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The first M_L scale for North of Vietnam

Le Minh Nguyen [a,d], Ting-Li Lin [a,*], Yih-Min Wu [a], Bor-Shouh Huang [b], Chien-Hsin Chang [c], Win-Gee Huang [b], Tu Son Le [d], Van Toan Dinh [e]

[a] Department of Geosciences, National Taiwan University, Taipei 106, Taiwan
[b] Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Nankang, Taipei 115, Taiwan
[c] Central Weather Bureau, Taipei 100, Taiwan
[d] Institute of Geophysics, Vietnamese Academy of Science and Technology, Hanoi, Viet Nam
[e] Institute of Geological Sciences, Vietnamese Academy of Science and Technology, Hanoi, Viet Nam

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ABSTRACT

The first local magnitude scale (M_L) for Northern Vietnam has been derived using a portable broadband seismic network in Northern Vietnam as part of the cooperation between the Vietnam Institute of Geophysics and the Institute of Earth Sciences at Academia Sinica, Taiwan. The composite horizontal peak amplitude data used in this study is comprised a total of 202 amplitude records from 14 broadband stations, which measure 36 shallow earthquakes with focal depths less than 36 km, occurred in and around north-western Vietnam during 01/2006–10/2007. The new distance-correction function obtained in this study is $-\log A_0 = 1.74\log(r) + 0.00048r - 0.522$, where A_0 and r are the empirically determined distance correction and hypocentral distance, respectively. This distance-correction relation for Northern Vietnam is quite similar to one for southern California, implying relative efficient attenuation with distances. The correlation between the new M_L and duration magnitudes (M_d), which is still being used for making the official earthquake bulletin in Vietnam, is expressed as $M_L = 0.955M_d + 0.17$.

1. Introduction

Vietnam, located in South East Asia, is bounded by the Pacific and Mediterranean–Himalayan seismic belts on its eastern, and western and southern sides, respectively. Seismicity in Vietnam is considered to be moderate and mostly occurs in north-western Vietnam. Most of the main faults in Northern Vietnam are NW–SE-trending, strike-slip faults, and are regarded as the south segment of the Red River Fault. Over recent decades, the economy of Vietnam has rapidly grown and infrastructure and buildings have being constructed in many cities and provinces of Northern Vietnam. Despite the fact that the seismicity in Northern Vietnam is known to be moderate, one of the major steps for a developing region are seismic hazard assessments for the sake of hardening the building design code and urban development plans, which undoubtedly require more effort and attention.

One of the basic seismological parameters partly related to seismic ground shaking and seismic hazard is the magnitude scale. There are many different definitions of a magnitude scale. Local magnitude (M_L), proposed by Richter (1935, 1958), is regarded as a useful parameter in estimating the relative earthquake size. It has the most relevance to engineering applications because it is determined within the period range of greatest engineering interest (Kanamori and Jennings, 1978; Kanamori, 1980). Moreover, local magnitude is important in quantifying the seismicity rate and the distance attenuation for a given region (Hutton and Boore, 1987; Kanamori and Jennings, 1978), even though it cannot be directly related to any physical parameter of a particular earthquake source.

The first magnitude scale for local earthquakes in Vietnam was established by Nguyen (1996), which was inferred from maximum amplitudes and durations of seismograms recorded by the short-period seismographs. That magnitude scale is loosely similar to the M_L and M_S scales. Because of the lack of data, Nguyen (1996) tried to find the attenuation curve by combining the amplitudes and the duration records of the events.

Le and Dinh (2008) also found an equation for M_L scale for North of Vietnam. Their resulting equation was found by using the broadband data to correct the M_L equation, which was originally given by group work on magnitude in IASPEI and CoSOI. However, Le and Dinh (2008) did not give the attenuation curve specifically for Northern Vietnam.

M_L in its original form is rarely used because the standard Wood–Anderson torsion seismograph is uncommon, unlike in state of California during the time Richter proposed the M_L scale.

* Corresponding author. Address: Department of Geosciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 106, Taiwan. Tel.: +886 2 33664956x309.
E-mail address: mulas62@gmail.com (T.-L. Lin).

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That is one of the reasons why Vietnam did not have the M_L scale for a long time. Moreover, until 1975 the seismic event occurring in North of Vietnam had first been determined by a seismic network consisting of merely five synchronic seismographs. However, with the development of signal processing technology, the Wood–Anderson seismogram can easily be simulated from a variety of digital broadband or short-period waveforms (Bakun et al., 1978; Uhrhammer and Collins, 1990). Also, a portable broadband seismic network, recently installed in Northern Vietnam, allows us to gather sufficient amounts of amplitude data with which to perform the first local magnitude scale determination.

The magnitude scale, determined from durations, has recently been used for compiling an official earthquake bulletins and catalogue in Vietnam (Nguyen et al., 2004). Therefore, a more accurate M_L that is more tightly connected with the ground shaking level will be essential in assessing earthquake hazards in regions with such fast economic growth like Northern Vietnam. The new local magnitude scale proposed in this study will provide general characteristics of seismic wave propagation and attenuation that depend on the properties of the crust and upper mantle beneath Northern Vietnam.

