Seismotectonics of Lower Assam, Northeast India, Using the Data of a Dense Microseismic Network

by A. Serpetsidaki, N. K. Verma, G.-A. Tselentis, N. Martakis, K. Polychronopoulou, and P. Petrou

Abstract Northeast India has been subjected to extensive compressional forces, mainly in north–south and east–west directions resulting from the convergence of the Indian plate with the Eurasian and Burmese plates, respectively. The area is characterized as one of the most seismically active regions of the world; however, the lower Assam valley’s microseismicity has not been monitored and studied intensively by a dense seismic network during the past. During this study, a seismic network of 76 stations was deployed in northeastern India for one year. Hundreds of microearthquakes were recorded. The most accurately located events, moment tensor solutions, and focal mechanisms were used in order to define the seismotectonic and stress regime in the area.

Introduction

The study area lies in Assam, northeast India, which is the easternmost projection of the Indian plate. In northeast India, convergence occurs between the following three major plates: India, Eurasia, and Sunda. These major plates interact along the following two convergent boundaries: the Himalayas and the Indo-Burma ranges, which merge in the upper Assam valley, forming the Assam Synaxis (Angelier and Baruah, 2009). The lower Assam valley, where the research has taken place, extends to the south of the Shillong plateau and the Mikir hills and is confined to the east by the Indo-Burmese trench. The valley includes the Barak river (Surma) and the northeast (NE) extremity of the Surma basin, which continues into Bangladesh and down to the Bay of Bengal (Fig. 1).

The entire area has evolved during Mesozoic to Tertiary time. Along with the mountain building in the Himalayan arc to the north and the Indo-Burmese arc to the east, large scale vertical movement has taken place, resulting in the uplift of the Shillong plateau in Assam during Tertiary times (Krishnan, 1960). The Assam valley consists of crystalline rocks, which are partly covered by gently dipping Tertiary and younger sediments (Kayal and Zhao, 1998).

The seismotectonic regime of northeast India is summarized as south-directed overthrusting from the north and northwest-directed overthrusting from the southeast (Mukhopadhyay and Das Gupta, 1988). To the north, the Indian plate is gently dipping beneath the Himalayas (Zhao et al., 1993). The present-day compression is approximately north–south (N–S), as indicated by focal mechanism solutions and analyses of borehole breakouts (Gowd et al., 1992). To the east, the Indian plate is plugging eastwards below the Burmese arc, which constitutes a fold and thrust belt, with west-verging thrusts (Mukhopadhyay and Das Gupta, 1988). The lower Assam valley is confined to the east and southeast (SE) by the fold belt, which is comprised of long, linear N–S trending anticlines separated by broad synclinal troughs (Angelier and Baruah, 2009).

The most prominent structures in the study area are as follows: the Dauki fault and its extensions, the Srikona thrust, and the Kaladan fault (Fig. 2). The Dauki fault is east–west (E–W) trending and separates the Shillong plateau to the north and the Bengal basin to the South; it is a Miocene, dextral strike-slip fault, which meets the Halflong thrust to the east (Rastogi et al., 1973). Toward the north-northeast (NNE), the Halflong meets the Naga thrust, which is a zone of complex thrust faults (Evans, 1964). The Kaladan fault marks the eastern boundary of Tripura folded belt, trends northeast–southwest (NE–SW), and is characterized as a right-lateral strike-slip fault (Maurin and Rangin, 2009). The Srikona thrust is an out-of-syncline forethrust associated with continued Late Miocene E–W compression (Mishra et al., 2006). The Silchar fault, south of the Dauki fault, is an E–W transverse fault with lateral movement, which indicates a southward shift (Das et al., 1995); Angelier and Baruah (2009) suggested that N–S to NE–SW trending transverse faults are also important structures in the region. The Sylhet fault is a normal active fault dipping to the southeast (Rastogi et al., 1973). Normal faulting in the area represents an extensional character of crustal movements and may be caused by tension in the upper surface of the plate as it bends beneath the arc (Isacks et al., 1968).

