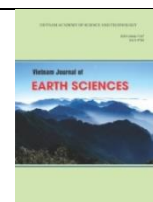




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## Relationship between seismicity and active faults in Thanh Hoa province detected by local seismic network

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### ABSTRACT

Thanh Hoa province belongs to the southwest part of Northwest Vietnam, which is considered a tectonically active region. In the area of Thanh Hoa province, there are three deep-seated tectonic faults, namely Son La-Bim Son, Song Ma, and Sop Cop. As predicted by scientists, these faults are capable of producing credible earthquakes that might be the strongest in the territory of Vietnam. Besides the three main seismogenic sources, in the province, there are other smaller active faults such as Thuong Xuan-Ba Thuoc and Thuong Xuan-Vinh Loc but the relationship of these faults with seismic activity is still rather blurred. This may be due to the sparseness of the Vietnamese National Seismic Network which can not record adequately small earthquakes in the area. This paper presents new results of additional monitoring from a local seismic network using 12 Guralp - 6TD broadband seismometers that have been deployed in Thanh Hoa province since November 2009. We found that the Thanh Hoa area is not seismically quiet. The average number of earthquakes recorded by the network has reached 80-90 events per year and some of them have magnitude from ML 3.0 to 4.0.

By integration of the earthquake epicenters derived from the local network and distribution of active faults, we can detect several earthquakes locating near the three active faults, not only along the main faults but also along its subsidiary faults. We focused on the active faults of Thuong Xuan-Ba Thuoc and Thuong Xuan-Vinh Loc by using the recent results of the gravity, seismic, and magnetotelluric data analyses. Several recorded earthquakes distribute along the two small faults and some of them reach magnitude 3.0 or greater on the ML scale. In this study, the Thuong Xuan-Vinh Loc is recognized as a seismogenic source. To identify seismic hazard potential caused by earthquakes generated from the active faults, segmentation of the Thuong Xuan-Ba Thuoc fault had been done based on geological and geomorphological indications and seismic activity, and then the peak ground acceleration was determined for each fault segment. Besides, a large number of earthquake epicenters do not have a good correlation with a specific fault, especially in the area of Thanh Hoa coastal plain, which is covered by thick layers of Neogene - Quaternary sediment. This shows that there may be hidden active faults in the area which are needed to study further.

*Keywords:* Seismic activity; active fault; local seismic network; Thanh Hoa.

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### 1. Introduction

Thanh Hoa province belongs to the Northwest Tectonic Region, where earthquake

activity is assessed to be the strongest in Vietnam. During the last 100 years, 2 earthquakes of magnitude 6.7 and 6.8 were recorded in this region along with 13 events with magnitude  $5.0 \leq M < 6.0$  and hundreds

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of earthquakes with magnitude  $4.0 \leq M < 5.0$ . The genesis relationship between the earthquakes and active tectonic faults has resulted from the previous studies. The earthquakes of magnitude  $M \geq 5.0$  have occurred in most of the main active tectonic fault zones in the region (Fig. 1) (Nguyen D.X. et al., 2004; 2009; Nguyen N.T. et al.,

2006). Several active faults were identified by the earthquake manifestation, including the Lai Chau-Dien Bien, Sop Cop, Song Ma, Son La-Bim Son, Song Da, and Muong La-Bac Yen. Among the faults, there are three deep-seated faults, including Son La-Bim Son, Song Ma, and Sop Cop which have gone through the study area.

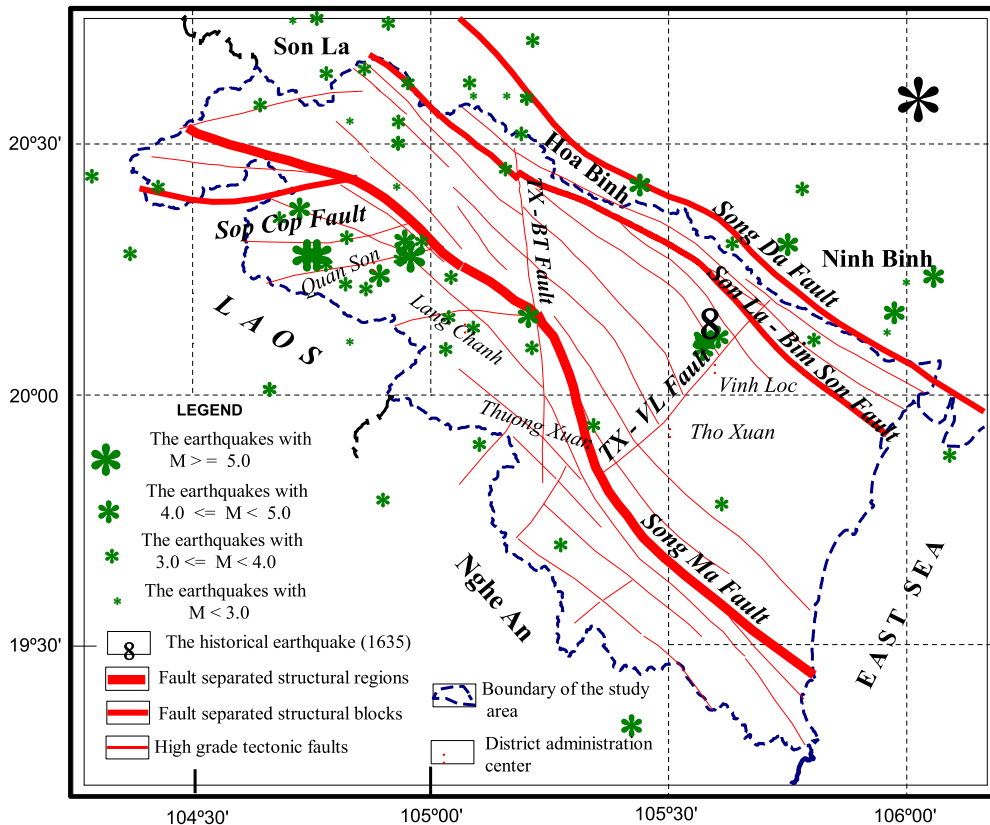


Figure 1. Distribution of earthquake epicenters (time period 114-2003) in the Northwestern of Vietnam from historical and intrumental catalog (Nguyen D.X. et al., 2004)

All these three faults are terminated by the sub meridian trending Lai Chau-Dien Bien fault in the northwest segment of each. Being the biggest faults in the Northwest region, the Song Ma and Son La-Bim Son faults demonstrate much stronger earthquake activity along with their northwestern segments in Son La and Dien Bien provinces whilst along with their southeastern segments in Thanh Hoa province the earthquakes of magnitude  $M \geq 3.0$  are clustered with much

lower density in comparison with their northwestern segments. In fact, the earthquakes observed along the southeastern segment of the Son La-Bim Son fault zone are mostly concentrated in the surroundings of the historical earthquake (1635) in Vinh Loc district, which supposedly caused intensity VIII by MSK-64 scale (Nguyen D.X. et al., 2004). Along the southeastern segment of the Song Ma fault zone, the seismicity is more intense where it intersects with the Sop Cop

and Thuong Xuan-Ba Thuoc sub meridian faults in Quan Son, Lang Chanh, and Thuong Xuan districts. A moderate earthquake with a magnitude of 5.1 occurred in 1954 at the intersection between the Song Ma and Sop Cop faults. More dense distribution of earthquake epicenters is observed in the intersection of the Song Ma and Thuong Xuan-Ba Thuoc faults. Though shorter than the Song Ma and Son La-Bim Son faults, but the Sop Cop fault generated a strong earthquake of  $M = 6.8$  (1935) in Dien Bien province. The Sop Cop and the Song Ma faults have segments of 100 and 80 km long respectively passing the Laos territory. Not much-studied results on these segments of the faults are available, however, several earthquakes  $3.0 \leq M \leq 4.0$  generated in both those segments were recorded (Nguyen D. X., et al., 2004; Nguyen T.Y. et al., 2014). In Quan Son, Thanh Hoa, where the Sop Cop fault changes the direction from the NW - SE to the sub-latitudinal, the earthquake activity is increased. Noteworthy that two earthquakes with magnitudes 5.5 and 5.7 occurred along this segment in 1948 and 1958 respectively (Nguyen D.X. et al., 2004). Recently on September 19, 2010, an earthquake with magnitude 4.5 happened in Son Ha Village, Quan Son district that located on the same segment of the fault. Thus, more seismic activity was observed in different locations in Quan Son, Lang Chanh, Thuong Xuan, and Vinh Loc districts within the study area. However, in the remaining locations, including a large space between the Son La-Bim Son fault and Song Ma fault, the earthquake epicenters are distributed very sparsely, and the relationship of the earthquakes with active faults is unclear. The uncertainty of the seismic activity of this area may be related to the sparse National Seismic Network, which can not record adequately the small earthquakes in the study area. To better understand the facts, in reality, a more detailed study of the seismic activity as well as the active faults, in particular, the high-grade faults is extremely needed.