2. Stations and data

Since December 2005, a seismic network that consisted of 24 broadband seismographs was gradually deployed in Northern Vietnam (Fig. 1) as part of the cooperation between the Vietnam Institute of Geophysics and the Institute of Earth Sciences at Academia Sinica, Taiwan (Huang et al., 2009). This network has been using two types of seismometers: STS-2 and Trillium40. The characteristic curves of these seismometers are shown in Fig. 2. As seen in Fig. 1, the stations provide a uniform coverage over Northern Vietnam with the aim to understand the crustal and mantle structures beneath the network. Although this network has only been operating in recent years and the number of recorded earthquake events is relatively limited, it still provides the opportunity to build a local magnitude scale for Northern Vietnam.

The peak displacement amplitude data used in this study was provided by the seismic broadband network in Northern Vietnam, comprising a total of 202 amplitude records by 14 stations from 36 shallow earthquakes occurred in and around north-western Vietnam during 01/2006–10/2007. Note that during the recoding time, at most 14 broadband stations were operating. The epicenter distance ranges are in between 20 and 600 km. The earthquakes have been located by using the 1D velocity model (Nguyen, 2009) and *S* minus *P* arrival times. The earthquake events used in this study have duration magnitudes in the range of $2.0 < M_d < 4.5$ and focal depths shallower than 35 km. The catalog of the 36 events is shown in Table 1. The locations of the stations and earthquakes are shown in Fig. 3. The station parameters such as the locations, number of records, and station corrections are also listed in Table 2. Originally, much larger event numbers were possible. However, to maintain data quality we restricted the events to those with good digital quality recordings, being recorded by at least three stations, and with an epicenter distance of less than 600 km. Although some events were not located inside but in an area

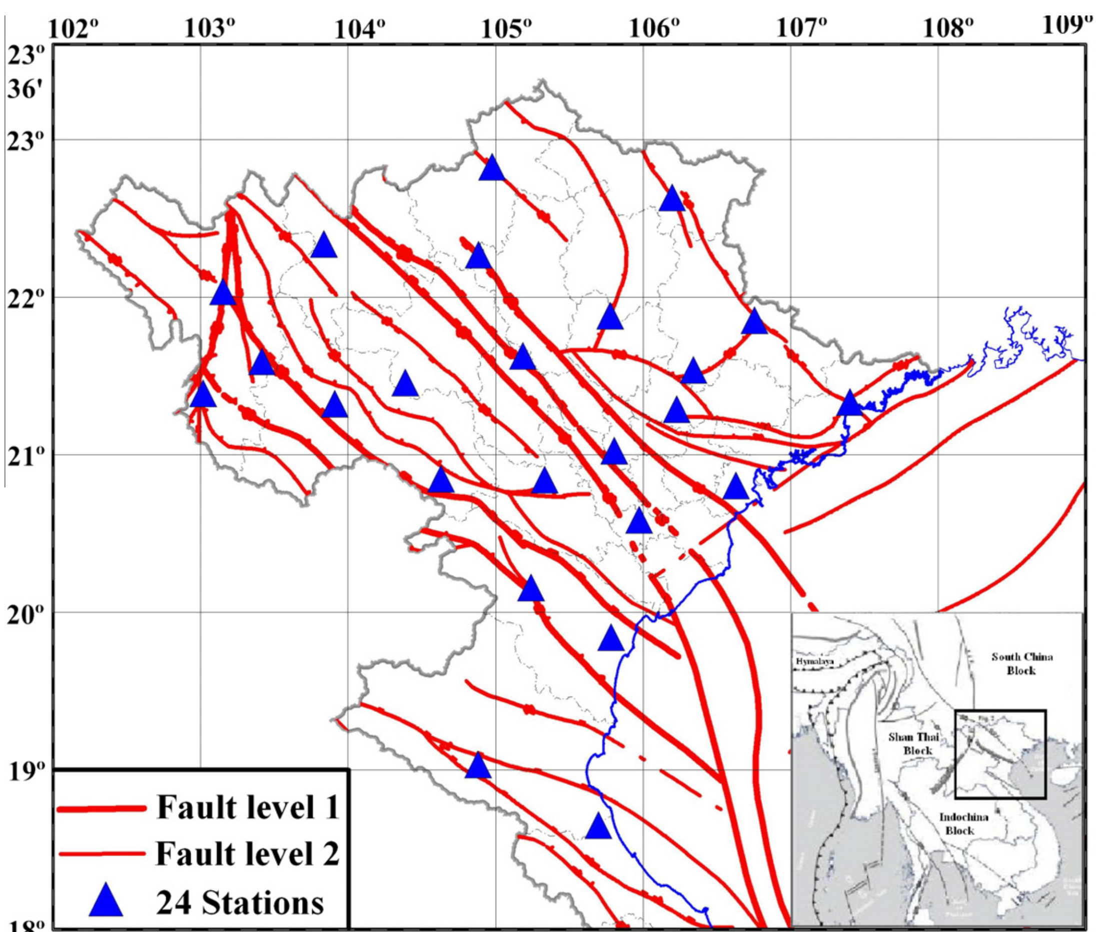

Fig. 1. Map of major fault systems and portable broadband stations in north of Vietnam.