Northeast India is one of the most seismically active regions of the world (Fig. 1; Kayal and De, 1991), which is believed to be due to its complex geologic and tectonic
structure (Goswami and Sarmah, 1982). The seismotectonic activity of the area was highlighted by two great $M_S \sim 8.7$ earthquakes: the 1897 Shillong plateau and the 1950 Assam earthquakes (Molnar, 1990), but microearthquake surveys were made in some parts of the region. Khattri et al. (1983) made a survey in the upper Assam gap area and Kharshing et al. (1986) and Kayal (1987) reported the microseismicity of the Shillong area, whereas Kayal and De (1991) studied the microseismicity beneath the Shillong plateau and Mikir hills areas.

Earthquakes in the Shillong plateau and the Assam Syn-taxis area are numerous (Kayal and De, 1991) but the Assam valley shows low-level seismicity compared to other regions of northeast India. During a seismicity study of the Shillong plateau and Mikir hills, Khattri et al. (1983) recorded high seismicity in the Kopili valley, which formed a northwest (NW) trending zone between the Shillong and Mikir areas. They also recorded epicenters along the prominent Dauki fault zone, demarcating the southern edge of the Shillong plateau. In this study the upper Assam, NE of Mikir hills, was characterized as a seismic gap because it was almost free from seismic activity. The Bengal basin is also characterized by less seismic activity (Kayal and De, 1991).

As far as the lower Assam valley is concerned, Kayal and De (1991) postulated that low seismic activity in Assam may be due to poor coverage of the national seismological network in the area. Moreover, Kayal et al. (2012) mentioned that the seismic network is poor due to thick Brahmaputra river sediments and indicated the need for more seismic stations in the lower Assam valley in order to monitor accurately the seismicity.

During the present investigation, a two-phase temporary network was installed and recorded the microearthquake seismic activity of the area. Selected data were used for moment-tensor and focal-mechanism calculations and, finally, stress-regime estimation. In this paper we focus on the lower Assam valley and we attempt to clarify the prevailing seismotectonic regime by combining our results with the tectonic structures known from previous studies.

### Network Data

The investigation was performed in two phases. First, in order to assess the seismicity of the area, 36 stations were installed and operated for three months. Based on the preliminary-phase observations, a denser network of the same dimensions was deployed in order to ensure the best possible coverage of the area. Thus, 40 stations were additionally installed, which operated for nine more months.

Out of the 76 stations of the network, 6 stations were equipped with Trillium-T40 three-component broadband sensors and 70 were equipped with Seismotech-S100 three-component wideband (0.2–96 Hz) sensors (Fig. 2). Based on the fact that the network area is mostly located on the top of alluvial deposits, the short period sensors were installed at depths between 6 and 10 m, in order to have an appropriate signal-to-noise ratio. The Trillium-T40 BB sensors were installed within a semiburied vault. All stations were equipped with Seismotech SR-24, 24-bit, 3-channel recorders. The recording was continuous with a sampling frequency of 100 Hz.

The 1D model that was used is presented in Table 1. It is a modified model of an initial regional model by Bhattacharya et al., 2005. This detailed, local model was derived from data (well logs and well stratigraphy) from two local wells as well as a vertical seismic profile test. Information was provided by the National Oil and Gas company (ONGC). The initial $V_P/V_S$ ratio was set to 1.72 based on Wadati diagrams estimations.
During the first phase, 116 events were located, whereas during the second phase 276 microseismic events were located (Fig. 2). Ninety percent of the 392 located events were situated within the area covered by the microseismic network. Most of the events were located by 10–40 picks (P- and S-wave arrivals). The mean root mean square (rms) was calculated as 0.15 s, the mean horizontal error was 0.8 km and the mean vertical error was 1 km. The majority of the events were weak with a duration magnitude ranging from M 0 to M 3.1. Most of the seismic events were shallow, at depths < 15 km, with a large number of the hypocenters concentrated at depths between 7 and 15 km. Fewer hypocenters were located below 17 km.