In the framework of cooperation between the Institute of Geological Sciences, Vietnam Academy of Science and Technology (IGS-VAST), and Chung Cheng University (CCU), a local network with 12 Guralp 6TD digital broadband seismometers was deployed in the area stretched from the Thuong Xuan-Ba Thuoc fault to the Thanh Hoa plain. The monitoring results indicated that the Thanh Hoa area is not so quiet in terms of seismic activity. The average number of earthquakes recorded by the local network has reached 80-90 events/year. Most of the earthquakes have magnitudes ML ranging from 1.0 to 3.0, and some of them have magnitude ML ranging from 3.0 to 4.0. Inside the three main aforementioned fault zones, several earthquake epicenters are distributed not only along the main faults but also along their auxiliary branches. Along the Thuong Xuan-Ba Thuoc (TX-BT) fault, a denser distribution of epicenters is observed in its southern segment. In particular, the earthquake epicenters are densely distributed along a northeast-southwest trending boundary separated the Thanh Hoa plain sub-zone from the Cam Thuy one. This boundary is given the name Thuong Xuan-Vinh Loc (TX-VL) fault, which is not recognized as a seismogenic source up to now. This paper presents the results of the earthquake monitoring and the relationship between the observed earthquakes with the active tectonic faults in the study area, especially our study will focus on the Thuong Xuan-Ba Thuoc and Thuong Xuan-Vinh Loc faults, which are still poorly investigated.

## 2. Tectonic settings

### 2.1. Main structural zones

The study area belongs to Thanh Hoa province where the regional active Song Ma fault separates the Northwest Structural Region in the northeast from Truong Son one in the southwest. A large part of the study area belongs to the Northwest Region and the remaining part belongs to Truong Son Region.

Due to the aforementioned position of the area, all the structural zones were formed by average orogenic uplift associated with an NW-SE trending linear fold belt. In this case, the uplift differentiation was simultaneously taking place along the NE-SW direction.

The similar characteristics are also reflected in the Moho, Conrad, and Crystalline discontinuities as described in Tran V.T. et al. (2011); Dinh V.T. et al. (2010), and Lai H.P. (2016). From the northeast to southwest of the study area, there is a belt running along the northeastern slope of the Son La-Bim Son fault zone temporarily called the Northeast structural belt, which is a part of the Cuc Phuong block on the southwestern edge of the

weak differentiated uplift zone of Song Da synclinal fold form (Fig. 2). The next large area is the area located between the Son La-Bim Son and the Ma River faults, occupying the southeastern part of the Su Sung Chao Chai structural block, here referred to as the Quan Hoa block, and the entire Thanh Hoa block. The remaining part which belongs to the Truong Son structural region with a given name Southwest zone is a narrow belt running along the southwestern flank of the Song Ma fault as described in studies of Nguyen V.H. (2002); Phung V.P. et al. (2002); Nguyen N.T. et al. (2006); Tran V.T. et al. (2011); Dinh V.T. et al. (2010; 2012); Nguyen V.H. et al. (2016); Lai H.P. et al. (2018).

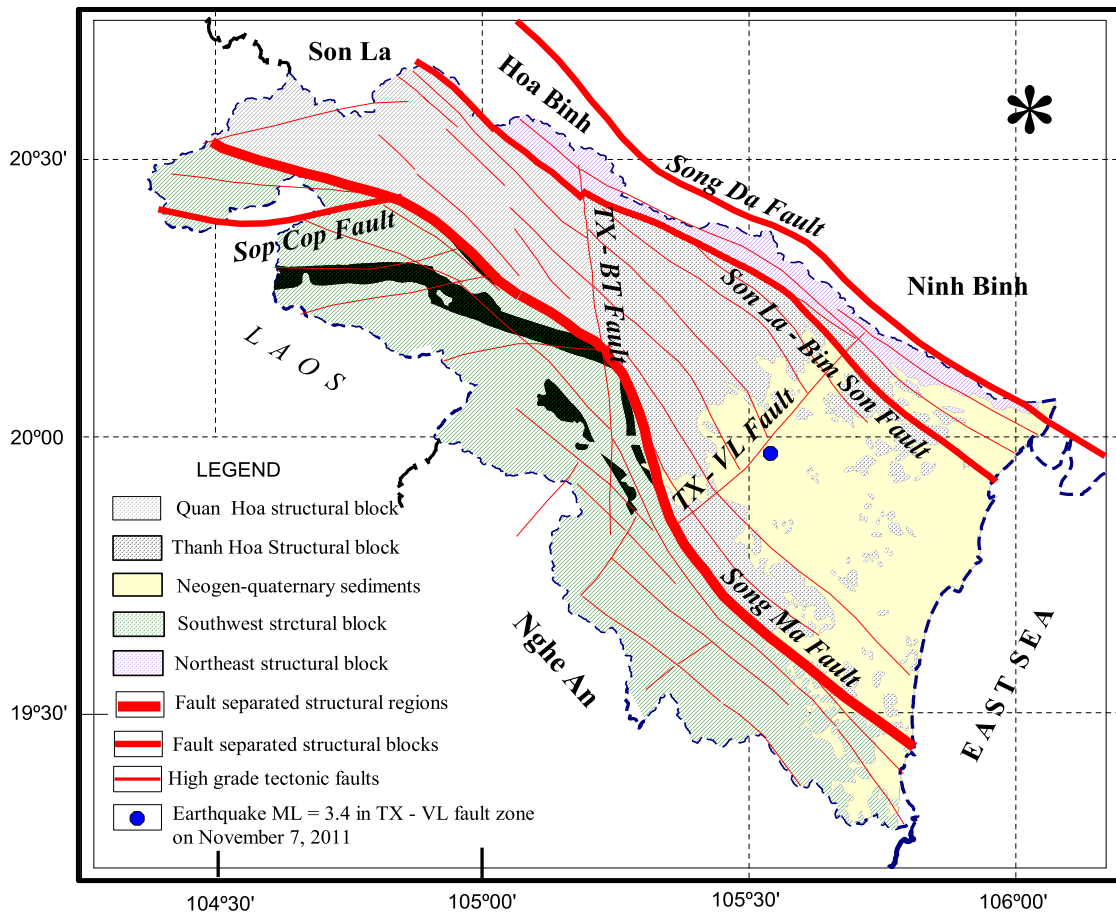


Figure 2. Distribution of tectonic zones in Thanh Hoa area in the broader geological context of Northwestern of Vietnam (Dinh V.T. et al., 2010)



## 2.2. Major tectonic faults

As mentioned above, the study area is crossed by three deep crustal faults including Son La-Bim Son, Song Ma, and Sop Cop faults (Fig. 2). All of them are terminated in the northwestern end by the sub meridian fault Lai Chau-Dien Bien. A lot of published results related to the maximum credible earthquake from these faults predicted that the faults could generate the largest magnitude in the territory of Vietnam ( Nguyen T.Y. et al. (1998); Tran T.H. et al. (2001); Nguyen V.H. (2002); Nguyen V.H. et al. (2006; 2009); Nguyen D.X. et al. (2004; 2009), Nguyen N.T. et al. (2006); Dinh V.T. et al. (2010; 2012); and Lai H.P. et al. (2018). However, the segments of the Song Ma and Sop Cop faults distributed in the Laos territory are poorly understood as compared to their segments in Vietnam as pointed out by Nguyen T.Y. et al. (2014) and Bui V.T. et al. (2014). The movement mechanism of all three faults is dominantly strike-slip during the Pliocene - Quaternary times. Depend on the local conditions, its movement mechanism may be strike-slip faulting with a thrust or normal components. In general, the Southeast of the fault zones are widely expanded and the normal component of its movement is also increased. In particular, a segment of the Sop Cop fault crossing from Laos into Vietnam's territory through the Quan Son district is indicated by the strike-slip motion with the thrust component. Except for the aforementioned regional faults in the study area there are also exist numerous smaller size faults with the manifestation of moderate seismic activity, including the Thuong Xuan-Ba Thuoc (TX-BT) and Thuong Xuan-Vinh Loc (TX-VL) faults. Most of these faults are not well studied up to present as mentioned by Nguyen D.X. et al. (2004); Nguyen N.T. et al. (2006); Dinh V.T. et al. (2012); 2013); Lai H.P. et al. (2018).

