-slip component.

The swarm 2006 starts on 9th March and ends on 19th March which includes 168 seismic events magnitude range 3.6 to 5.1 and clusters around 10°N (Figure 2). The swarm in March 2006 was identified from ISC Catalog. This swarm started the spatial gap between the 1984 and 1993 swarm and moved southwestward along the Andaman Spreading Ridge. The b-value of the 2006 swarm calculated from the ISC catalogue is close to 1.5. This swarm occupied approximately 50 km around the ASR centre. It is noted that at the same time, volcanic eruptions took place in Barren island\textsuperscript{15}. The CMT solution of this swarm shows these events are pure normal fault earthquakes. The majority of events occur at shallow depths up to 35 km.

The swarm 2008 occurred in a very short time from 3rd October to 18th November including 25 seismic events magnitude 3.5-5.2 and clusters around 10°N and 92°E (Figure 2) near the Andaman trench. The majority of events were noted on 4th October 2008. The swarm occupied nearly 50km along the eastern side of the Andaman trench with the NE-SW trend. The majority of events occur at shallow depths up to 30 km whereas the maximum number of events occurs in the focal depth of 10 to 20 km. The b-value of the 2008 swarm calculated from the ISC catalogue is close to 1.5.

The 2009 swarm is similar to the 2006 swarm, it starts on 26th July and ends on 28th July including 160 seismic events magnitude 3.5 to 5 which cluster around 10°N and the maximum events 123 were recorded on 26th July 2009 at the southwest segment of the Andaman Spreading Rift (Figure 2). This swarm started at the same place where the 1983-84 swarm ended and in 1993, 2006 swarms started and further moved towards the southwest to along the West Andaman Fault. The b-value of the 2009 swarm calculated from the ISC catalogue is close to 1.5. This swarm occupied approximately 50 km around the ASR centre. The majority of events originated at the depths of 10-20 km. The CMT solution of this swarm shows that these events are pure normal fault earthquakes.

The swarm 2011 occurred on 30th November to 16th December 2011 that contained 15 seismic events magnitude 3.8 to 5.4 and clusters around 7.3°N and 93.8°E (Figure 2) in the Back-arc Basin and just above the twin seamounts of Andaman Sea\textsuperscript{11} with the NW-SE trend where 2003 swarm ends and 2005 swarm took place. The maximum events were recorded on 16th December 2011. The b-value of the 2011 swarm calculated from the ISC catalogue is close to 1.5. This swarm occupied approximately 20 km around the southern part of WAF. The majority of events originated at the depths of 10-30 km. The 2011 swarm cluster is a flat shape.

The swarm 2012 starts occurred for very short period from 24th April to 28th April 2012 with 27 events of magnitude 3.5 to 5.6. The swarm was relocated from ISC Catalogue (Figure 2). This swarm detects in the Back-arc basin of the Andaman Sea and near West Andaman fault with the NW-SE trend. The swarm Sept. 2012 occurred at the same place where the 1970 and 2004 swarm triggered. The maximum events 17 were recorded on 25th April 2012 at the southern part of the West Andaman fault and occupied almost 25km along with
the WAF. Most of these seismic events occurred in a depth of around 22 km. The CMT solution of this swarm shows that these events are normal faults with strike-slip component earthquakes. The b-value for this swarm is nearly 1.5.

The swarm Sept. 2012 is a minor swarm that starts on 20th August and ends on 10th September including 7 seismic events of magnitude 3.8 to 4.9 which clustered around 10°N and the maximum events were recorded on 10th September 2012 at the southwest segment of the Andaman Spreading Rift (Figure 2). This swarm started at the same place where the 1993, 2006, 2009 swarms ended and further moved towards the Diligent Fault with NW-SW direction. The b-value of the 2012 Sept. swarm calculated from the ISC catalogue is 1.09. This swarm occupied approximately 15 km between the DF and WAF.

The 2014 swarm activity occurred from 8th August to 26th December 2014 and a total of 138 seismic events of magnitude 3.5 to 5.4 (ISC Catalogue). Major pulses were noted on 11th and 18th December 2014. The 2014 swarm happened mainly in the Back-arc basin of the Andaman Sea where 2003, 2005 2011 swarms took place and further moved the NE-SW trend (Figure 2). The b-value of the 2014 swarm calculated from the ISC catalogue is close to 1.5. This swarm occupied approximately 50 km around WAF. The majority of events occur at shallow depths up to 30 km and the maximum number of events occur in the focal depth range of 10 to 22 km. The 2014 swarm cluster is parallelogram shape. No CMT solutions are available for this swarm.