A special program was developed, based on the short term average/long term average algorithm (Korn and Korn, 1968), in order to identify events and merge event files automatically. Next, the selected events from all the stations were crosschecked and triggered as events when detected in more than six stations. Finally, P- and S-wave arrivals have been manually picked using the SeismWin software package (Xanalatos and Tselentis, 1997). HYPO71PC (Lee and Lahr, 1975; Lee and Valdes, 1985) was used to initially locate the events.

### Method

#### Relocation

In order to improve the initial locations of the hypocenters, which were calculated using HYPO71PC, the earthquakes were relocated. Based on the detailed local model (Table 1), the whole sequence was relocated using HYPODD, which is useful for relocation of small magnitude earthquakes. The HYPODD algorithm determines relative locations within clusters using the double-difference algorithm developed by Waldhauser and Ellsworth (2000). The program attempts to improve relative location accuracy by removing from the initial location effects due to unmodeled velocity structures. Relocation minimizes the residual travel errors by reducing the arrival-time reading errors between event pairs.

#### Table 1

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>(V_p) (km/s)</th>
<th>(V_p/V_s)</th>
</tr>
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<tr>
<td>8</td>
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</tr>
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</tr>
<tr>
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<td>2.82</td>
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<tr>
<td>50</td>
<td>8.10</td>
<td>3.18</td>
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</table>

The HYPODD final results show a mean rms of 0.02 s and a mean \(x, y, z, t\) formal inaccuracy of 110 m, 120 m, 120 m, and 27 ms, respectively. The HYPODD relocation epicenters formed a major cluster and several smaller clusters. The major cluster contains 77% of the relocated events and shows a spatial pattern (Fig. 3a) that is more compact compared to the HYPO71 solution (Fig. 2). The smaller clusters include less than 15 events each, and they also appear shifted to a denser scheme. The basis of this stage is the possibility that accurate relative event locations in a few clusters can illuminate the seismogenic faults.

The relocated events appear in Figure 3a, whereas Figure 3b and 3c show the cross sections along the N–S and west–east (W–E) directions, respectively. The distribution of the relocated events in the cross sections shows that the seismic activity mainly occurs in depths up to 10–12 km. The picture suggests that the deeper seismic activity is distributed in a different scheme than the shallow one, which indicates that shallow events are connected with smaller mapped faults, whereas the deeper events can be attributed to major thrust of the area. From north to south (Fig. 3b) the events of larger hypocentral depth are dipping to the south (dotted lines). The west-to-east cross section (Fig. 3c) shows a complicated distribution of the shallow events but some concentrations still seem to indicate small faults dipping steeply towards the west or east. The deeper events show a general dip toward the east.

#### Focal Mechanism

The fault-plane solutions were determined using the FPFIT program (Reasenberg and Oppenheimer, 1985) with the events’ azimuth and angle of incidence computed during the relocation. For each fault-plane solution, FPFIT calculates several uncertainty indexes to characterize the quality of the final solution. Main indexes are the norm misfit function \(F_j = 0.0\) represents a perfect fit and the station distribution ratio, which varies between a value of 0 and 1 \((0.0 \leq \text{STDR} \leq 1.0)\). When STDR is low \((\text{STDR} < 0.5)\) a relatively large number of data lie near nodal planes in the solution. Such a solution is less robust than one for which \(\text{STDR} > 0.5\). The perturbations in strike, dip, and rake...
(ΔSTR, ΔDIP, ΔRAK) of the final solution should be less than 20° (Reasenberg and Oppenheimer, 1985).

Out of the 392 events, more than 300, located using 10 or more P-wave first arrivals, were used as input to FPFIT. Only unique solutions were selected, resulting in a dataset of 168 reliable fault-plane solutions and well-constrained nodal planes with mean misfit function $F_j = 0.19$, mean STDR = 0.7, and errors in strike, dip, and rake (ΔSTR, ΔDIP, ΔRAK) less than 10°. The computed fault-plane solutions were used for stress-tensor inversion using the method of Gephart and Forsyth (Gephart and Forsyth, 1984; Gephart, 1990).