## 3. Results and discussion

### 3.1. Geological structure

Not all earthquakes in the study area were recorded by the Vietnam National Seismic Network since the seismometers of the network are distributed very sparsely, just only 1 or 2 instruments are operated alternately at different times in this area. Thus, most of the recorded earthquakes are characterized by a magnitude 3.0 or greater. The lack of smaller earthquake data may cause it to reflect inadequately the spatial relationship between seismic activity and active faults. Even in some segments that belong to the main branches of the three aforementioned strongest earthquake generating faults, there were no earthquakes recorded. Also, rarer earthquakes were detected along their auxiliary branch. Since the end of the year 2009, a local network consisting of 12 Guralp-6TD broadband seismometers was deployed in the study area. A large number of earthquakes are recorded and a large portion of them are characterized by a magnitude from 1.0 to 3.0. In particular, magnitudes of several earthquakes reached 4.0 or greater as indicated in the studies of Dinh V.T. et al. (2012; 2013); Wen S. et al. (2015); Su. C.M. et al. (2018), Lai H.P. et al. (2018); Wu J.W. et al. (2018). This supplement data allowed us to study more detail and more adequate the spatial relationship between the active faults and seismic activity in the study area. According to the monitoring results, the earthquakes are not only detected in the faults of regional character, but numerous tremors were recorded on several smaller faults, including the Thuong Xuan-Ba Thuoc and Thuong Xuan-Vinh Loc faults. Up to now their spatial distribution and seismic generation potential are still not well studied. In this study, except for the location of an additional number of the earthquakes recorded over the past few years, a comprehensive study to define the lengths and the penetration depths of the Thuong Xuan-Ba Thuoc and

Thuong Xuan-Vinh Loc faults was also conducted. New data make it possible to get a more improved estimation of the relationship between the seismic activity and the active fault distributions in the study area.

*Location of new recorded earthquakes*

For the earthquake data collection in the first stage from 2009 to 2013, the broad-band instruments were deployed along the main branch of the Song Ma fault, on both its flanks from Lang Chanh to Nong Cong districts extending more than 80 km long. From 2014 to the present, the space of the network distribution was expanded with the expectation to record not only the earthquakes generated by the Song Ma fault but also the earthquakes generated by the Son La-Bim Son fault (Fig. 3). The location of the recorded earthquakes was carried out for the data collected from 2010 to 2019 years in both organizations: The CCU and the IGS-VAST (Dinh V.T. et al., 2010, 2013; Wen S. et al., 2015; Lai H.P. et al., 2018; Su C.M. et al.,

2018). The determined earthquake parameters comprised the earthquake epicenter coordinates, origin time, depth, and magnitude in ML scale based on the travel times of the P and S waves from the source to stations, the wave amplitude, and the crustal velocity model by using the HYPO71 software package (Lee. et al., 1972; 1985; 2009). The Geiger location algorithm realized by this software package is described in detail in several publications such as studies of Thorne L., Terry C.W. (1995); Dinh V.T. et al. (2013); Wen S. et al. (2015). In this study, the location of the earthquakes was just carried out for a portion of the events collected from 2014 to the middle of 2019. This time the crustal velocity model (Table 1) obtained from 1D seismic modeling with the use of the earthquake data collected by the local network in the study area was used for the location of the earthquakes by Wen S. et al. (2015). This model is more appropriate to the local conditions.

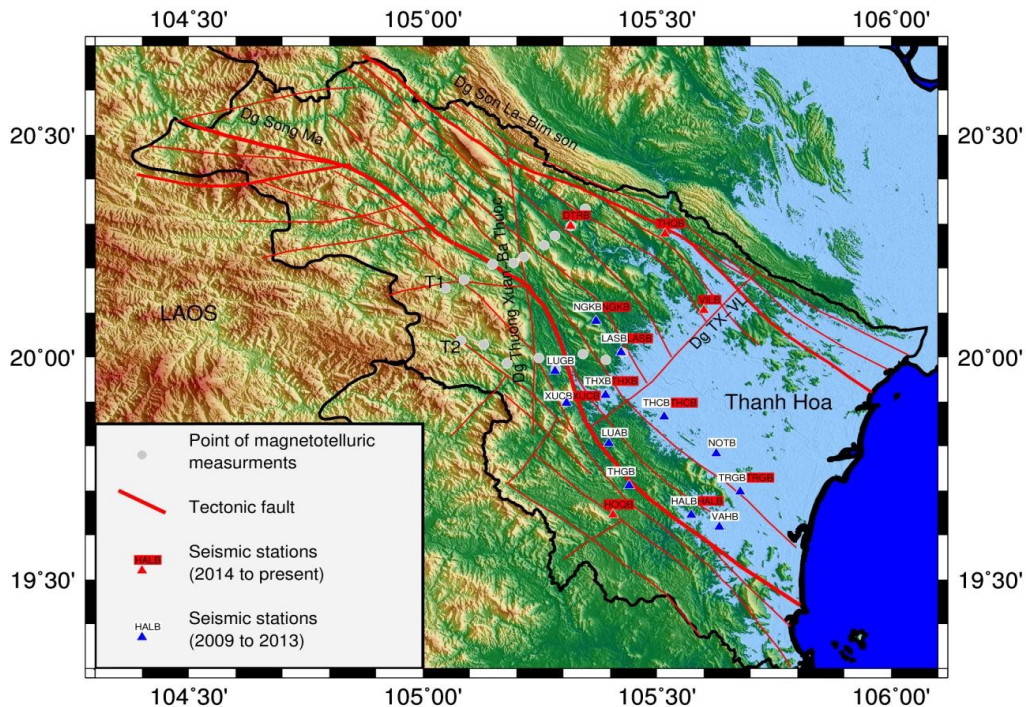


Figure 3. Map of local seismic network and points of magnetotelluric survey in Thanh Hoa area

*Table 1.* Seismic wave velocities (km/s) in the shallow layering crust (0-50 km)

No.	Depth of seismic layer (km)	P-wave ( $V_p$ , km/s)	S-wave ( $V_s$ , km/s)	$V_p/V_s$
1	0 - 2	4,034	2,463	1,64
2	2 - 4	4,608	3,094	1,49
3	4 - 10	5,187	3,105	1,67
4	10 - 18	5,653	3,303	1,71
5	18 - 26	6,292	3,619	1,74
6	26 - 34	6,334	3,620	1,75
7	34 - 50	6,866	4,232	1,62

Among the earthquakes recorded during the time from 2014 to May 2019 more than 300 events were located. This result combined with the earthquakes recorded in the first stage was used for the determination of the spatial relationship between the seismic activity and active faults of the study area in the next section. Several earthquakes considered as the representative events located in this study are listed in Table 2.

*Table 2.* Representative earthquakes (2009-2019) recorded by the Thanh Hoa local seismic network