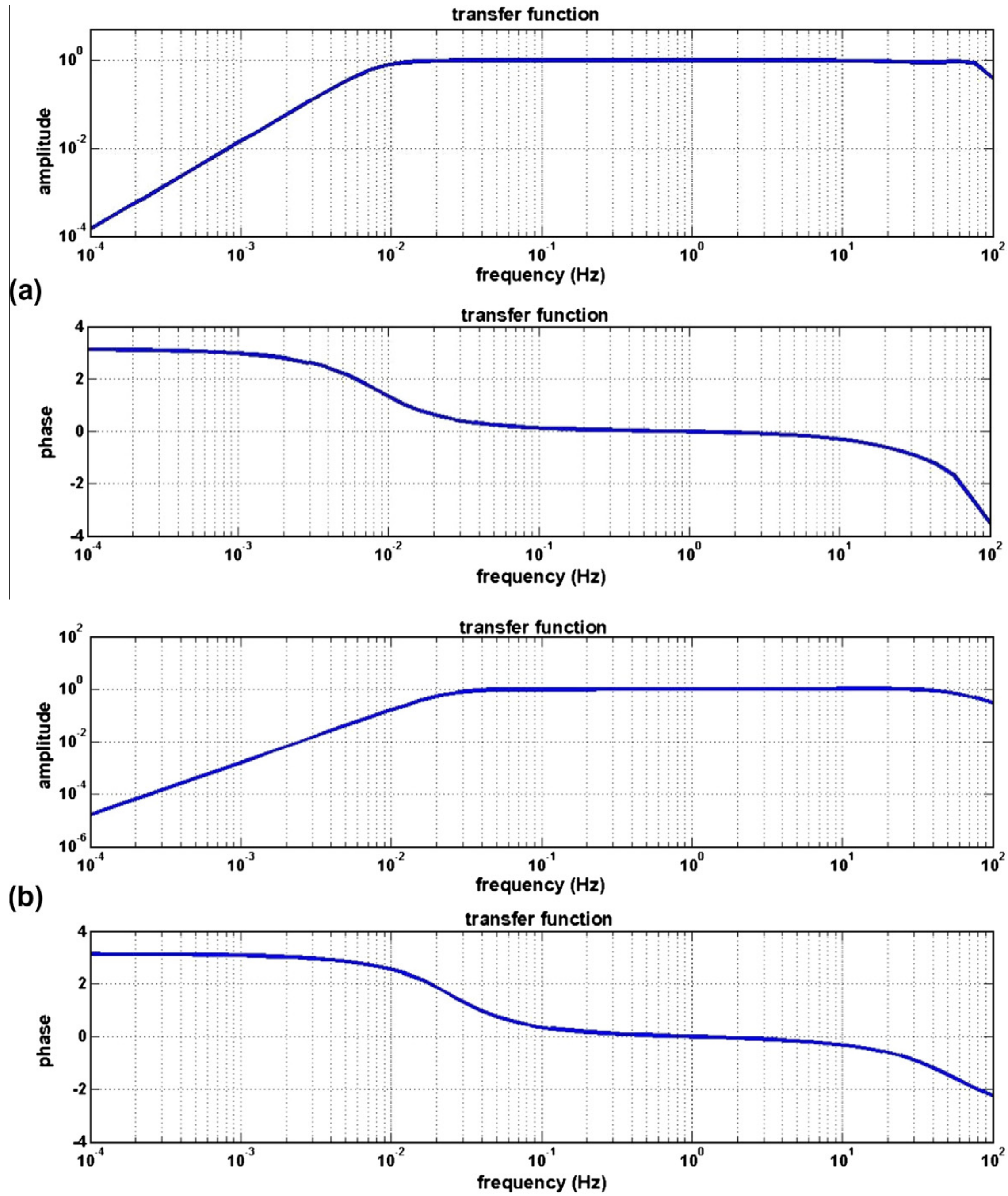

Fig. 2. Characteristic curves of seismometers deployed in the portable broadband network: (a) for STS-2 sensor and (b) for Trillium40 sensor.

adjacent to Vietnam, they were still chosen as they provide the chance to study the crustal structure of the complete region affecting Northern Vietnam.

3. Method of analysis and result

Local magnitude scale is originally based on the observed level of earthquake ground shaking in southern California, in which most earthquakes occurred in the shallow crust. Its determination is based on the peak amplitudes recorded by a standard Wood–Anderson torsion seismograph with a natural period of 0.8 s, a damping constant of 0.8, and a static magnification of 2800. The relationship between the relative size of an earthquake and its amplitude follows Richter (1935) as

$$M_L = \log A(\Delta) - \log A_0(\Delta) + S \quad (1)$$

where A is the observed peak amplitude (zero-to-peak) in millimetres of the horizontal seismogram, A_0 is the empirically determined distance correction, S is the empirical station correction and Δ is the epicentral distance in kilometers. According to the definition of Richter (1935), an $M_L = 0$ event at an epicentral distance of 100 km has a peak amplitude of 0.001 mm on a standard Wood–Anderson seismograph with $S = 0$, or equally an $M_L = 3$ event has a peak amplitude of 1 mm at 100 km.