The results are presented in Figure 4. The majority of the focal mechanisms indicate thrust- and strike-slip faulting. The thrust focal mechanisms show mainly N–S to north-northeast–south-southwest (NNE–SSW) direction. The strike-slip focal mechanisms indicate NE–SW and NW–SE directions of faults. Small shallow faults are also indicated in the eastern part of the study area and in the central-to-western part.

Figure 3. (a) Distribution of the relocated with HYPODD events. (b) Distribution of the relocated events in the cross section NS (north to south direction). Dotted lines show hypothetical fault lines. (c) Distribution of the relocated events in the cross section WE (west to east direction). Focal mechanism solutions are included. Dotted lines show hypothetical fault lines. The color version of this figure is available only in the electronic edition.

Figure 4. Map of the unique fault-plane solutions (lower hemisphere projection, compressive quadrant shaded) calculated with FPFIT and moment-tensor solutions (large beach ball black shaded quadrants). The color version of this figure is available only in the electronic edition.
Moment Tensor

The moment-tensor (MT) inversion was performed by the so-called iterative deconvolution of Kikuchi and Kanamori (1991), modified for regional distances and newly encoded by Zahradnik et al. (2005). Complete waveforms are used, without separation of individual phases; full-wave Green functions are calculated by the discrete wavenumber method in a 1D velocity model. As the present study involves weak events, we focused on the case of single-source and deviatoric inversion (no volume change). Following a common deviatoric tensor decomposition approach, the double-couple (DC) part and the compensated linear vector dipole part—as the non-double-couple (non-DC) component—were determined. The results are expressed in terms of the double-couple component of the deviatoric solution, represented by the scalar moment, strike, dip, and rake.

The MT calculation was performed using the crustal model of Table 1 and the frequency range 0.6–2.0 Hz. Those are the lowest frequencies with satisfactory signal-to-noise ratio for such weak events ($M_w < 2$). The low frequencies are preferred because in this case the modeling is less dependent on the inherently incomplete knowledge of the crustal structure.

The variance reduction, which represents the synthetic-observed waveforms fit for a moment-tensor solution, is acceptable when it is positive. The total variance reduction is considered to indicate a good fit when it is larger than 40% (Fig. 5). In order to achieve the best fit and a more reliable solution, we selected the larger and shallower events, recorded in closer epicentral distances from the stations. The waveforms depicting a poor fit were excluded from the calculations in order to determine the finest solution possible. Table 2 presents in detail the MT solutions, which were calculated using the ISOLA platform (Sokos and Zahradnik, 2007).

Figure 4 shows the results of the MT solutions (large beach ball, black colored compression quadrants). The MT solutions indicate that the main types of faulting in the area are thrust and strike slip, which is in agreement with previous studies as well as the focal mechanisms calculated in this study. The thrust directions indicated by the MT solutions are N–S to NNE–SSW. Moment tensor attributed to the major thrusts of W–E direction was not calculated because the events attributed to them were not large enough or in depths shallower than 10 km. The moment tensors, which indicate strike-slip faulting, show two directions, NE–SW and NW–SE, that can both exist in the area.

Stress Tensor

The Gephart and Forsyth (1984) method has been applied in order to calculate stress orientations from earthquake

![Figure 5. Example of synthetic and observed waveform fitting during moment tensor calculation. The color version of this figure is available only in the electronic edition.](image-url)
assumed that the deviatoric stress tensor is uniform over a certain region and over the time interval considered. Moreover, the method assumes that earthquakes are shear dislocations on pre-existing faults and that slip occurs in the direction of the resolved shear stress on the fault plane (Gephart, 1990).