No.	Time		Coordinates		Magnitude ( $M_w$ )	Focal Depth (km)
	Year/ Month / Day	Hour: Minute: Second	Longitude	Latitude		
1	2009/12/06	17:48:20.99	105.3173	19.83017	1.2	10.0
2	2010/05/17	04:19:17.37	105.594	20.1355	1.2	10.9
3	2010/09/04	04:54:43.92	105.2220	20.0459	2.7	07.0
4	2010/09/19	15:58:45.67	104.9470	20.2200	4.2	10.3
5	2011/04/29	03:16:37.52	105.2594	19.8744	1.7	05.1
6	2011/05/21	20:32:14.39	105.3044	20.1091	2.1	12.6
7	2011/11/07	06:25:48.64	105.4866	19.9605	3.5	08.5
8	2012/09/29	12:57:13.33	105.5750	19.7358	2.5	07.0
9	2012/10/03	03:19:05.79	105.7110	20.1070	3.2	15.0
10	2013/06/12	05:14:25.26	105.6867	20.0909	1.1	05.0
11	2013/05/27	14:02:07.99	105.4810	19.6468	2.6	20.0
12	2014/06/12	00:25:04.46	105.7313	20.3578	1.2	05.0
13	2014/11/27	04:02:42.36	105.5596	19.9211	2.0	05.5
14	2015/03/29	14:50:59.46	105.2340	19.8400	1.3	05.5
15	2015/11/27	10:53:37.00	105.5090	20.0770	2.2	10.2
16	2016/04/19	19:15:18.60	105.6370	20.4040	1.6	05.1
17	2016/09/23	11:23:08.40	105.5210	20.0650	2.2	04.4
18	2017/09/06	05:41:03.60	105.8100	20.4020	1.9	04.3
19	2017/06/23	08:57:03.20	105.4250	19.9090	2.7	11.1
20	2018/05/16	02:00:54.10	105.3660	20.0660	1.5	05.0
21	2018/03/27	22:39:21.10	105.2780	19.8900	2.8	10.2
22	2018/03/12	20:08:31.60	105.2740	19.8900	3.3	10.7
23	2018/05/16	00:27:27.40	105.2860	19.8940	3.2	10.2
24	2019/03/04	04:00:04.00	105.2720	19.8730	1.4	09.7
25	2019/07/23	04:37:41.30	105.3680	20.3750	2.1	10.6
26	2019/05/26	23:21:59.00	105.2560	20.1280	3.0	10.4

*Detail study of the Thuong Xuan-Ba Thuoc and Thuong Xuan-Vinh Loc faults*

For a more detailed estimation of the spatial relationship between the seismic activity and active faults, not only the earthquake data need to be more adequately collected but a more detailed study of some fault parameters, such as their spatial distribution as well as the movement characteristics are also needed. The three large faults including Son La-Bim Son, Song Ma, and Sop Cop passing the study area are estimated as the sources of strong earthquake generation, however, the earthquake data collected previously are not detailed enough to track the seismic activity of the different fault branches. Some smaller faults show evidence of seismic activity but their earthquake generation potential is not estimated up to now, e.g. the Thuong Xuan-Ba Thuoc fault. Some faults are not considered as seismogenic sources in previous studies, but reveal positive seismic activity according to data sources recorded by the local network such as Thuong Xuan-Vinh Loc fault. Noteworthy that earthquakes of magnitude  $M > 3.0$  were recorded in both of these fault zones (Nguyen D. X., et al., 2004; Dinh V.T. et al., 2012; 2013; Wen S. et al., 2015; Lai H.P. et al., 2018). This fact may be related to the stronger earthquake generation in the faults and further study is needed. Besides that, if the depth to the bottom of the seismogenic structure is known, the maximum credible earthquake generated in these faults can be estimated, of course, it also depends on their length (Nguyen D.X. et al., 2009). Among the two mentioned above faults, the Thuong Xuan-Ba Thuoc one is more or less studied for the last recent years. This active fault is clearly observed on the topographic and geomorphologic maps along 75 km of its whole length, as indicated by Tran V.T. et al. (2012) and Lai H.P. et al. (2018). Related to the Thuong Xuan-Vinh Loc fault, up to the

present it is just known by quite general information as a boundary between the two sub-zones which belong to the Thanh Hoa structural zone. In this study, the spatial distribution and penetration depths of the Thuong Xuan-Ba Thuoc and Thuong Xuan-Vinh Loc faults were determined by using the results of the gravity, earthquake seismic, and magnetotelluric data analyses. The preliminary segmentation based on the results of the geologic, geomorphologic and seismic activity investigations was carried out for the Thuong Xuan-Ba Thuoc fault by Dinh V.T. et al. (2012); Tran V.T. et al. (2012); Lai H.P. et al. (2018); Su C.M. et al. (2018); and Pham N.D. et al. (2018).

*Thuong Xuan-Ba Thuoc and Thuong Xuan-Vinh Loc faults on the map of the gravity anomalies and main discontinuities of the Earth's crust*

On the map of Bouguer gravity anomalies, the Thuong Xuan-Ba Thuoc fault zone is reflected by the linear anomaly strip of the north-south direction with the largest horizontal gradient. Meanwhile, the Thuong Xuan-Vinh Loc fault is identified as a boundary that separated from the concave negative anomaly covering the Thanh Hoa plain sub-zone in the coastline area from the positive anomaly reflects the Cam Thuy sub-zone in the Northwest (Fig. 4). Similar signs can be found on the maps of gravity anomalies upward continued to the levels 5km (Fig. 5) and 10 km. However, on the map of gravity anomalies upward continued to the level of 15m only the Thuong Xuan-Ba Thuoc fault can be detected by the aforementioned signs, the Thuong Xuan-Vinh Loc fault is disappeared on it (Dinh V.T. et al., 2010); Lai H.P. et al. (2016). This indication allowed us to qualitatively estimate their penetration depths, that the Thuong Xuan-Ba Thuoc has penetrated deeper into the earth's crust than the Thuong Xuan-Vinh Loc one. The spatial distribution and penetration depth of the faults

also can be qualitatively estimated based on the structural characteristics of the interface in the Earth's crust. Often the fault is presented as a boundary separated one structural zone from another; it also appears along the narrow linear belt with a quick change of the layers boundary depths along the vertical direction or where a sudden change of its form. According to the results of the studies on the crustal structures in North Vietnam in recent times of Dinh V.T. et al. (2010; 2018) and Lai H.P. et al. (2016), both aforementioned faults

are identified on the crystalline basement and Conrad interface. On the crystalline basement, the two faults are presented as a boundary separated one structural unit from another (Fig. 6). Whilst on the Conrad discontinuity these two faults appear as the boundary between the structural units just along some of its segments. In the remaining segments, these faults are identified by the sudden change of the shape and direction of the structural units on their boundary interfaces (Fig. 7).

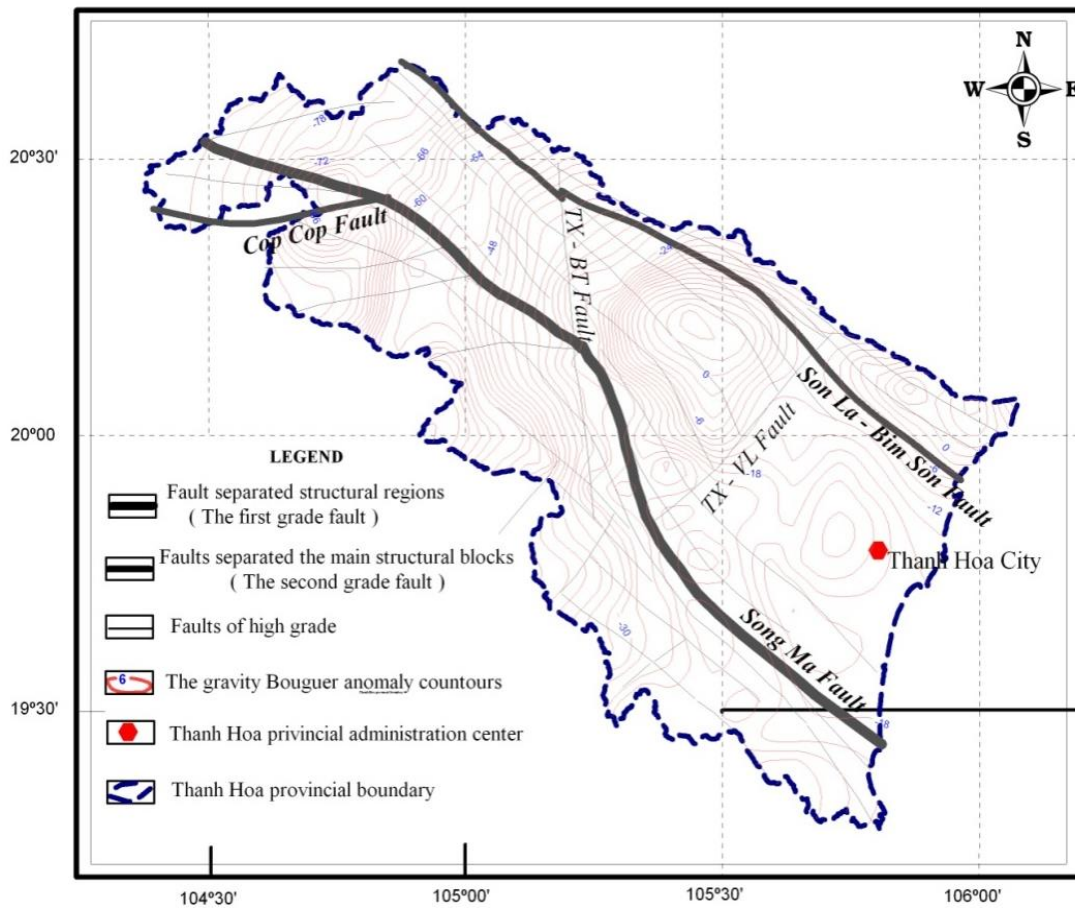


Figure 4. Thuong Xuan-Ba Thuoc (TX-BT) and Thuong Xuan-Vinh Loc (TX-VL) faults on the Bouguer gravity anomaly map