Log A_0 is a distance correction term given as (Bakun and Joyner, 1984; Hutton and Boore, 1987)

$$-\log A_0 = a \log(r/100) + b(r - 100) + 3.0 \quad (2)$$

Table 1
List of 36 earthquakes used in this study.

No.	Origin time (UTC)		Lat	Long	Depth (km)	M_L	M_d (VN)
1	01/06/2006	11:50:03	22.951	104.316	10	3.89	4.1
2	01/06/2006	18:28:08	22.091	102.411	2.74	4.00	4
3	01/06/2006	18:43:03	22.113	102.398	2.44	3.80	3.9
4	01/15/2006	14:29:47	21.738	103.297	10.7	3.14	3
5	01/16/2006	17:58:01	22.296	103.282	12.95	2.67	
6	01/23/2006	21:09:20	22.29	103.227	10.98	2.33	
7	02/03/2006	1:08:44	20.886	105.728	9.61	2.42	3
8	02/19/2006	13:16:52	21.687	103.431	9.98	2.54	
9	02/26/2006	16:12:37	21.242	103.351	8.33	3.59	3.5
10	03/09/2006	22:04:52	22.615	103.336	10.77	2.80	2.8
11	03/16/2006	16:22:32	22.27	104.222	7.19	3.14	3.4
12	03/18/2006	20:18:04	21.24	103.354	7.87	2.05	2.6
13	04/03/2006	17:06:56	20.029	107.252	10.9	3.84	4.3
14	04/09/2006	21:55:31	21.48	103.278	6.46	1.55	
15	04/13/2006	13:24:57	21.402	102.973	8.84	2.36	
16	06/30/2006	18:18:56	22.092	103.47	14.21	1.82	
17	08/15/2006	20:49:06	21.691	103.353	6.41	3.40	
18	08/15/2006	21:24:16	21.695	103.349	5	1.94	
19	08/26/2006	4:20:40	21.296	102.903	14.16	1.64	
20	08/30/2006	22:36:19	20.216	104.927	6.28	2.74	2.5
21	09/02/2006	18:16:53	22.308	102.271	17.1	3.01	2.8
22	09/06/2006	19:24:17	22.97	102.28	15	3.07	
23	09/06/2006	19:28:19	23.103	102.727	17.1	2.73	2.7
24	09/17/2006	6:10:38	21.033	103.287	11.2	2.94	2.7
25	09/18/2006	16:18:39	20.905	103.075	17.3	2.53	2.6
26	09/18/2006	16:33:10	20.85	103.012	20.01	2.74	
27	09/23/2006	20:07:13	21.415	102.969	4.38	2.13	2.1
28	10/16/2006	19:38:23	22.064	102.296	8.5	3.08	2.8
29	11/11/2006	18:46:02	23.554	102.521	8.9	4.07	3.9
30	11/23/2006	16:30:02	22.605	102.401	10	4.45	
31	11/24/2006	05:19.7	22.9593	104.267	10	4.01	
32	03/31/2007	3:15:56	22.376	102.364	18.2	3.75	3.7
33	05/31/2007	15:44:31	22.525	102.841	17.1	3.18	2.9
34	06/07/2007	5:31:13	21.929	103.029	0.5	3.43	3.3
35	07/21/2007	8:47:11	21.456	104.102	0.5	3.14	3
36	09/06/2007	18:51:48	23.266	105.487	15.09	4.60	3.8

where a and b are empirical coefficients for geometrical spreading and anelastic attenuation for a given region, respectively, and r is the hypocentral distance in kilometres. A value of 3 is added to follow Richter's original definition of M_L. To establish the new magnitude scale, we combine Eqs. (1) and (2) to give an explicit distance-correction function as

$$\sum_{k=1}^{m} M_k\delta_{ik} - \sum_{l=1}^{n} S_l\delta_{lj} - a\log(r_{ij}/100) - b(r_{ij}-100) = \log A_{ij} + 3.0, \quad i,k = 1,2,\ldots m;\; j,l = 1,2,\ldots n \tag{3}$$

where A_{ij} is the maximum horizontal zero-to-peak amplitude of the ith event at the jth station, M_k is the magnitude of kth event, S_l is the station correction of lth station, r_{ij} is hypocentral distance from the ith event to the jth station, δ is the Kronecker delta, m is number of events (m = 36) and n is number of stations (n = 14). The parameters to be determined are a, b, M_k, and S_l, representing the geometrical spreading, anelastic attenuation, magnitude, and station correction, respectively. Eq. (3) can be rewritten in matrix form as (Alsaker et al., 1991; Miao and Langston, 2007)