Using the most accurate data, 168 well-constrained focal mechanisms were computed. The stress inversion was carried out using the Zmap software (Wiemer and Zuniga, 1994) in order to calculate the directions of the principal stress axes $\sigma_1$, $\sigma_2$, $\sigma_3$ ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) and the shape factor $R$ ($R = (\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$), which indicates the magnitude of $\sigma_2$ relative to $\sigma_1$ and $\sigma_3$. The best-fitting stress is achieved when the misfit between the values computed from the stress tensor and the observed fault plane and slip direction reach a minimum on each plane of the focal mechanism (Gephart and Forsyth, 1984). This misfit is calculated through a grid search, systematically varying the orientation of the principal stresses and the parameter $R$. The stress tensor that corresponds to the minimum average rotation angle is assumed to be the best stress tensor for the specific population of focal mechanisms (Kiratzi, 1999).

The events are distributed in depths varying from 1 to 35 km and many events are concentrated at shallow depths. The first attempt at stress analysis was deployed for the whole study area, modifying the depth of analysis. We investigated in detail the upper 10 km, as a large amount of events are located within this part. The analysis results are presented in Figure 6. The investigation of stress regime in the upper 5 km shows a normal type of faulting with NNE–SSW direction. This is also apparent in Figure 4 where most of the focal mechanisms in depths up to 5 km indicate normal faulting. The results at depths between 5 and 10 km were not sufficient. The final outcome was characterized as unknown, which suggests a complex setting of several fault types coexisting in this depth range. The results for events located deeper than 10 km are very precise and constant up to 40 km; the faulting type is thrust, obviously associated with the major thrusts of the area.

The stress-tensor analysis confirms a complex tectonic stress field where normal thrust and strike-slip faulting occur in nearby areas, which is indicated by the focal mechanisms in Figure 4. Consequently, the technique was applied to parts of the study area according to the spatial distribution of the seismic events (Fig. 7). Four areas were defined within the study area: (a) the northern part of the study area (N); (b) the southern part of deeper events, which was subdivided to the southwestern (SW) part, the south-central (SC) part, and the southeastern (SE) part.

The N part of the area (Fig. 7) contains a large portion of seismicity that is mainly shallow. The stress indicates strike-slip faulting, which is associated with the small transfer faults of approximately N–S direction mapped to the northern part of the study area. The SW area also shows strike-slip faulting with a different direction (Fig. 7); this NE–SW faulting can be associated with the existence of small strike-slip faults located to the west. In the SC part, thrust faulting dominates the area. The stress direction is NNE–SSW (Fig. 7), indicating thrust faulting in an approximately W–E direction. Further to the east, the SE area is dominated by thrust-type faulting of NE–SW direction.

### Discussion and Results

The study area is located in lower Assam, to the SSE of the Shillong plateau. The region has been subjected to extensive compressional forces, mainly in N–S and E–W directions resulting from the convergence of the Indian plate with the Eurasian and Burmese plates, respectively. This type of plate tectonism has been responsible for the formation of significant faults, and the area is crisscrossed by several fractures (Das et al., 1995). In this study the microseismicity of the lower Assam valley was investigated by a microearthquake network, which operated for 12 months.

Because the seismic activity in the Shillong plateau and Assam is categorized as intraplate seismicity the occurrence

### Table 2

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<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Depth (km)</th>
<th>$M_w$</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake</th>
<th>Mo (N·m)</th>
<th>Variance Reduction (%)</th>
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Frequency band (Hz): 0.7–1.8 (tapered 0.6–0.7 and 1.8–1.9)
of shallow events (~10 km) is expected; moreover, the microseismicity study of Kayal and De (1991) reveals intense crustal (10–40 km) seismicity in the area. Our results show that the area is seismically active and the distribution of the relocated microearthquakes indicates that the main seismic activity is concentrated in depths up to 10 km, whereas several hypocenters were located in depths up to 45 km.

The shallow seismicity shows complicated distribution and subvertical dip. Although it is difficult to correlate the epicenters of the events with individual faults, locally in the northern and eastern parts of the study area some concentrations seem to be related to small faults. The events are clustered in the vicinity of NE–SW to NNE–SSW or NW–SE mapped faults and can be linked to these faults. The cross sections suggest that the hypocenters are distributed within layers that are dipping steeply westward or eastward.