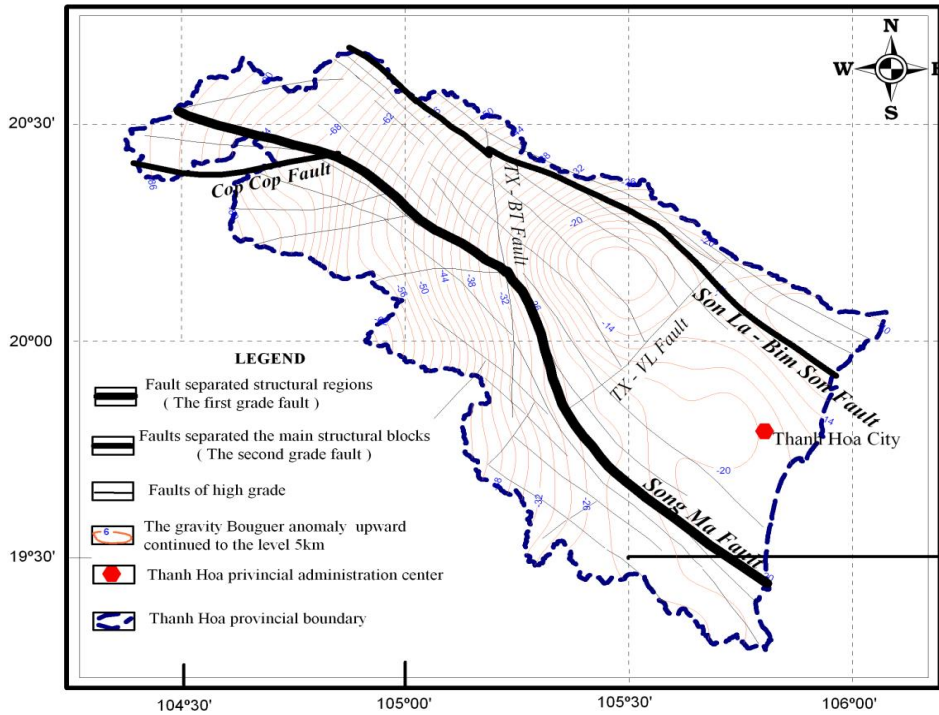


Figure 5. Thuong Xuan-Ba Thuoc (TX-BT) and Thuong Xuan-Vinh Loc (TX-VL) faults on the map of gravity anomalies upward continued to the level 5 km

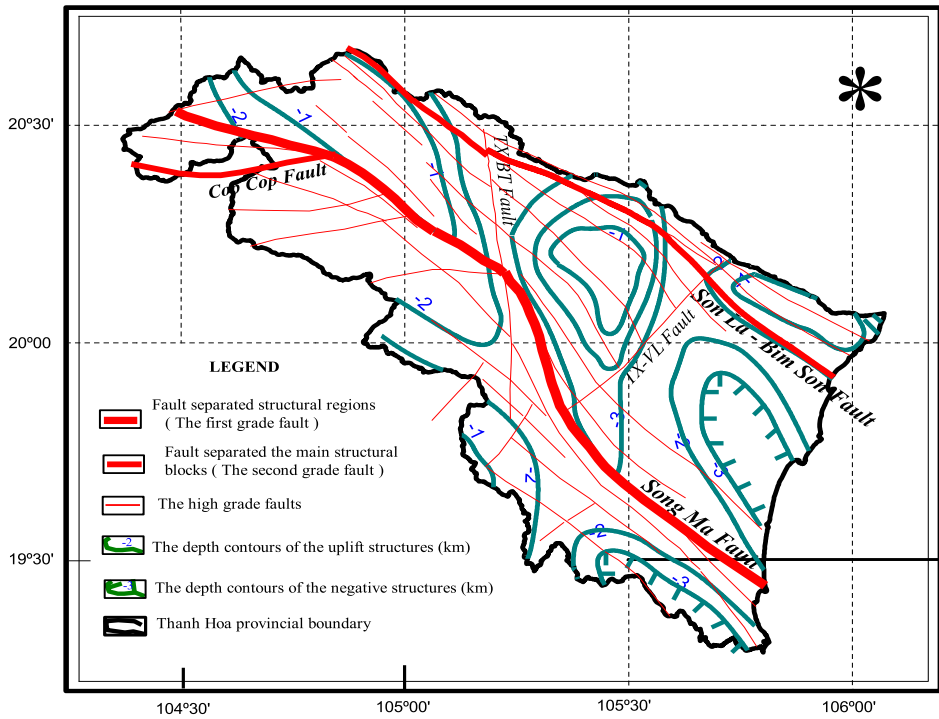


Figure 6. Map of the crystalline basement of Thanh Hoa province calculated from gravity data with overlaid TX-BT and TX-VL faults



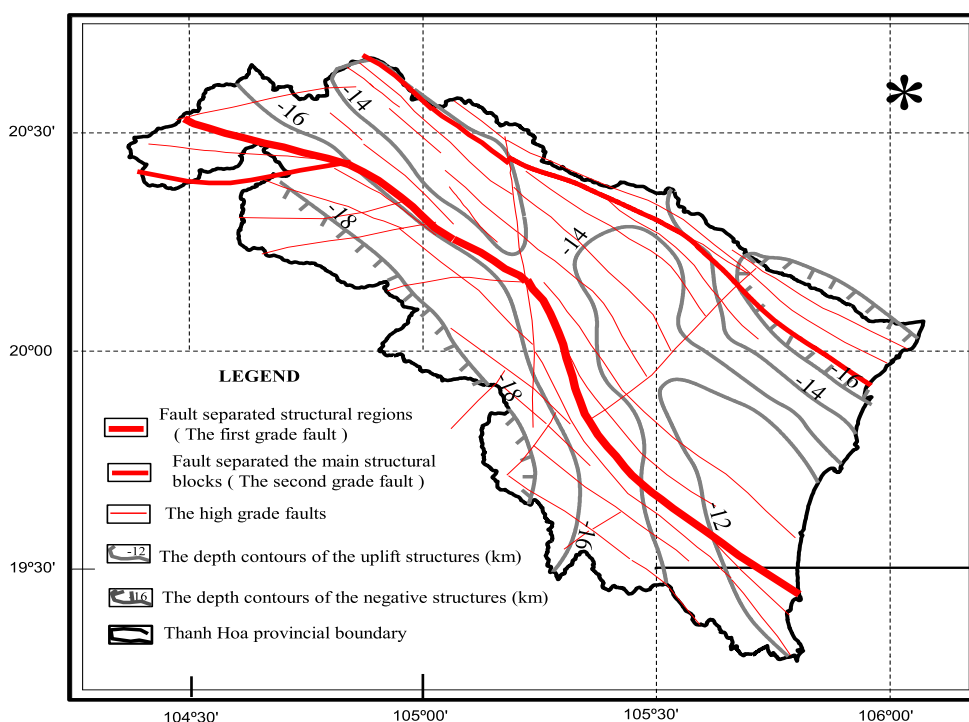


Figure 7. Map of the Conrad discontinuity with overlaid TX-BT and TX-VL faults

No indications related to the existence of the faults can be found on the Moho discontinuity and in this case, the penetration depths of these faults are limited by the Conrad discontinuity. Thus the penetration depth of the Thuong Xuan-Ba Thuoc fault was estimated by a range of  $H > 16-18$  km and a smaller depth of  $H = 13-15$  km may be reached by the Thuong Xuan-Vinh Loc fault. To obtain more data for estimation of the penetration depths of these two faults, in this study the magnetotelluric measurements along the profile crossing the Thuong Xuan-Ba Thuoc fault and the results of seismic data analysis along the profile crossing the Thuong Xuan-Vinh Loc fault were used.