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & -1 & 0 & \cdots & 0 & p_{11} & q_{11} \\ 1 & 0 & \cdots & 0 & 0 & -1 & \cdots & 0 & p_{12} & q_{12} \\ & & \vdots & & & & \vdots & & \vdots & \vdots \\ 1 & 0 & \cdots & 0 & 0 & 0 & \cdots & -1 & p_{1n} & q_{1n} \\ 0 & 1 & \cdots & 0 & -1 & 0 & \cdots & 0 & p_{21} & q_{21} \\ 0 & 1 & \cdots & 0 & 0 & -1 & \cdots & 0 & p_{22} & q_{22} \\ & & \vdots & & & & \vdots & & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 & 0 & \cdots & -1 & p_{mn} & q_{mn} \\ 0 & 0 & \cdots & 0 & 1 & 1 & \cdots & 1 & 0 & 0 \end{bmatrix}_{(mn+1)\times(m+n+2)} \cdot \begin{bmatrix} M_1 \\ \vdots \\ M_m \\ S_1 \\ \vdots \\ S_n \\ a \\ b \end{bmatrix}_{(m+n+2)\times 1} = \begin{bmatrix} y_{11} \\ y_{12} \\ \vdots \\ y_{1n} \\ y_{21} \\ y_{22} \\ \vdots \\ y_{mn} \\ 0 \end{bmatrix}_{(mn+1)\times 1} \tag{4}$$

or $G\mathbf{u} = d$, which is a system of $(m \times n) + 1$ linearly independent equations with $m + n + 2$ parameters to be determined. In Eq. (4), $p_{ij} = -a\log(r_{ij}/100)$, $q_{ij} = -b(r_{ij} - 100)$, and $y_{ij} = \log A_{ij} + 3.0$. The vector of unknowns ($\mathbf{u}$) can be found through generalized inverse matrix of $G(G^{-g})$ using singular value decomposition (Menke, 1984) as proposed by Miao and Langston (2007). Miao and Langston (2007) adopt a one-step linear inversion without iteration (Hutton and

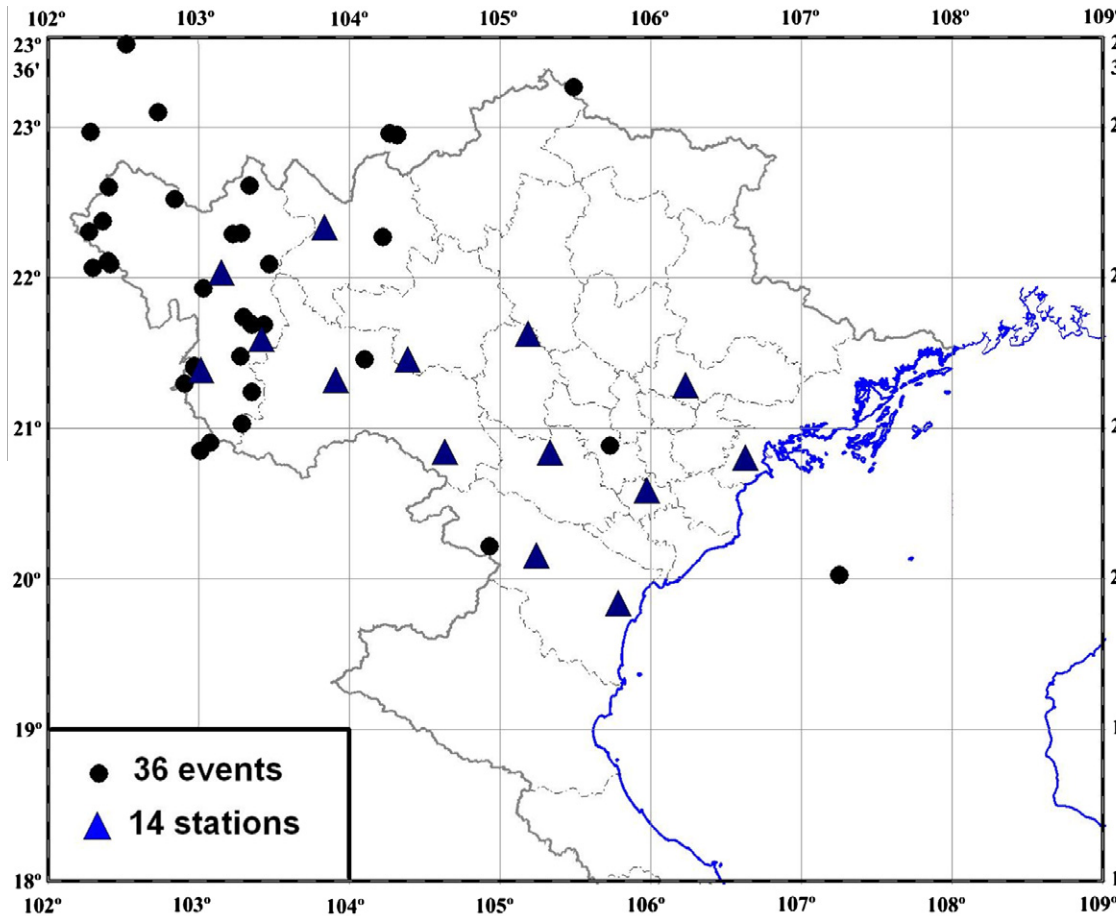

Fig. 3. Map of earthquake events and portable broadband stations used in this study.

