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RESEARCH PAPER

Scaling relations of moment magnitude, local magnitude, and duration magnitude for earthquakes originated in northeast India

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Abstract In this study, we aim to improve the scaling between the moment magnitude (M_W), local magnitude (M_L), and the duration magnitude (M_D) for 162 earthquakes in Shillong-Mikir plateau and its adjoining region of northeast India by extending the M_W estimates to lower magnitude earthquakes using spectral analysis of P-waves from vertical component seismograms. The M_W-M_L and M_W-M_D relationships are determined by linear regression analysis. It is found that, M_W values can be considered consistent with M_L and M_D, within 0.1 and 0.2 magnitude units respectively, in 90 % of the cases. The scaling relationships investigated comply well with similar relationships in other regions in the world and in other seismogenic areas in the northeast India region.

Keywords Local magnitude · Moment magnitude · Duration magnitude · Shillong-Mikir plateau

1 Introduction

The earthquake magnitude is regarded as the most directly measurable and simple parameter to specify quantitatively the size of an earthquake. The Richter local magnitude M_L scale (Richter 1935) for an earthquake is still widely used in different parts of the world. Following Richter, multitude of magnitude scales, each defined in terms of amplitudes recorded on a particular type of seismograph (i.e., over a particular limited spectral band) have been introduced.

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From the study of source mechanism by an elastic dislocation theory, Aki (1966, 1967) stated that the amplitude of a very long-period wave is proportional to the seismic moment, M_0, of an earthquake. Aki (1966) first measured the value of M_0 of the 1964 Niigata, Japan, earthquake. Ben-Menahem et al. (1969) also suggested that the far-field static-strain field is proportional to M_0. From then on, seismic moment was considered as a new parameter to specify the size of an earthquake. Based on M_0, moment magnitude M_W has been defined by Hanks and Kanamori (1979). The moment magnitude scale (M_W), as defined by Kanamori (1977), has an advantage of not getting saturated for larger earthquakes, unlike the Richter amplitude-based scales (e.g., Hanks and Kanamori 1979; Howell 1981; Ottemoller and Havskov 2003). This enables the wide acceptance of M_W as a stable scale, for larger as well as small to moderate magnitude earthquakes (Lay and Wallace 1995).

The magnitude by definition quantifies the energy radiated over a particular fixed frequency band, M_0 is estimated seismically from the amplitude of far-field "long-period" seismic radiation (Aki 1966). Because the frequency distribution of radiated seismic energy changes with earthquake size (e.g., Aki 1967), magnitude scales suffer severe intrinsic limitations, such as saturation (Kanamori 1977; Hanks and Kanamori 1979; Hutton and Boore 1987) and discrepancies between the scales (Gutenberg and Richter 1956). Since the moment can be estimated from the recording of all suitable seismographs, the only limitation for M_0 is the difficulty in locating and properly processing on scale recording from seismograph with adequate long-period response.

Estimating the duration magnitude (M_D) from signal duration is an empirical relation between the magnitudes of the earthquake and the duration of its recorded signal. This correlation has been consistently observed in different parts of the world. Lee et al. (1972) established an empirical formula for estimating the magnitude of local earthquakes using signal durations. A partially satisfactory theoretical basis for this correlation has been sought in terms of the properties of coda waves (Suteau and Whitcomb 1979; Lee and Stewart 1981). Castello et al. (2007), Sitaram and Bora (2007), and Al-Arifi and Al-Humidan (2012) derived an empirical relationship between the total signal duration of local earthquakes and magnitude for the area in Italy, NW Saudi Arabia, and northeast India, respectively.

Conversion of magnitude scales for small earthquakes plays an important role for seismic hazard calculations. Several studies have been made to examine region-specific relation between M_W and M_L (Ristau et al. 2003). Although the size of the events occurring in northeast India region is designated by M_L in The India Meteorological Department (IMD) catalog, its consistency with moment magnitude (M_W) is not examined or reported. Sitaram and Bora (2007) reported an empirical relation between M_L and M_D for northeast India and they observed that M_L starts to saturate above magnitude 6.5. Recently Baruah et al. (2012) examined relationship between M_W and M_L for the northeastern region of India and they observed with a magnitude discrepancy 0.04 units.

In this paper, we aim to improve the scaling between M_W and M_L, M_W and M_D, M_0 and M_L, and M_0 and M_D for 162 earthquakes in Shillong-Mikir plateau and its adjoining region of northeast India by extending the M_W estimates to lower magnitudes using the spectral analysis of P-waves from vertical component seismograms. We attempt to obtain the frequency-independent, long-period spectral level Ω_0 below the corner frequency of a displacement spectrum (Brune 1970, 1971). The long-period spectral amplitude of the source spectrum can be related to M_0 (Brune 1970), from which M_W can be computed (Hanks and Kanamori 1979).

2 Tectonic setting

The northeastern region (NER) (see Fig. 1) of India is one of the most complex tectonic domain in the world which is manifested by the ongoing India-Asia collision to the north and Indo-Burmese subduction to the east (Bilham and England 2001; Kayal et al. 2012). During the last ~ 118 years since 1897, the region has experienced 20 large ($M \geq 7.0$) and two great earthquakes ($M \geq 8.5$); one on 12 June, 1897 (Oldham 1899) and the other on 15 August, 1950 (Tandon 1954). It may be mentioned that the 1897 great earthquake is the first instrumentally recorded event in India.

The NER, India comprises distinct geological units, like the Himalayan frontal arc to the north, the highly folded Indo-Myanmar mountain ranges or Burmese arc to the east, the Brahmaputra river alluvium in the Assam valley and the Shillong-Mikir plateau is sandwiched between these two arcs, and thick sediments of the Bengal basin to the south. Seismotectonics of the region has been the subject of several studies (e.g., Tapponnier et al. 1982; Kayal and De 1991; Kayal 2001, 2008; Nandy 2001). Bilham and England (2001), on the basis of geodetic and GPS data, interpreted the Shillong plateau as a pop-up structure bounded by two reverse faults and argued that the 1897 great earthquake was produced by a south dipping hidden fault at the northern boundary of the Shillong plateau, which they named Oldham fault, that extends from a depth of about 9 km down to 45 km. They further suggested that the Shillong plateau earthquakes are caused by the deformation of this pop-up structure between the Dauki fault and the Oldham fault (Fig. 1). The northwest-southeast trending Kopili fault separates the Shillong plateau from its fragment part, Mikir Hills. The Assam valley is an ENE-WSW trending narrow valley, which lies between Shillong plateau and the eastern Himalayan tectonic domains. Recent seismicity and tectonics of the region have been reviewed by Kayal et al. (2008, 2012), Baruah et al. (2011), and Bora and Baruah (2012), Bora et al. (2013); Bora et al. (2014). Prominent geological units of the northeastern region of India, however, remain geophysically less studied due to inaccessibility of the terrain.