#### *Estimation of the depth of Thuong Xuan-Ba Thuoc fault using magnetotelluric data*

Two magnetotelluric investigation profiles were carried out in the study area, both of them cross the Song Ma and Thuong Xuan-Ba Thuoc faults. The first profile consists of 9

measurement points and stretches from Lang Chanh to Ba Thuoc districts 35 km long; the second profile is comprised of 8 measurement points stretching along 36 km from Thuong Xuan to Yen Dinh districts (Fig. 3). The data analysis was performed by the calculation of the differential resistivity distribution and 2D magnetotelluric inversion by using the software package ZondMT2D by Pham N.D. et al. (2018) and Lai H.P. et al. (2018). Based on these results the spatial distributions and penetration depths of the faults were estimated (Fig. 8).

According to the results, on the differential resistivity cross-section, the Thuong Xuan-Ba Thuoc fault is reflected by the lower resistivity zone in comparison with surroundings, whilst the Song Ma fault is demonstrated by the boundary that separated the lower resistivity zone from the higher one. Besides, the southwest dip direction with the penetration depth exceeded the Moho depth



data analysis results is reached 15-16 km, which just surpassing the Conrad discontinuity (Fig. 10). The fault is detected as a boundary, which separates the two part of the survey profile, of which from the beginning of the survey profile to the Tho Xuong seismic station (THXB), the amplitude of the wave changes in the layer above the Conrad surface is larger than in the rest part of the profile. The southeast dip direction of the fault is also clearly reflected in the above-mentioned conversion wave cross-section.

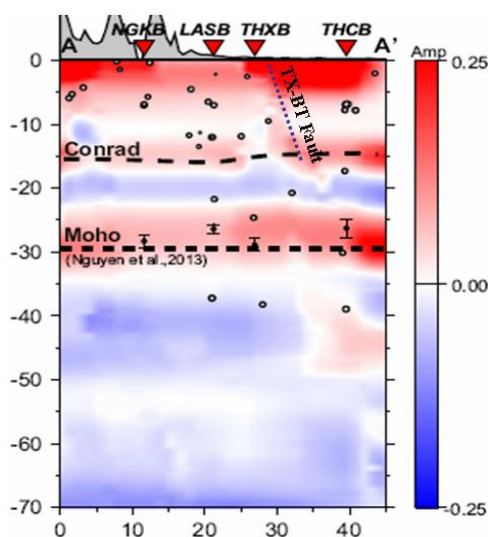
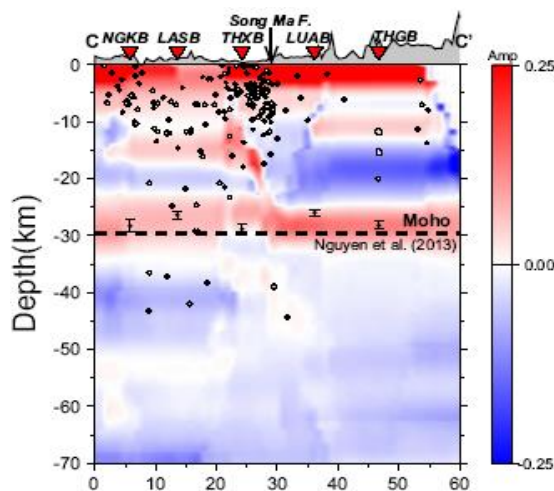


Figure 10. Crustal structure across Thuong Xuan-Ba Thuoc fault imaged from seismic data along the A-A' profile (Su et al., 2018)

+ Profile C-C' (Ngoc Lac-Nhu Xuan)

This profile is stretched about 60 km mostly along the north-south direction from Ngoc Lac to Nhu Xuan districts. On the seismic cross-section, the Song Ma fault is detected by a sudden change of the depths to the Conrad and Moho discontinuities at its two flanks. Along the first segment of the profile, which distributes between the Son La-Bim Son and Song Ma fault the Moho surface is uplifted to the depth of fewer than 30 km, meanwhile, in the southwest flank of the Song Ma fault, this surface is deeper submerged to 32 km (Fig. 11). The contrary feature is

observed on the Conrad discontinuity, this boundary is sunk into the depths 16-18 km in the northeast flank of the Song Ma fault and upraised to the depth of 14 km in its southwest flank. The southwest tendency of the fault dip direction is also detected.



Hinh 11. Crustal structures across Song Ma fault imaged from seismic data along the profile C-C' (Su et al., 2018)

Thus the penetration depths of the 75 km long Thuong Xuan-Ba Thuoc fault are estimated at 20-23 km by using magnetotelluric investigations. Meanwhile, the penetration depth of the Song Ma fault exceeded the Moho depth in the study area as shown in the previous studies is reconfirmed by the seismic data by Dinh V.T. et al. (2010; 2018) and Lai H.P. et al. (2016). Besides, the subsidence of the Moho surface in the southwest flank of the fault is reflected.

The results also indicate that the penetration depth of the Thuong Xuan - Vinh Loc fault is limited by the Conrad discontinuity and reached about 15-16 km. Bearing the aforementioned geometric parameters, the strong earthquake with a magnitude range  $5.0 < M < 6.0$  may be generated by these high-grade faults, of course, it also depends on their length as pointed out by Nguyen D.X. et al. (2009).



### 3.2 Relationship between seismic and fault activities

#### *Relationship between earthquake epicenters and distribution of active faults*

Regarding earthquake activity of Thanh Hoa area, the previous studies mainly reflect the seismogenic zones, which are the main branches of the three big size faults: Son La-Bim Son, Song Ma, and Sop Cop. According to the data collected by the local network, the Thanh Hoa area is not quiet by seismic activity. The earthquakes are recorded not only along their main branches, but a

considerable number of them are observed near the auxiliary branches (Fig. 12). There are clusters of epicenters distributed along the northeast and southwest auxiliary branches of the Song Ma fault. Particularly, the earthquake epicenters are observed in different locations along the total length of the southwest branch. The earthquakes are also detected inside the main branch of the Son La-Bim Son fault zone and in its northeast and southwest auxiliary branches, though not so many detected as in the Song Ma fault zone.

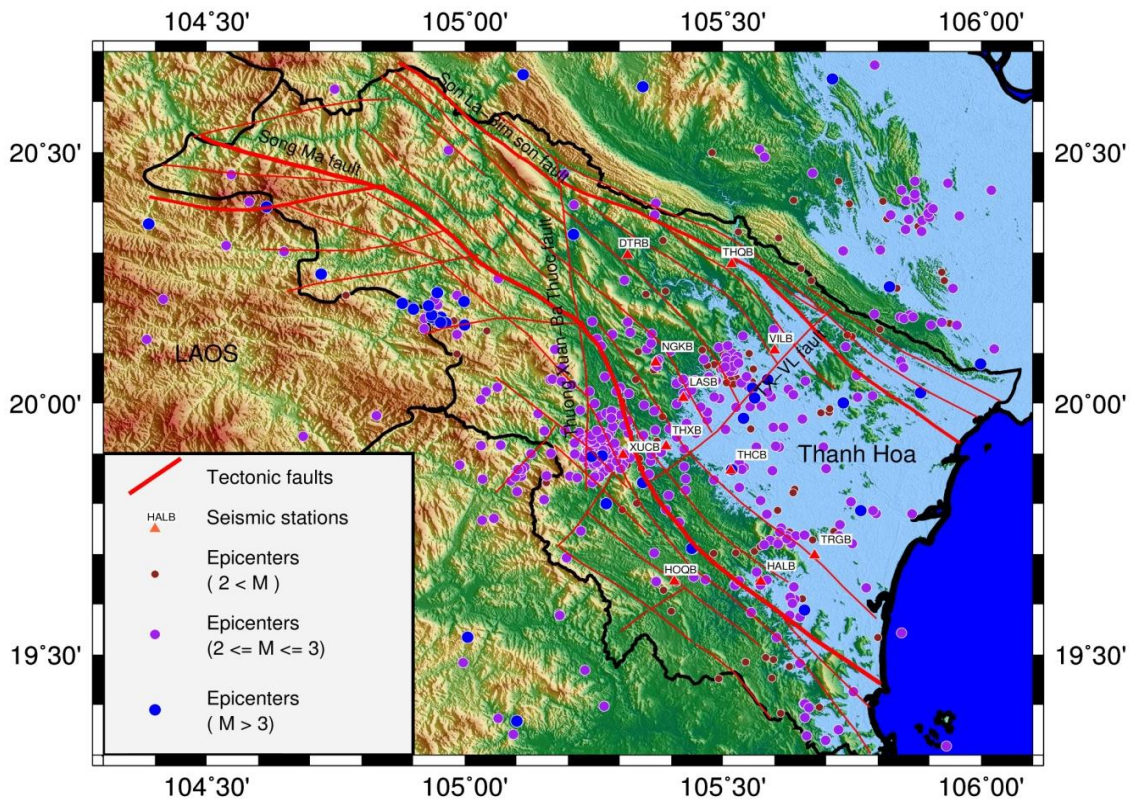


Figure 12. Spatial relationship between earthquake epicenters and active faults in Thanh Hoa province