Table 2
List of 14 stations used in this study.

Name	Code	Long	Lat	Elev (m)	Sensor	Readings	Sta crt.
Sapa	SPVB	103.835	22.338	1582	STS-2	20	−0.09
Lai Chau	LCVB	103.152	22.038	250	Trillium40	28	−0.04
Tuan Giao	TGVB	103.416	21.595	580	Trillium40	30	0.20
Hoa Binh	HBVB	105.333	20.842	50	Trillium40	7	−0.38
Bac Giang	BGVB	106.228	21.290	50	Trillium40	4	−0.18
Doi Son	DSVB	105.974	20.587	70	Trillium40	6	−0.10
Lang Chanh	LAVB	105.240	20.157	80	Trillium40	2	−0.04
Phu Lien	PLVB	106.628	20.805	18	STS-2	4	0.15
Thanh Hoa	THVB	105.784	19.843	20	Trillium40	3	0.16
Tram Tau	TTVB	104.388	21.460	600	Trillium40	16	0.17
Moc Chau	MCVB	104.631	20.847	800	Trillium40	8	0.13
Doan Hung	DHVB	105.185	21.628	70	Trillium40	3	−0.33
Dien Bien	DBVB	103.018	21.390	490	STS-2	26	0.03
Son La	SLVB	103.909	21.323	590	Trillium40	20	0.30

Boore, 1987; Langston et al., 1998) for a typical over-determined inversion problem such as presented in Eq. (4). The last expression of Eq. (4) is a constraint such that the average station correction is equal to zero (*i.e.* $\sum_{l=1}^{n} S_l = 0$; Hutton and Boore, 1987). The inverted coefficients a (geometrical spreading) and b (anelastic attenuation) will determine the form of the $-\log A_0$ curve in accordance with Eq. (2).

In following the methodological approach outlined above, the instrument response-corrected waveforms were first simulated to Wood–Anderson seismograms. Although there is an issue regarding the magnification of the standard Wood–Anderson instrument (Uhrhammer and Collins, 1990), the standard torsion with a natural period of 0.8 s, a damping constant 0.8 and a static magnification of 2800 were used. This convolution procedure was applied to both horizontal components. The average of log A was determined from the two horizontal components providing one composite horizontal peak amplitude observation per event–station pair. By substituting these values as y_{ij} in Eq. (6), the new attenuation curve for North of Vietnam was obtained by a one-step linear inversion.

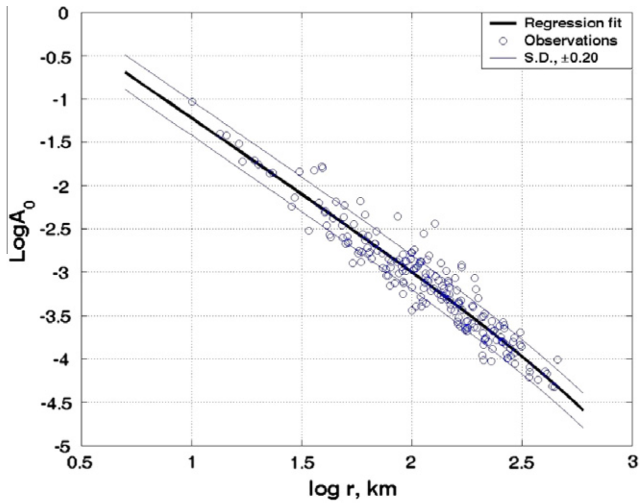

Fig. 4. Comparison between the calculated $\log A_0$ by distance-correction function as Eq. (5) and 202 observed peak amplitudes of "synthetic" Wood–Anderson seismograms from 14 stations of 36 shallow earthquakes.

With 202 records from 36 events recorded by 14 stations in North of Vietnam, the first distance-correction function (attenuation curve) is obtained as

$$-\log A_0 = 1.74\log(r/100) + 0.00048(r - 100) + 3.0. \quad (5)$$

Fig. 4 shows the 202 readings of $\log A_0$ after applying station corrections and the regression curve defined by Eq. (5). The station corrections were also determined in the regression analysis and listed in Table 2.

From the determined attenuation curve, the new M_L scale is also obtained as follows

$$M_L = \log A_{W-A} + 1.74\log(r) + 0.00048r - 0.522 + S. \quad (6)$$

4. Discussion and conclusion

Fig. 5 compares the distance-correction function ($-\log A_0$) obtained in this study for Northern Vietnam and those for the other tectonic regions. The shape of our attenuation curve (combining geometric spreading and anelastic attenuation) for Northern Vietnam is quite similar to the one for southern California. The similarities suggest that the attenuation characteristics of the crust and upper mantle beneath northern Vietnam are similar to that beneath southern California and imply that Northern Vietnam has an efficient attenuation with distance similar to the attenuation of southern California. Both Northern Vietnam and southern California are located on continental regions and in general the *P*-wave velocity model for North of Vietnam (Nguyen, 2009) is comparable with that for southern California (Lin et al., 2007) at depths up to about 30 km. A sufficient attenuation with distance will have an encouraging implication on seismic hazard assessments.