The 2017 swarm is a minor swarm that starts on 15th September and ends on 9th December including 12 seismic events magnitude 3.5 to 4.5 which clustered around 12.5°N and 91°E at the northern part of the Andaman trench (Figure 2). The first event was recorded on 15th September its magnitude is 3.5, then on 17th September, the main activity started. The b-value of the 2017 swarm is 1.45. This swarm occupied approximately 40 km around Andaman Trench. No CMT solutions are available for this swarm. The majority of events occur at shallow depths 10 to 40 km. The 2017 swarm cluster is kite shape.

The 2019 swarm activity starts on 16th March and ends on 19th June with 137 events of magnitude 3.6 to 5.5. The swarm was relocated from ISC Catalogue (Figure 2). Major pulses were noted on 1st June 2019. The 2019 swarm happened mainly in the Back-arc basin of the Andaman Sea where 2003, 2005 2011, 2014 swarms took place and further moved the NE-SW trend. This swarm occupied approximately 50 km around WAF. The majority of events occur at shallow depths up to 45 km and the maximum numbers of events occur in the focal depth range of 10 to 30 km. The 2019 swarm cluster is an oval shape. Out of 22, CMT solutions 2 are strike-slip earthquakes and the remaining 22 events indicate normal faulting with a significant strike-slip component. The b-value of the 2019 swarm calculated from the ISC catalogue is close to 1.5.

The swarm 2019 occurred on 14th November and ends on 20th November including 10 seismic events (magnitude 3.5-5), clustering around the West Andaman Fault in the Back-arc Basin of Andaman Sea and further moving NE-SW trend (Figure 2). This swarm occupied approximately 25 km around WAF. The maximum events were recorded on 17th November 2019. No CMT solutions are available for this swarm. The b-value of the 2019 swarm calculated from the ISC catalogue is close to 1.5. The 2005 swarm cluster is trapezium shape.

**Discussion**

We performed a search for earthquake swarms in the Andaman Sea Region and determined their basic characteristics and evaluated the Spatiotemporal pattern of earthquake swarms. The highest rate of occurrence of earthquake swarms is located in the Andaman Spreading Rift and near the Nicobar Islands (Figure 2). The epicentral distribution and migration path of earthquake swarms in the Andaman and Nicobar Islands region from NE to SW along the ASR and WAF are documented. The upper mantle beneath the Andaman Sea is very thin, too hot. Dyke intrusions events are recommended as the most important drivers for the earthquake in the Andaman Back-Arc Spreading system. The results of this study suggest that the occurrence of earthquake swarms in the Andaman and Nicobar Island region is because of magma intrusion in the thin and hot oceanic crust.

The rise and fall of magma or fluids in the magma chambers triggered the swarms’ activity by the fluctuation of the effective stresses in this region. The swarms 1983-1984, 1993, activities took place along the ASR system as a result of magma intrusion from the upper mantle. Swarms in 2006 and 2009 started at the Andaman Spreading Rift due to fluctuation of effective stress and showed a similar migration path toward the NE-SW trend. The swarms in 1970, 2004 and 2012 initiated at the end of DF segment and western part of Swell Rise and showed similar propagation toward NE-SW. A cratered seamount is located at the centre of the 2003, 2005, 2011 and 2019 swarm and this supports the volcanic background of these swarms. High b-values and active normal faults of these swarms suggest that these are magmatic origin swarms. Swarm 2008 and 2017 near the Andaman trench had a magnetic origin based on the duration of swarms, high b values, normal faulting and speed of hypocentre migration.

**Conclusion**

Spatiotemporal migration of hypocentre due to fluid diffusion is the primary mechanism for triggering earthquake swarms in this region. Analyzing the depth distribution of events within each cluster allows measuring the depth to horizontal movement. We are also suggesting that the majority of swarm sequences in the Andaman and Nicobar Islands region are associated with magmatic origin.
Nicobar Islands Region tend to migrate from the northeast to the southwest.

References


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