3 Database

In this study, we use 162 best located earthquakes in the period from 2001 to 2010 by a network of broadband seismic stations in the Shillong-Mikir Plateau and its adjoining region (Fig. 2). These stations are operated by different agencies/Universities viz. National Geophysical Research Institute (NGRI)—Hyderabad, North East Institute of Science and Technology (NEIST)—Jorhat, Indian Institute of Geomagnetism (IIG)—Mumbai, and Gauhati University (GU). The selected events have higher signal-to-noise ratio (SNR) and distinct direct P and S phases. All broadband seismic stations are operated both in continuous mode and trigger mode, and the seismograms are recorded at 100 samples per second. To avoid aliasing effect, low-pass filters with corner frequencies of 35 Hz were applied. The recorded seismograms have been corrected using instrumental response based on the electrodynamic constant, critical damping, natural frequency of seismometers, and bit weight of unit gain of each recording unit for all stations. Because all the stations are located on hard rock, the site effects are neglected. The station parameters are given in Table 1. The hypocentral parameters are located by the HYPOCENTER location program of Lienert et al. (1986) based on crustal velocity model of Bhattacharya et al. (2008) and Baruah et al. (2011). Uncertainties involved in the estimates of

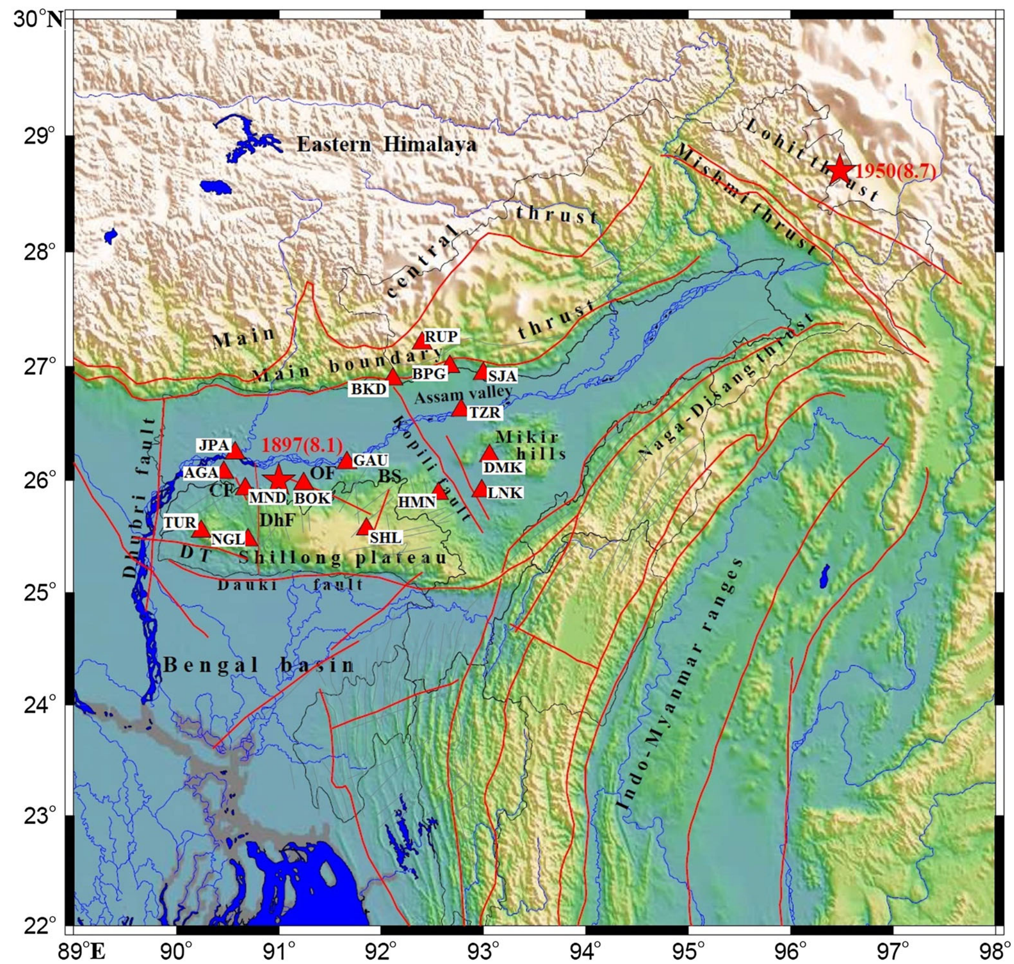

Fig. 1 Map showing the major tectonic features of the study region (modified from Kayal et al. 2012). The great earthquake of 12 June, 1897 and 15 August, 1950 is shown by a larger *red star*. The digital broadband seismic stations are shown by the *red triangles*. The major tectonic features in the region are indicated: Main Central Thrust, Main Boundary Thrust, Kopili Fault, Dauki Fault, *Dh F* Dudhnoi fault, *DT* Dapsi thrust, *OF* Oldham fault, *CF* Chedrang fault, *BS* Barapani shear zone. *Inset* Map of India indicating the study region

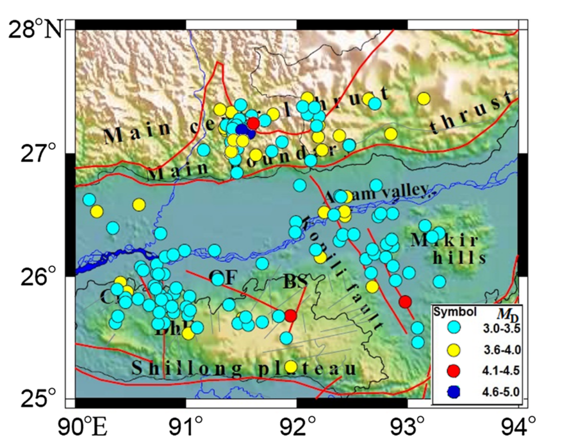

Fig. 2 Hypocentral distributions of 162 earthquakes used in this study. To the *right*, different magnitude ranges of the epicenters are defined. M_DA is the average duration magnitude

epicenters show that about 85 % of the events are located with an error of <2 km in depth and epicenter, and the error in origin times is of the order of 0.3 s. Duration magnitude (M_D) of these events are estimated in the range 3.0–4.96 (Lee et al. 1972; Sitaram and Bora 2007). The focal depth of the events are in the range from 5 to 44 km.

4 Theoretical consideration

Most earthquake source theories predict a far-field displacement spectrum that is constant at low frequencies and inversely proportional to some power of frequency at high frequencies (Haskel 1964; Savage 1966; Aki 1967; Brune 1970; Molnar et al. 1973). From a body wave spectra two quantities are obtained, the long-period spectral level, Ω_0, and the corner frequency, f_c.