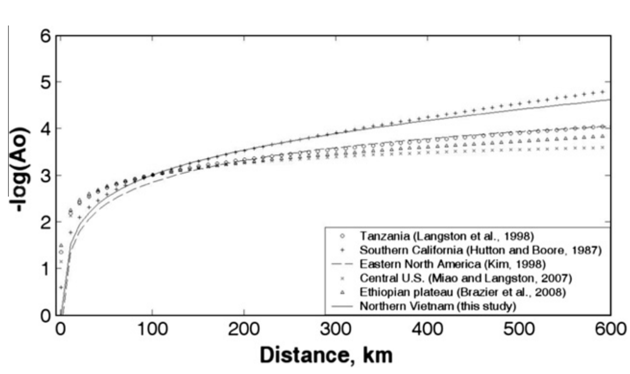

Fig. 5. Comparisons between distance-correction functions obtained in this study for Northern Vietnam and those for the other tectonic regions. The distance-correction curves for Northern Vietnam and southern California are quite similar, and show relative strong attenuations. (See above-mentioned references for further information.)

Station corrections range from −0.38 to 0.30 in the units of the M_L magnitude (Table 2). As indicated in Eq. (6), a station with a positive correction will result in a smaller $\log A_{W-A}$ (*i.e.* peak amplitude), while one with a negative station correction will cause an amplification. Station correction factor reflects the local site conditions at the recording station to some extent (Miao and Langston, 2007; Richter, 1958; Wu et al., 2005). In general, stations located in the northwestern regions of Vietnam have positive station corrections while ones located in the south-eastern regions of Vietnam have negative station corrections (Fig. 6). Note that there are two stations in the southeast, PLVB and THVB, that have positive station corrections, and three stations in the northwest, as HBVB, LCVB and SPVB, that have negative station corrections. According to the preliminary analysis of site responses to ambient noise and *in situ* site inspection during the station selection process in this study, the stations PLVB and THVB are located in relatively firm sites, which have lower amplification of noise recordings than those of the other southeastern stations. In opposite, the stations HBVB, LCVB and SPVB are located on weaker sites and have higher amplification compared to those of the other northwestern mountain stations.

As mentioned in the Introduction, the result of Le and Dinh (2008) was based on the M_L equation for crustal earthquakes in regions with attenuate properties similar to those of southern California, which were originally given by The Working Group on Magnitudes (*Magnitude WG*) of the IASPEI and CoSOI. In this study we have derived a new attenuation relation that is more specific for the Northern Vietnam region.

We also have compared the new M_L in this study with duration magnitudes, which were derived from records of respective stations and are still being used for making the official earthquake bulletin in Vietnam (Fig. 7). The relationship between them is obtained as

$$M_L = 0.955M_d + 0.17 \pm 0.31.$$

Due to the moderate seismicity in Northern Vietnam, with most earthquakes having magnitudes of less than 6.0, this relationship can be applied for most events in the region.

Although there are only 23 events that were recorded by both two types of magnitude, the slope of 0.955 shows that new M_L are somewhat suitable with M_d. Previous studies have pointed out that the duration-based magnitude varies slightly with epicentral distance because of its dependence on coda-waves. As a result, M_L is more rather physically suitable for describing the crustal attenuation behavior for a given region and it has the direct relevance to engineering applications (Kanamori and Jennings, 1978; Kanamori, 1980), which is the main purpose of our study. Although M_d is quite similar to the new M_L magnitude scale, there is no station correction in the M_d equation for Vietnam (Nguyen, 1996). The local site effects influence the ground motions and can, dependent on the station, overestimate or underestimate M_d up to 0.5 magnitude (Mouyan et al., 2004). Besides that, it is unable to assign magnitudes to multiple events or large earthquakes having immediate aftershocks (Real and Teng, 1973).

We have derived the first local magnitude scale (M_L) for Northern Vietnam. The resulting attenuation curve is similar to that of southern California. The first attenuation curve with distance for