It is noteworthy that the earthquake epicenters are relatively concentrated along the NE-SW trending Thuong Xuan-Vinh Loc fault zone, some earthquakes reached the magnitude  $M \geq 3.0$ . This more than 50 km long fault with the penetration depth limited by the Conrad boundary is still not

recognized as an earthquake generation source in the previous regional studies. The movement characteristics of the fault are estimated by the focal mechanism of the earthquake with  $M_L = 3.4$  (November 7, 2011) (Fig. 13) in the Tho Xuan district, according to which the dominant dip-slip

component in combination with the right strike-slip is the movement mechanism of the fault (Wen S. et al., 2015; Wu W.J. et al., 2018).

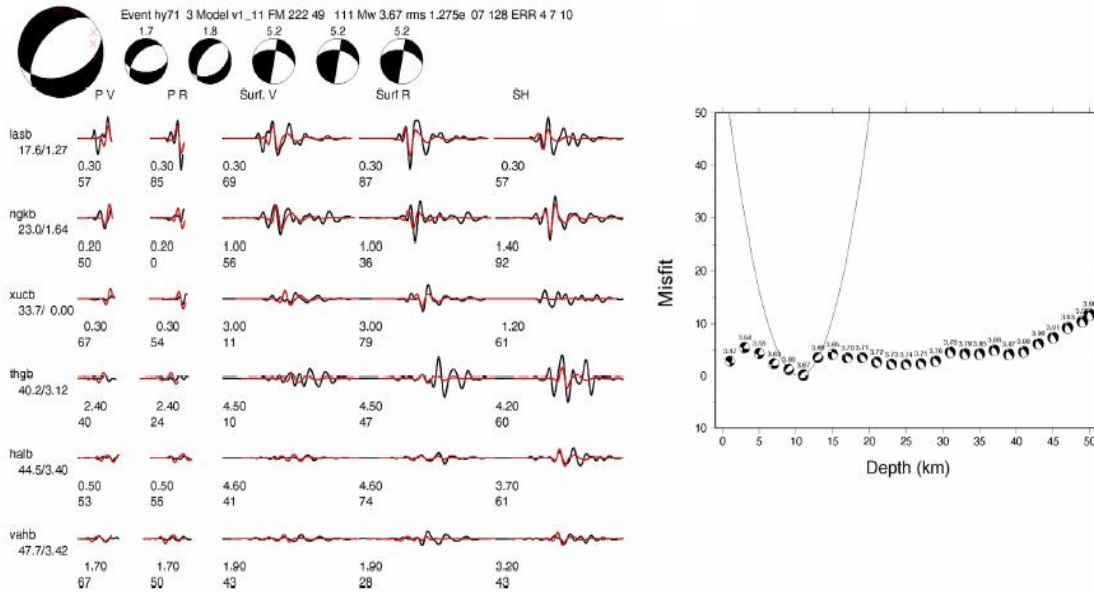


Figure 13. Seismic waveforms and focal mechanisms earthquakes occurred in Tho Xuan on November 7, 2011; ML=3.4

Since the fault cuts through the Song Ma structure zone and the number of the high-grade faults distributed in the area between the Son La-Bim Son and Song Ma faults, so the TX-BT fault is separated into different segments with a relative difference in their structural, geologo-geomorphologic characteristics and seismic activity.

Based on the deformation characteristics and seismic activity the fault can be divided into two big segments. The first segment running from the northern end to Lang Chanh town is characterized by the squeezed deformation in its fracture zone with almost vertical laminated layers. While in the remaining segment the fault is presented as a heavily fractured zone elevated with nearly vertical flat shear fractures (Tran V.T. et al., 2011; Lai H.P. et al., 2018). Among these segments, the seismic activity in the southern segment is much stronger than in the northern one. However, by considering the other indications, such as the difference of the

terrain elevations between the western and eastern flanks of the fault; the change of the segment direction; the feature of the distribution of the grabens and sinkholes in the fault zone, each from aforementioned segments can be divided into 2 smaller segments. Thus, the TX-BT fault now can be divided into 4 segments. The earthquake generation potential of the fault was estimated after doing the segmentation in terms of the maximum credible earthquake and maximum ground acceleration.

+ *Chieng Lau-Dong Tam fault segment*

The west branch which stretches continuously along the meridian direction with 17.6 km long and the average terrain elevations of 500-600 m is the main branch of this segment. The auxiliary branch revealed in the East is represented by several much shorter faults with 2-3 km long, which are distributed consecutively from North to the South. The west-dipping direction of the auxiliary branch combined with the east-

dipping main branch has created some subsidence valleys in the form of narrow grabens, which are distributed consecutively from the northern beginning to the southern end of the segment. Besides, the segment is intersected by 4-5 high-grade NW-SE trending faults in different locations.

+ *Dong Tam-Lang Chanh fault segment*

This segment is slightly slanting to the southeast direction with 15.2 km long and distributed in the area of the limestone mountains and the low denudate-erosion hills. The main branch in the West is rather reflected by almost vertical limestone cliffs or the hills with very steep slope consecutively distributed along the whole segment. Unlike the first segment, the main branch of this segment is not straight and constructed from a number of the bending faults consecutively distributed along the branch. A large number of faults are developed in the auxiliary branch along the eastern margin of the segment. They are shorter in comparison with the first segment and distributed along the limestone cliffs and the steep slope of the hills. The terrain elevations on the main branch are varied in a range of 700-800 m. Except for the aforementioned properties this segment is distributed in the area affected by the Song Ma fault.

+ *Lang Chanh-Giao Thien fault segment*

This segment is started from the southern flank of the main branch of the Song Ma fault and stretching again along the meridian direction with 14.1 km long. Spreading from the foot of the 1000m high mountain range in the West to the Song Am riverbank in the East, this segment of the fault zone is distributed in the area of the low hills constructed mainly from silt sandy stone. The western main branch of the fault is stretched continually along the foot of the mentioned above the high mountain range, which is reflected by the topographic picture in the location. The auxiliary branch comprises

several much shorter faults is distributed in the eastern part of the fault zone. A number of the step-down subsidence structures with a gradual decrease of the elevations to the East were created by the fault activity. The east-dipping direction of all the faults in the auxiliary branch as in the main branch is the property to distinguish this segment from the two previous ones. For this reason, no grabens of the meridian direction were revealed in the fault zone. Besides the aforementioned distinct signs, the east shifting about 1.5km of the next segment is also the indication to separate one from the other.

+ *Giao Thien-Van Xuan fault segment*

This segment is also stretched along the meridian direction with 18.2 km long. A number of the narrow dry and deep stream valleys are observed in the fault zone at this segment and the soft materials are not accumulated in these valleys. Most of the faults in the auxiliary branch in this segment are longer than those in the previous segment and represented as a number of the bending lines. The same east-dipping direction of the faults in the eastern auxiliary branch as in the main branch is revealed, but the step-down subsidence amplitude is not so strong as in the previous segment. The elevations along the western main branch reach more than 1100 m.

Using this fault segmentation results, the maximum credible earthquakes were estimated by applying the Wells L. and J. Coppersmith (1994) empirical formulas. Based on the empirical relationship between the earthquake rupture length and the total length of the fault segment (Mark R.K., 1977; Shuka J. and Choudhury D., 2012) in this study the maximum magnitude is calculated using 1/3 total length of each segment as rupture length (SRL). The maximum credible earthquake, which can be generated by the different fault segments is calculated using the following formula:

$$M_w = a + b \log \left( \frac{SRL}{3} \right) \quad (1)$$



Where  $M_w$  is a moment magnitude, a and b are the empirical coefficients depend on the fault types (Wells L. and Coppersmith J., 1994). Since the movement of the TX-BT fault is dominantly normal in association with the

strike-slip component, so a and b coefficients satisfied for all the types of faults were chosen for this study, for that  $a = 5.08$  and  $b = 1.16$  (Wells L. and Coppersmith J., 1994). The results of the calculation are listed in Table 3.