Table 1 Station parameters along with abbreviations

No.	Name	Abbreviations	Latitude (°N)	Longitude (°E)	Elevation (m)
1	Jogighopa	JPA	26.239	90.575	42
2	Manikganj	MND	25.924	90.676	40
3	Nangalbibra	NGL	25.472	90.702	330
4	Gauhati University	GAU	26.152	91.667	69
5	Shillong	SHL	25.566	91.859	1590
6	Bhairabkunda	BKD	26.890	92.115	210
7	Rupa	RUP	27.203	92.401	1470
8	Seijusa	SJA	26.938	92.999	150
9	Tezpur	TZR	26.617	92.783	140
10	Dokmok	DMK	26.216	93.062	200
11	Bhalukpong	BPG	26.999	92.671	130
12	Hamren	HMN	25.880	92.560	520
13	Lanka	LNK	25.905	92.985	90
14	Agia	AGA	26.066	90.464	75
15	Tura	TUR	25.546	90.243	305
16	Boko	BOK	25.969	91.244	50

In agreement with the widely used theoretical models of seismic sources, the far-field displacement spectrum $\Omega(f)$ can be described by a one-corner frequency model

$$\Omega(f) = \frac{\Omega_0}{\left[1 + \left(f/f_c\right)^{\gamma n}\right]^{1/\gamma}}, \tag{1}$$

where Ω_0 is the low frequency spectral level, f_c is the corner frequency, n is the high frequency spectral fall-off, and γ is a constant. If $\gamma = 1$, Eq. (1) is the spectral shape proposed by Brune (1970).

The seismic moment (M_0) is estimated from the low frequency level (Ω_0) through the relation (Keilis-Borok 1959)

$$M_0 = 4\pi\rho v_P^3 R \frac{\Omega_0}{R_{\theta\phi}}, \tag{2}$$

where $\rho = 2700$ kg/m^3 is the average crustal density of the study area, "v_P" is the average P-wave velocity as a function of depth (Bhattacharya et al. 2008; Baruah et al. 2011; Bora et al. 2014), R is the source-to-receiver distance and $R_{\theta\phi}$ is accounted for the radiation pattern of P-waves. The root mean square averages of radiation pattern coefficient $R_{\theta\phi} = 0.52$ is used for all the events in accordance with Boore and Boatwright (1984). Since the data utilized correspond to small earthquakes, the solution for the fault plane may not be unique, either by the first impulses technique or by calculating the moment tensor. As a result the use of average value is adequate since the stations have good azimuthal coverage. An average seismic moment $<M_0>$ was determined from the average of the logarithmic values obtained at different stations, as proposed by Archuleta et al. (1982), following the equation

$$< M_0 > \; = \text{anti}\log\left[\frac{1}{N}\sum_{i=1}^{N}\log M_{0_i}\right], \tag{3}$$

where N is the number of stations used, and M_0 is the seismic moment determined from Eq. (2) for the ith record.

The obtained seismic moments (M_0) were used to estimate the moment magnitude (M_W) using Hanks and Kanamori (1979) relationship:

$$M_W = \left(\frac{\log M_0}{1.5}\right) - 6.03, \tag{4a}$$

where M_0 is in (N·m). Hanks and Kanamori (1979) showed that moment magnitude M_W is equivalent to the local magnitude M_L. M_W is not generally considered as the primary magnitude in earthquake catalogs and knowing how other magnitudes relate to M_W in a particular region is a topic of great interest because of seismic hazard estimation.

In order to obtain empirical relations for the determination of duration magnitude (M_D) for a given station is usually given in the form, according to Lee and Stewart (1981),

$$M_D = C_0 + C_1 \ln D_s + C_2 D + C_3 h, \tag{4b}$$

where D_s is signal duration in s, D is epicentral distance in km, h is focal depth in km and C_0, C_1, C_2, and C_3 are empirical constants. These constants usually are determined by correlating signal duration with Richter magnitude for a set of selected earthquakes taking epicentral distance and focal depth into account. Duration magnitude is computed for each station and the average of the station magnitudes is taken to be the network duration magnitude (M_DA) which is basically used in this study.

An empirical relation between M_L and M_D is reported by Sitaram and Bora (2007) for NER India, which is given by

$$M_D = (1.05 \pm 0.01)M_L + (-0.17 \pm 0.05). \quad (5)$$

Further the M_L is computed using the Eq. (5). Although the size of the events occurring in northeast India region is designated by M_L in the Shillong catalog of the India Meteorological Division (IMD), its consistency with moment magnitude (M_W) is not examined or reported.

5 Data analysis

The first step of the data processing was the selection of time windows for which P-wave spectra has to be computed. The selected spectra were filtered between 1 and 20 Hz using a four-pole band-pass Butterworth filter after correcting them for their individual baseline effect. The Fast Fourier Transform (FFT) of the P-wave signal was calculated using the vertical component of the ground motion. The P-wave spectra at each window was computed on a 1.28 s long (128 samples) starting from the P-onset, in order to avoid contamination from the S-phase. The time windows were tapered with a 10 % cosine taper at the beginning and end of the series to minimize the spectral energy leakage. Moreover, to avoid near-field effects and to fulfill the point-source approximation, only the stations having epicentral distances greater than 10 km were taken into account (Bora et al. 2013).

The spectral parameters are estimated by fitting every P-wave displacement spectrum with the theoretical general model for displacement spectra as expressed by Eq. (1). To avoid potential biases due to inspection by eye, an iterative non-linear best fitting search algorithm is used to minimize the difference between the theoretical and observed displacement spectra. The waveform analysis tool in seismology seismographer by Abdelwahed (2011) is used to estimate the spectral parameters. In this method of spectral fitting the marquard linearized least-square method is used to solve the non-linear problems (Press 1989). The method is able to fit the spectra efficiently without a trade off between the corner frequency and flat part. To secure the stability of our estimations, we performed different tests on a sample of spectra by varying the starting values of Ω_0, f_c, and n. It has been assumed that the amplitude source spectrum has the shape of Brune's model (1970). The best fits to the observed displacement spectra to the theoretical one at a number of stations are plotted in Figs. (3, 4, 5).