The deeper seismic events, up to 45 km, indicate larger surfaces dipping to the east and to the south. More specifically, the N–S hypocentral distribution reveals a south-dipping plane that extends up to 35 km depth. The distribution of these events appears to represent the major thrust directions like the Halflong thrust (dipping to the south) and the Shrikona thrust (dipping to the east). The dip of both faults, as it is pictured in the cross section, corresponds with previous studies concerning these faults like Alam et al. (2003), Uddin and Lundberg (1998), and Bhattacharya et al., 2005). The shallow events can be attributed to the small faults, which appear in the northern part of the study area.

The focal-mechanism analysis show normal, thrust, and strike-slip types of faulting. The strike-slip types are mainly concentrated to the north, principally in depths shallower than 30 km. The focal mechanisms, which indicate thrust type of faulting mainly, appear in depths larger than 15 km up to 40 km. The thrust faulting represents the main compression in which the area has been subjected, whereas the strike-slip focal mechanism designates the transverse faults, which cross the major structures of the area. The moment-tensor analysis also showed that thrust- and strike-slip faulting dominates the area.

The normal focal mechanisms are clustered in shallow depths indicating a west-northwest–east-southeast (WNW–ESE) direction normal fault. This small fault is located to the north of the large normal Silchar fault. The stress analysis showed that in shallow depths up to 4 km the predominant faulting type is the normal faulting with extension directing NE–SW. Normal faulting has also been identified in the broader area in previous studies. To the west of the study

Figure 6. Vertical distribution of the stress-tensor solutions. The color version of this figure is available only in the electronic edition.

Figure 7. Stress-inversion results distributed in the study area. The stress regime is indicated by arrows (stress direction). The color version of this figure is available only in the electronic edition.
northern part of the study area indicates strike-slip faulting, thrust- and strike-slip faulting occurs in nearby areas. The analysis confirms a complex tectonic stress field where suggested thrust faulting in an approximately W–E direction, pointing towards the Assam-Bengal foredeep (Alam et al., 2003).

In agreement with the focal mechanism, the stress-tensor analysis confirms a complex tectonic stress field where thrust- and strike-slip faulting occurs in nearby areas. The northern part of the study area indicates strike-slip faulting, which is associated with the small transfer faults of approximately N–S direction. The western part of the study area is also characterized by strike-slip faulting. In this part, the suggested faulting is NE–SW direction, indicating association with the Kaladan strike-slip fault and minor faults to the west.

The thrust faulting is confirmed by the stress analysis dominating the central and eastern parts of the study area. In the central part, the stress direction is NNE–SSW, suggesting thrust faulting in an approximately W–E direction, which can be attributed to the major thrusts of the area to the north. Moreover, the thrust faulting suggested for the eastern part is of ENE–WSW direction, indicating a thrust-like Shrikona thrust.

The NNE–SSW compression is related to the N–S convergence between India and Eurasia. The WNW–ESE compression is related to the convergence of the area and the Indo-Burma ranges. The NE–SW extension in the surface layers can be explained as dilation as the underlying block is retracting and the subducting plate is bending upward.

The seismicity distribution, focal mechanism, and stress analysis focus in a small area of lower Assam; thus, the results may differ slightly from the general regime of the entire northeastern India. Notwithstanding, the results represent the major forces to which the area has been subjected resulting from south-directed overthrusting from the north due to collision tectonics at the Himalayan arc and northwest-directed overthrusting from the southeast due to subduction tectonics at the Burmese arc.

Data and Resources

The seismological data used in this study were collected during a Passive Seismic Tomography project by Oil and Natural Gas Corp. (ONGC) Ltd. Seismicity catalog data were obtained from the U.S. Geological Survey (USGS) National Earthquake Information Center, World Data Center A for Seismology, http://earthquake.usgs.gov/regional/neic/ (last accessed December 2012). The maps were produced using the Generic Map Tools (GMT, http://gmt.soest.hawaii.edu, last accessed January 2012; Wessel and Smith, 1998).

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