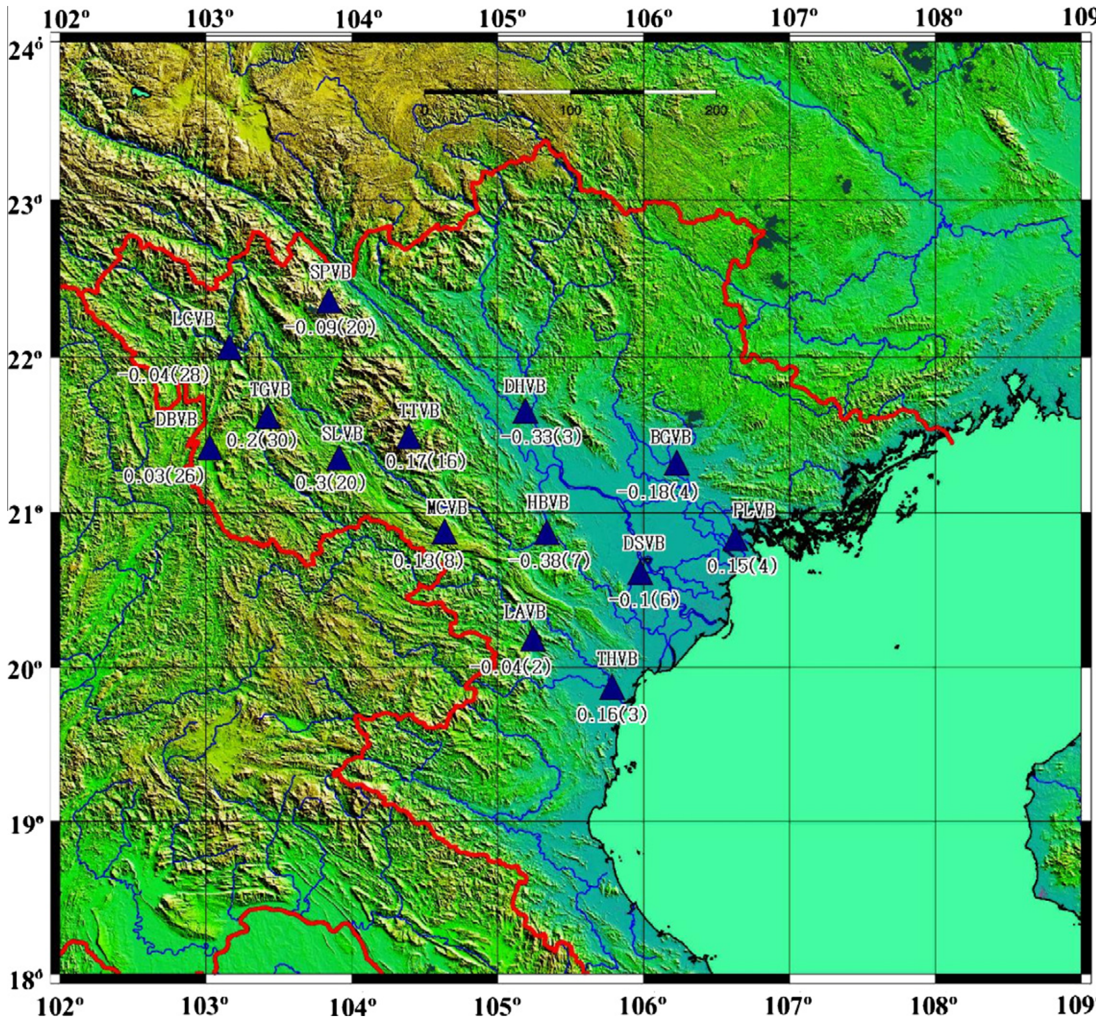

Fig. 6. Distribution of station corrections obtained in this study. Numbers without and with parentheses are the values of station correction and the numbers of amplitude reading, respectively (Table 2).

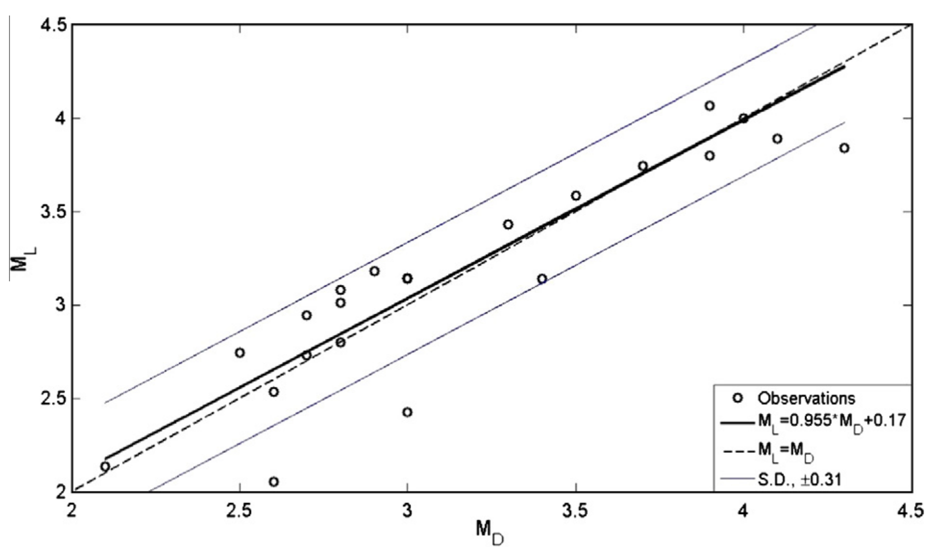

Fig. 7. Relationship between new local magnitude obtained in this study and duration magnitude (Table 1) currently being used in the Vietnam official earthquake bulletin.

northern Vietnam proposed in this study will provide the essential parameters needed in seismic hazards assessments such as for Probabilistic Seismic Hazards Assessment (PSHA) and earthquake shaking maps.

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