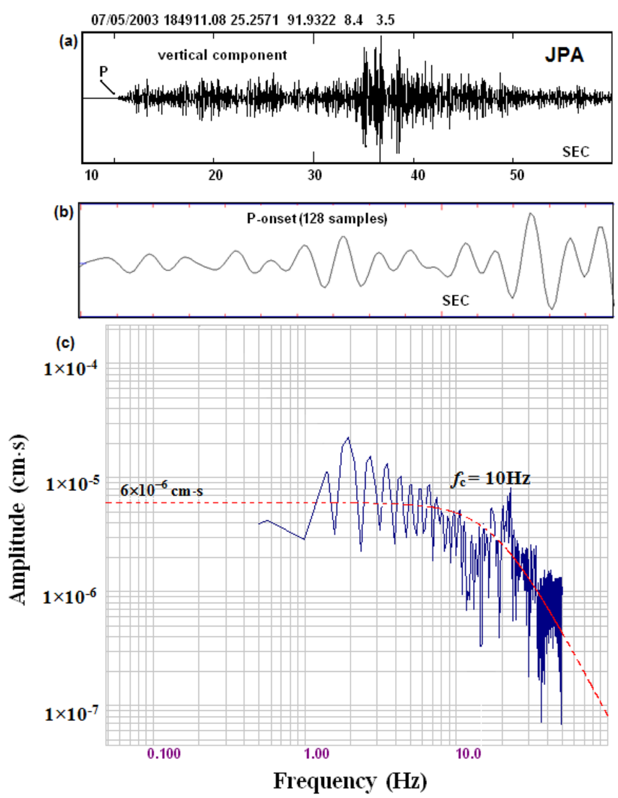

Fig. 3 **a** Example of vertical component instrument corrected seismogram recorded at JPA station. **b** P-onset (128 samples). **c** *Blue line* indicates the observed spectrum and the *red-dashed line* is its best fitting.

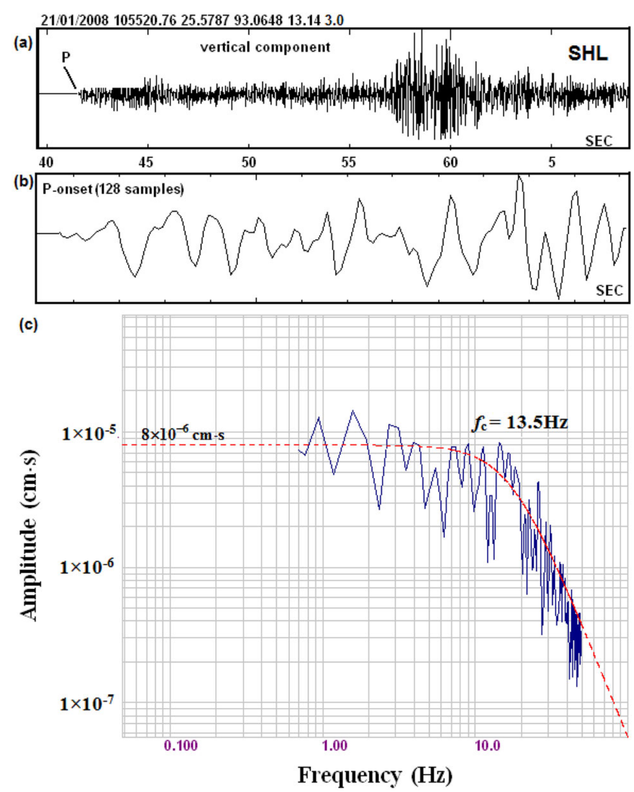

Fig. 4 **a** Example of vertical component instrument corrected seismogram recorded at SHL station. **b** P-onset (128 samples). **c** *Blue line* indicates the observed spectrum and the *red-dashed line* is its best fitting

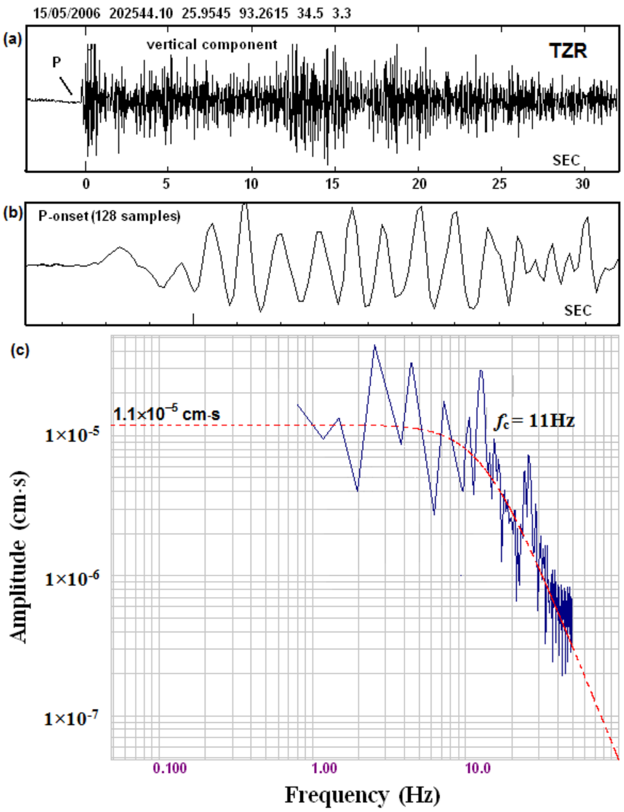

Fig. 5 a Example of vertical component instrument corrected seismogram recorded at TZR station. **b** P-onset (128 samples). **c** *Blue line* indicates the observed spectrum and the *red-dashed line* is its best fitting

6 Scaling relationships

In this study, the seismic moment (M_0) of 162 events are estimated for small to moderate earthquakes ($3.0 \leq M_D \leq 5.0$) originated in the Shillong-Mikir plateau and its adjoining region. The seismic moment ranges from 1.90×10^{13} to 2.00×10^{16} N m. The estimated seismic moment from this study was used to estimate the moment magnitude (M_W) using Eq. (4a). These results are summarized in Table 2. Hanks and Kanamori (1979) showed that the moment magnitude M_W is equivalent to the local magnitude M_L. In this study, the M_L is estimated using Eq. (5) and also the M_L value obtained from Shillong catalog of the IMD. We perform linear regressions for the scalar seismic moment M_0 versus M_L and M_D, respectively. The seismic moment M_0 versus M_L and M_D plots are shown in Fig. 6; the fits are well constrained by the regression line:

$$\log\,(M_0) = (1.46 \pm 0.07)\,M_L + (9.32 \pm 0.22) \quad r^2 = 0.76 \text{ and } \sigma = 0.25, \tag{6}$$

$$\log\,(M_0) = (1.39 \pm 0.06)\,M_D + (9.54 \pm 0.21) \quad r^2 = 0.76 \text{ and } \sigma = 0.25, \tag{7}$$

where r and σ are the correlation coefficient and standard error, respectively.

The dependency between M_W versus M_L and M_D are presented in Fig. 7 and the corresponding regression lines are given in Eqs. (8, 9)

Table 2 Hypocentral parameters and Seismic moment (M_0), Moment magnitude (M_W), Local Richter magnitude (M_L) of the earthquakes analyzed in this study

ID	Date (dd-mm-yy)	OT (hr:mm)	Lat. (°N)	Long. (°E)	Mag (M_DA)	Depth (km)	M_0 (N m)	M_W	M_L
1	13-11-2004	05:32	26.484	92.712	3.00	10.4	1.90E+13	2.82	3.02
2	15-12-2002	11:26	25.609	91.454	3.00	44.1	1.98E+13	2.83	3.02
3	21-09-2009	12:37	27.155	91.486	3.01	8.7	2.51E+13	2.90	3.03
4	03-01-2003	07:56	25.737	90.985	3.20	8.3	2.63E+13	2.92	3.21
5	05-12-2004	17:51	26.030	92.990	3.20	14.3	3.12E+13	2.97	3.21
6	01-01-2008	19:00	25.460	93.068	3.10	18.4	3.19E+13	2.97	3.11
7	14-07-2003	22:51	25.595	91.545	3.10	13.6	3.64E+13	3.01	3.11
8	02-09-2009	12:00	25.822	91.013	3.06	15.3	4.22E+13	3.05	3.08
9	18-02-2003	22:37	27.123	91.408	3.30	9.1	4.39E+13	3.06	3.30
10	21-01-2010	22:32	26.201	91.233	3.12	15.0	4.45E+13	3.07	3.13
11	22-08-2009	13:15	25.765	90.436	3.14	5.3	4.65E+13	3.08	3.15
12	18-11-2001	19:37	26.287	92.358	3.10	24.8	4.75E+13	3.09	3.11
13	25-08-2009	23:37	25.796	90.550	3.11	6.4	4.75E+13	3.09	3.12
14	26-07-2009	18:56	25.570	91.086	3.11	8.4	4.78E+13	3.09	3.12
15	12-11-2002	18:38	26.350	93.260	3.20	10.5	4.79E+13	3.09	3.21
16	28-09-2009	15:53	27.220	91.473	3.12	15.9	4.95E+13	3.10	3.13
17	01-10-2003	21:25	25.903	90.693	3.20	11.8	5.15E+13	3.11	3.21
18	21-09-2009	17:49	27.109	91.409	3.23	12.8	5.15E+13	3.11	3.24

Table 2 continued

ID	Date (dd-mm-yy)	OT (hr:mm)	Lat. (°N)	Long. (°E)	Mag (M_DA)	Depth (km)	M_0 (N m)	M_W	M_L
19	20-10-2009	04:57	26.008	90.713	3.03	19.8	5.22E+13	3.12	3.05
20	02-10-2003	17:37	25.650	90.370	3.30	24.4	5.43E+13	3.13	3.30
21	12-04-2003	13:10	26.330	90.743	3.40	18.3	5.87E+13	3.15	3.40
22	03-01-2010	12:13	26.055	90.566	3.06	10.2	6.02E+13	3.16	3.08
23	01-10-2009	17:32	27.207	91.469	3.03	10.1	6.20E+13	3.16	3.05
24	27-01-2003	17:23	25.967	92.867	3.00	4.9	6.22E+13	3.17	3.02
25	21-09-2009	19:25	27.032	91.429	3.02	13.3	6.22E+13	3.17	3.04
26	21-01-2005	23:54	26.196	90.962	3.30	11.5	6.22E+13	3.17	3.30
27	23-03-2010	16:24	26.594	90.089	3.00	19.6	6.52E+13	3.18	3.02
28	11-05-2003	22:08	26.000	90.780	3.40	9.1	7.48E+13	3.22	3.40
29	30-05-2003	22:42	25.880	90.710	3.40	9.0	7.48E+13	3.22	3.40
30	19-01-2010	23:51	25.595	90.733	3.39	20.0	7.75E+13	3.23	3.39
31	06-02-2005	16:49	26.354	91.957	3.40	26.5	7.75E+13	3.23	3.20*
32	21-09-2009	23:27	27.208	91.401	3.39	12.2	7.95E+13	3.24	3.39
33	21-01-2005	20:33	27.408	92.678	3.30	7.7	8.15E+13	3.24	3.30
34	26-12-2003	20:08	27.380	92.020	3.30	19.0	9.06E+13	3.27	3.30
35	29-09-2003	18:45	25.594	90.349	3.00	9.7	9.21E+13	3.28	3.02
36	09-06-2003	17:58	26.000	90.730	3.50	11.1	9.39E+13	3.29	3.50
37	19-01-2010	18:34	25.803	90.436	3.07	10.8	1.02E+14	3.31	3.09
38	09-11-2009	03:31	26.652	92.360	3.37	14.9	1.06E+14	3.32	3.37
39	02-03-2003	23:03	25.670	91.815	3.40	10.6	1.06E+14	3.32	3.40
40	21-09-2009	14:34	27.231	91.420	3.09	14.6	1.08E+14	3.33	3.10
41	21-09-2009	09:16	27.086	91.367	3.42	14.1	1.08E+14	3.33	3.42
42	28-12-2009	10:44	26.834	91.426	3.07	12.3	1.10E+14	3.33	3.09
43	01-12-2004	11:28	26.027	92.646	3.10	16.2	1.14E+14	3.34	3.11
44	07-05-2003	18:49	25.257	91.932	3.60	8.4	1.14E+14	3.34	3.59
45	21-09-2009	11:11	27.195	91.414	3.07	13.7	1.15E+14	3.34	3.09
46	29-12-2003	02:38	25.736	90.854	3.50	10.2	1.19E+14	3.35	3.50
47	21-01-2008	10:55	25.579	93.065	3.00	13.1	1.23E+14	3.36	3.02
48	18-12-2003	20:50	26.082	92.844	3.30	24.1	1.23E+14	3.36	3.30
49	21-09-2009	19:58	27.168	91.425	3.07	11.3	1.25E+14	3.37	3.09
50	26-09-2002	18:49	26.437	91.965	3.10	16.4	1.25E+14	3.37	3.11
51	21-09-2009	23:19	27.229	91.393	3.36	14.3	1.26E+14	3.37	3.36
52	12-09-2009	00:54	26.143	90.786	3.20	7.0	1.28E+14	3.37	3.21
53	31-12-2009	10:43	26.946	91.408	3.29	14.4	1.32E+14	3.38	3.30
54	07-11-2001	06:21	27.319	92.061	3.30	10.6	1.32E+14	3.38	3.30
55	08-03-2003	16:55	27.068	92.448	3.40	14.2	1.33E+14	3.39	3.40
56	21-09-2009	10:58	27.232	91.459	3.40	10.8	1.33E+14	3.39	3.40
57	08-03-2003	17:15	27.065	92.444	3.50	15.8	1.33E+14	3.39	3.50
58	26-08-2009	18:25	25.758	91.366	3.17	8.6	1.38E+14	3.40	3.18
59	03-09-2009	11:44	25.846	90.872	3.20	12.2	1.38E+14	3.40	3.21
60	23-01-2010	17:50	25.898	90.716	3.15	9.9	1.40E+14	3.40	3.16
61	21-09-2009	16:01	27.217	91.497	3.33	8.2	1.42E+14	3.40	3.33
62	28-09-2009	13:22	26.942	92.094	3.15	19.2	1.48E+14	3.42	3.16
63	26-07-2009	00:53	26.078	90.714	3.18	14.3	1.50E+14	3.42	3.19
64	27-10-2002	20:27	26.409	93.135	3.30	37.6	1.50E+14	3.42	3.30
65	21-09-2009	21:55	27.222	91.322	3.24	11.9	1.52E+14	3.42	3.25

Table 2 continued

ID	Date (dd-mm-yy)	OT (hr:mm)	Lat. (°N)	Long. (°E)	Mag (M_DA)	Depth (km)	M_0 (N m)	M_W	M_L
66	24-10-2003	23:37	25.744	90.651	3.20	27.9	1.53E+14	3.43	3.21
67	28-10-2003	07:33	26.367	90.308	3.50	24.8	1.55E+14	3.43	3.50
68	21-11-2003	19:56	25.670	91.000	3.30	30.8	1.56E+14	3.43	3.30
69	21-09-2009	11:50	27.388	91.452	3.15	7.8	1.58E+14	3.44	3.16
70	24-08-2003	17:20	26.154	92.781	3.20	19.2	1.58E+14	3.44	3.21
71	04-10-2009	20:42	27.152	91.464	3.61	13.7	1.59E+14	3.44	3.60
72	01-03-2010	09:45	25.964	91.266	3.22	12.4	1.62E+14	3.44	3.23
73	22-01-2008	22:12	26.183	92.675	3.20	27.6	1.68E+14	3.45	3.21
74	10-04-2009	15:34	25.870	90.360	3.20	18.7	1.68E+14	3.45	3.21
75	21-01-2010	01:05	25.796	90.804	3.21	19.4	1.68E+14	3.45	3.22
76	21-09-2009	12:31	27.101	91.429	3.29	16.0	1.69E+14	3.46	3.30
77	07-06-2003	22:27	25.491	91.888	3.30	42.2	1.69E+14	3.46	3.30
78	18-08-2009	22:49	25.604	90.791	3.21	14.5	1.78E+14	3.47	3.22
79	08-05-2003	16:20	26.262	92.787	3.40	43.5	1.80E+14	3.47	3.40
80	23-04-2003	23:06	26.160	90.860	3.40	15.0	1.80E+14	3.47	3.40
81	28-09-2009	17:32	27.180	91.477	3.40	18.2	1.80E+14	3.47	3.40
82	15-05-2006	20:25	25.955	93.262	3.30	34.5	1.82E+14	3.48	3.30
83	08-11-2009	16:59	27.248	91.483	3.32	17.0	1.82E+14	3.48	3.32
84	30-09-2009	13:23	27.301	91.555	3.22	11.7	1.87E+14	3.48	3.23
85	18-01-2001	02:47	26.321	93.201	3.20	42.1	1.99E+14	3.50	3.60*
86	29-05-2003	02:03	27.160	92.823	3.70	10.6	1.99E+14	3.50	3.69
87	21-09-2002	19:08	26.141	92.600	3.20	21.1	2.00E+14	3.50	3.21
88	16-11-2003	18:59	26.335	92.391	3.30	6.8	2.05E+14	3.51	3.30
89	20-01-2005	02:16	25.689	90.742	3.40	8.1	2.08E+14	3.52	3.60*
90	06-11-2001	19:58	27.300	92.170	3.20	24.5	2.12E+14	3.52	3.21
91	19-12-2003	22:08	25.690	90.870	3.50	23.0	2.22E+14	3.53	3.50
92	17-11-2002	17:35	25.660	91.520	3.50	9.0	2.26E+14	3.54	3.50
93	07-12-2002	18:37	27.223	92.145	3.50	18.4	2.29E+14	3.54	3.50
94	24-09-2009	18:51	27.152	91.386	3.52	17.5	2.29E+14	3.54	3.51
95	17-04-2003	19:23	26.299	92.832	3.50	20.5	2.31E+14	3.55	3.50
96	07-01-2003	02:04	25.740	90.810	3.30	12.9	2.34E+14	3.55	3.30
97	03-10-2009	18:02	27.262	91.672	3.47	9.4	2.35E+14	3.55	3.47
98	21-01-2005	13:50	27.446	92.620	3.60	16.0	2.41E+14	3.56	3.59
99	21-09-2009	16:14	27.218	91.510	3.26	6.4	2.48E+14	3.57	3.27
100	22-12-2009	17:24	27.015	91.121	3.27	17.5	2.48E+14	3.57	3.28
101	04-12-2004	14:52	26.097	91.663	3.30	25.5	2.48E+14	3.57	3.30
102	04-06-2003	23:28	26.498	92.308	3.50	11.0	2.56E+14	3.58	3.70*
103	22-09-2009	08:27	27.193	91.473	3.50	10.2	2.56E+14	3.58	3.50
104	21-06-2003	21:05	26.030	90.590	3.50	7.4	2.58E+14	3.58	3.50
105	01-06-2003	12:57	25.830	90.752	3.20	12.2	2.62E+14	3.58	3.21
106	16-11-2004	23:05	26.214	92.145	3.30	19.5	2.63E+14	3.58	3.30
107	17-12-2003	14:21	26.245	92.845	3.30	9.1	2.64E+14	3.58	3.30
108	01-12-2002	17:58	26.340	92.490	3.50	24.2	2.65E+14	3.59	3.50
109	26-10-2002	11:36	26.645	92.372	3.40	21.0	2.70E+14	3.59	3.40
110	21-09-2009	09:32	27.009	91.381	3.44	16.3	2.70E+14	3.59	3.44
111	21-09-2009	21:45	27.270	91.442	3.44	11.7	2.80E+14	3.60	3.44
112	14-02-2005	02:07	25.890	90.890	3.30	28.3	2.82E+14	3.60	3.80*

Table 2 continued

ID	Date (dd-mm-yy)	OT (hr:mm)	Lat. (°N)	Long. (°E)	Mag (M_DA)	Depth (km)	M_0 (N m)	M_W	M_L
113	01-12-2009	11:23	27.170	91.379	3.30	17.3	2.82E+14	3.60	3.30
114	25-06-2003	21:23	25.710	91.020	3.50	31.9	3.02E+14	3.62	3.50
115	17-03-2003	15:02	26.560	90.540	3.70	37.2	3.17E+14	3.64	3.69
116	24-07-2003	12:39	26.220	92.657	3.50	25.1	3.18E+14	3.64	3.50
117	19-11-2003	21:26	26.154	92.190	3.60	9.9	3.34E+14	3.65	3.59
118	29-10-2010	01:17	27.013	91.743	3.38	10.6	3.62E+14	3.68	3.38
119	05-01-2004	20:03	26.510	92.840	3.40	10.2	3.62E+14	3.68	3.40
120	01-04-2003	14:50	25.650	91.490	3.80	41.9	3.63E+14	3.68	3.78
121	16-11-2002	22:39	25.790	90.760	3.50	10.2	3.79E+14	3.69	3.50
122	24-09-2002	23:42	25.926	90.387	3.70	19.6	3.94E+14	3.70	3.69
123	24-03-2007	21:55	27.090	91.831	3.40	22.5	4.39E+14	3.73	3.40
124	05-01-2003	18:18	26.500	90.160	3.70	22.4	4.44E+14	3.73	3.69
125	26-07-2003	17:03	27.027	92.197	3.70	22.4	4.44E+14	3.73	3.69
126	05-01-2005	10:56	25.620	91.671	3.50	8.5	4.45E+14	3.74	3.50
127	21-09-2009	10:22	27.224	91.417	3.52	10.9	4.45E+14	3.74	3.51
128	31-01-2005	20:19	26.735	91.998	3.50	44.3	4.48E+14	3.74	3.50
129	16-12-2002	01:57	26.740	92.690	3.30	33.3	4.62E+14	3.75	3.30
130	23-09-2009	17:46	27.179	91.317	3.55	13.1	4.87E+14	3.76	3.54
131	01-12-2002	17:28	27.330	91.370	3.60	19.4	4.87E+14	3.76	3.59
132	04-01-2003	19:39	25.914	92.658	3.70	35.9	5.17E+14	3.78	3.69
133	14-07-2003	09:08	26.489	92.408	3.70	33.3	5.40E+14	3.79	3.69
134	22-01-2010	04:07	25.519	91.007	3.74	13.7	5.40E+14	3.79	3.72
135	13-01-2004	23:16	27.373	92.127	3.50	16.8	5.68E+14	3.81	3.50
136	21-09-2009	09:07	27.195	91.383	3.54	15.0	5.68E+14	3.81	3.53
137	23-02-2005	22:44	26.645	92.424	3.70	28.9	5.69E+14	3.81	3.69
138	25-02-2005	07:07	26.510	92.732	3.50	32.9	6.05E+14	3.82	3.50
139	20-03-2001	16:15	27.133	92.164	3.70	10.1	6.05E+14	3.82	3.69
140	22-09-2009	17:54	26.980	91.594	3.72	17.3	6.09E+14	3.83	3.70
141	01-11-2009	03:55	27.347	91.265	3.69	11.9	6.17E+14	3.83	3.68
142	23-09-2009	00:02	27.197	91.310	3.58	11.4	6.78E+14	3.86	3.57
143	06-04-2003	14:07	27.448	93.124	3.60	12.1	6.78E+14	3.86	3.59
144	21-09-2009	09:41	27.055	91.376	3.61	16.1	6.78E+14	3.86	3.60
145	08-01-2010	17:15	27.108	91.453	3.61	12.1	7.13E+14	3.87	3.60
146	22-09-2009	18:20	26.988	91.370	3.56	15.1	8.23E+14	3.91	3.55
147	02-06-2003	15:14	27.317	91.750	3.60	5.4	8.23E+14	3.91	3.59
148	21-09-2009	11:07	27.206	91.392	3.62	14.2	8.23E+14	3.91	3.61
149	11-02-2005	08:13	26.526	92.404	3.80	8.3	1.05E+15	3.98	3.78
150	28-06-2003	13:31	27.275	92.155	3.80	15.3	1.12E+15	4.00	3.78
151	30-11-2009	12:38	27.235	91.445	3.94	14.3	1.12E+15	4.00	3.91
152	11-01-2002	14:51	27.450	92.062	3.80	28.4	1.19E+15	4.02	4.00*
153	22-03-2007	14:02	27.230	92.166	4.00	6.4	1.54E+15	4.10	3.97
154	06-04-2009	17:57	27.145	92.353	3.81	14.1	1.55E+15	4.10	3.79
155	15-02-2003	21:37	25.850	90.450	3.90	36.6	1.94E+15	4.16	3.88
156	02-11-2004	08:23	26.517	92.220	4.00	25.0	2.13E+15	4.19	3.97
157	13-08-2009	21:34	25.674	91.923	4.27	21.7	2.74E+15	4.26	4.23
158	14-03-2007	01:09	27.235	91.543	4.30	7.1	2.94E+15	4.28	4.00*
159	02-10-2009	08:38	27.169	91.453	4.35	11.3	3.14E+15	4.30	4.30

Table 2 continued

ID	Date (dd-mm-yy)	OT (hr:mm)	Lat. (°N)	Long. (°E)	Mag (M_DA)	Depth (km)	M_0 (N m)	M_W	M_L
160	29-11-2003	18:34	25.792	92.957	4.00	17.7	3.35E+15	4.32	3.97
161	30-09-2009	08:21	27.160	91.532	4.91	13.0	2.00E+16	4.84	4.84
162	29-10-2009	17:00	27.182	91.467	4.96	15.4	2.00E+16	4.84	4.89

ID is the identification of the event; M_0 is the average seismic moment; M_DA is the average duration magnitude; M_W is the moment magnitude estimated from Hanks and Kanamori relation (1979); M_L is the local magnitude estimated from the relation Sitaram and Bora (2007)

* is the M_L estimated from IMD, Shillong observatory

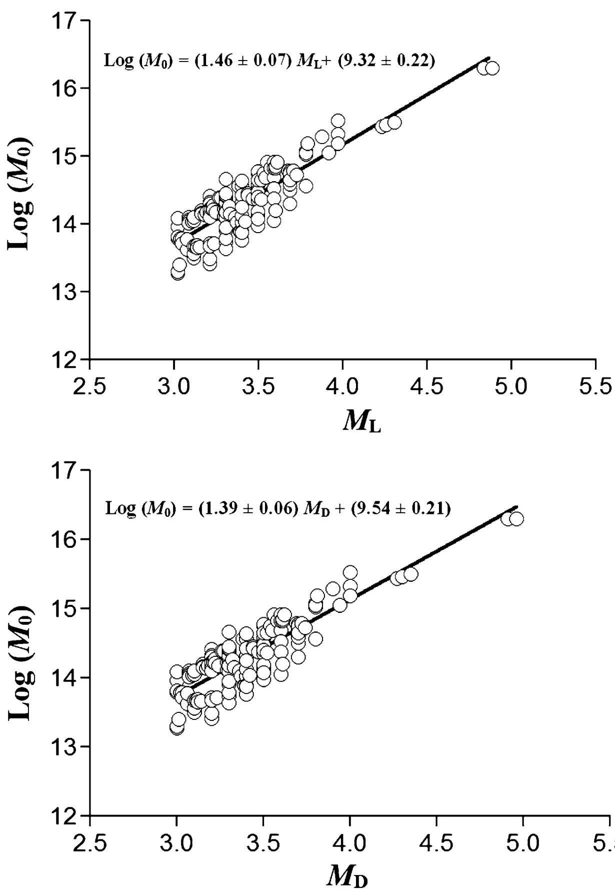

Fig. 6 Plot of average seismic moment (M_0) versus local magnitude (M_L) and duration magnitude (M_D). The *line* was obtained by *least squares* fitting the observations. The *errors* associated with the slope and the intercepts are the standard errors

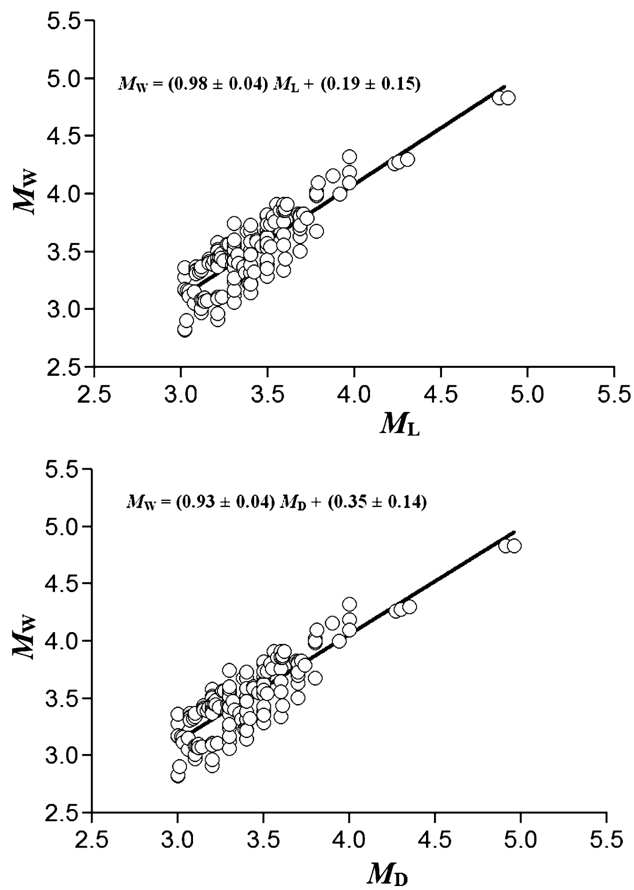

Fig. 7 Scaling relationship between M_W versus M_L and M_D for selected earthquakes and associated regression line

$$M_W = (0.98 \pm 0.04)\, M_L + (0.19 \pm 0.15)$$
$$r^2 = 0.76 \text{ and } \sigma = 0.17, \quad (8)$$

$$M_W = (0.93 \pm 0.04)\, M_D + (0.35 \pm 0.14)$$
$$r^2 = 0.76 \text{ and } \sigma = 0.17, \quad (9)$$

where r and σ are the correlation coefficient and standard error, respectively..

7 Discussion and conclusions

This work represents the calculation of seismic moment of 162 local earthquakes in Shillong-Mikir Hills plateau and its adjoining region of northeastern India using the spectral analysis of P-waves. The estimated seismic moments (M_0) range from 1.90 × 10^{13} to 2.00 × 10^{16} N m.

The relationship between seismic moment M_0 versus M_L and M_D are examined for Shillong-Mikir Hills plateau and its adjoining region. The scaling (Eqs. 6 and 7) is similar to determinations obtained in different regions for logarithm of the seismic moment as a function of local magnitude, M_L and duration magnitude, M_D (e.g., Archuleta et al. 1982; Bakun and Lindh 1977; Bindi et al. 2001; Bora et al. 2013; De Luca et al. 2000; Dutta et al. 2003; Fletcher et al. 1984; Radulain et al. 2014; Castello et al. 2007). Thus, the slope value of 1.46 and 1.39 falls within the values previously obtained by other authors: ~ 1.1 (e.g., Bindi et al. 2001; De Luca et al. 2000; Fletcher et al. 1984) and ~ 2.5 (e.g., Bakun and Lindh 1977; Bora et al. 2013; Dutta et al. 2003; Radulain et al. 2014; Castello et al. 2007).

Also the relationship between M_W versus M_L and M_D has been examined for the studied region of NE India. The regression lines (Eq. 8 and 9) obtained from this study are in agreement with the determinations obtained by other authors (e.g., Bakun and Lindh 1977; Archuleta et al. 1982; Fletcher et al. 1984; Wang et al. 1989; Trifu and Radulian 1991; De Luca et al. 2000; Bindi et al. 2001; Dutta et al. 2003; Radulain et al. 2014; Castello et al. 2007; Baruah et al. 2012) for the M_L scale in a range of magnitude similar to that investigated here. Using Eqs. (8) and (9), we computed M_L and M_D for all the events. The M_L values can be considered consistent with M_W, within 0.1 magnitude units, in 90 % of the cases. The M_D values can be considered consistent with M_W, within 0.2 magnitude units, in 90 % of the cases. This authenticates our empirical approach. Higher discrepancies in some cases may be ascribed to the fact that superposition of relative amplitudes of earthquake phases hinders estimating magnitude values which was also observed by Giampiccolo et al. 2007. Thus, the estimated M_W values in the earthquake catalog need to be examined with respect to M_L and M_D for an effective seismic hazards analysis and tectonic studies in the Shillong and Mikir plateau region of northeast India.

Accurate estimation of M_W for small magnitude earthquakes is important for the prediction of ground motion at low magnitudes. For example, ground motion prediction equations for peak ground acceleration and velocity are usually expressed as functions of M_W (e.g., Atkinson and Boore 2006; Akkar and Bommer 2007; Sokolov et al. 2008). For this reason, it is usual to find empirical formulae relating M_W to the magnitude scales used locally in seismological practice. Empirical relations between M_W and M_L, M_W and M_D, and M_0 and M_L are developed for local earthquakes that may be useful for seismic hazard assessment.

7.1 Data and resources

The seismograms which are used for this study were recorded by various stations of different organizations like North East Institute of Science and Technology (CSIR-NEIST), Jorhat, Assam, India; National Geophysical Research Institute (CSIR-NGRI), Hyderabad, India; Indian Institute of Geomagnetism (IIG), Mumbai, India; and Gauhati University, Guwahati, Assam, India. The catalog data from India Meteorological Department (IMD)—Shillong observatory were also used for the study.

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