Table 3. Maximum credible earthquakes ( $M_{max}$ ) determined for four main fault segments

Name of fault segment	Length of segment (L, km)	L/3 (km)	E. quake a value	coeff. b value	E. quake magnitude ( $M_w$ )
Chieng Lau-Dong Tam	17.6	5.87	5.08	1,16	5.97
Dong Tam-Lang Chanh	15.2	5.07	5.08	1,16	5.90
Lang Chanh-Giao Thien	14.1	4.70	5.08	1,16	5.86
Giao Thien-Van Xuan	18.2	6.06	5.08	1.16	5.98

For estimation of the maximum ground acceleration, a more suitable for active region Campbell ground motion attenuation equation

$$L_n(A_H) = -3.512 + 0.904M_w - 1.328L_n \sqrt{R_{seis}^2 + [0.149 \exp(0.647 M_w)]^2} + [1.125 - 0.112L_n R_{seis}] \frac{0.0957M_w}{F} + [0.440 - 0.171L_n R_{seis}] S_{SR} + [0.405 - 0.222L_n R_{seis}] S_{SH} \quad (2)$$

where  $A_H$  is the maximum horizontal acceleration in units of g ( $g = 981c/sec^2$ );  $R_{seis}$  is the source-site distance (km); F - the fault type coefficient, where  $F = 0$  for the strike-slip fault,  $F = 1$  for the thrust fault and  $F = 0.5$  accepted for the normal fault;  $S_{SR}$  and  $S_{SH}$  - the coefficients related to site conditions, where  $S_{SR} = S_{SH} = 0$  for firm soil,  $S_{SR} = 1$  and  $S_{SH} = 0$  for soft rock,  $S_{SR} = 0$  and  $S_{SH} = 1$  for hard rock. This equation was also applied effectively for some region in the territory of Vietnam by Nguyen D.X. et al. (2004). By considering the local conditions, such as the earthquake hypocenter depths, the crustal velocity model as mentioned above, an average depth to the top of the seismogenic layer is chosen by 4 km in this study. That is also similar to the value accepted in the Nguyen Dinh Xuyen's (2004) study. Since the TX-BT fault has both components of dip slip and strike slip, in which dip slip motion dominates over strike slip motion, so the coefficient  $F = 0.3$  is accepted for this study. The soft rock is more suitable for the local ground, that  $S_{SR} = 1$  and  $S_{SH} = 0$  were used for this application. The ground accelerations

(1997) was chosen for this study (Campbell K.W. 1997; Douglas J., 2011).

resulting from the calculations indicate that, the first contour line encompassing the total length of the TX-BT fault and creating the belt of 6.2 to 8.5 km wide is demonstrated by the value 350 gal. Inside that belt, the ground motion has higher values and the highest value reached 390 gal (Fig. 14).

This value is rather high in comparison with the PGA derived from some regional studies for that location such as studies of Nguyen D. X. et al. (2004); Nguyen H.P. et al. (2015). The difference of the ground acceleration obtained from this and previous studies may be related to the different choice of the coefficient F, with  $F = 0$  in the previous study of Nguyen D.X. et al. (2004) and  $F = 0.3$  for this study. In the other study such as Nguyen H.P. et al. (2015), the probabilistic approach applied for PGA calculations is different from the deterministic approach used in this study. Moreover, the ground motion attenuation equation used in that study is more suitable for a relatively stable region, that's making the difficulty for comparison between the results. Further away from the fault line along its perpendicular direction as well as

from the contour line 350 gal the ground acceleration is too fast decreased. Namely, the ground motion is represented by the value of about 100 gal at the distances of 10.5-12,5 km from the contour line 350gal, and by the value of 50 gal at the distances of 25-26 km from the fault line. Most of the constructions are not subjected to damage by the last value of the ground acceleration. For this reason, the

structures located in the area limited by a distance <26 km along both sides of the fault are capable of the damage by the maximum earthquakes. Therefore, the space captured by the contour line 250 gal or restricted by the radius about 10 km from the fault line is accepted as a strong damage potential zone if the maximum earthquake occurs.

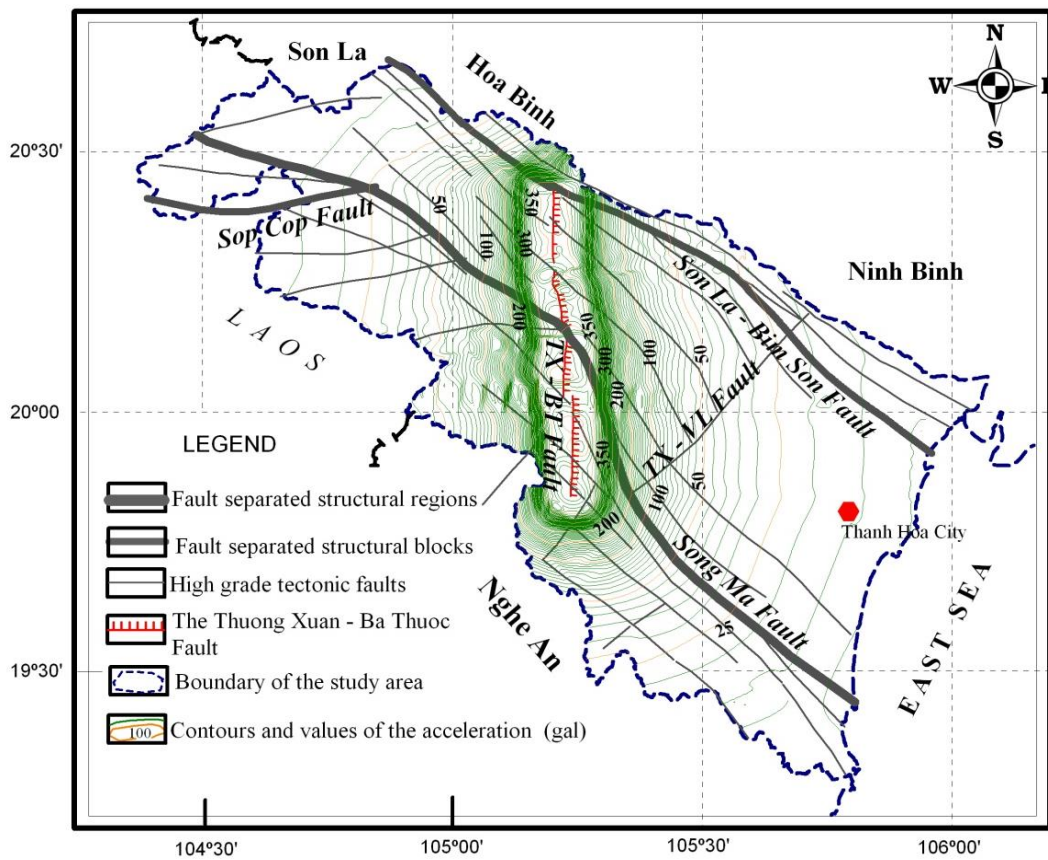


Figure 14. Prediction map of peak ground acceleration caused by maximum earthquakes in the Thuong Xuan-Ba Thuoc (TX-BT) fault

#### 4. Conclusions

According to the earthquake data collected by the local network, the Thanh Hoa area is not seismically quiet. Although not all of the recorded earthquakes were located, on average, more than 80 events are detected every year in the study area and its adjacent one. These data allowed us to study a more

detailed relationship between the distributions of the fault systems and earthquakes in the study area. Namely, the earthquakes are not only generated in the main branches of the three big size faults: Son La-Bim Son, Song Ma, and Sop Cop, but their auxiliary branches are also reflected by the active seismic manifestation. Among the high-grade faults,

the most notable fault is the Thuong Xuan-Vinh Loc fault which is reflected by a rather high seismic activity where several events reached the magnitude ML 3.0 or even higher, but the fault is still not recognized as the seismogenic source in previous works.

Preliminary segmentation of Thuong Xuan-Ba Thuoc fault is implemented. The maximum credible earthquakes and maximum ground accelerations that can be generated by this fault were estimated. The obtained results are considered as a preliminary product, that is needed to be improved in future studies. According to the seismic activity feature, the Thuong Xuan-Ba Thuoc fault can clearly be divided into 2 segments: The northern segment closely to the Song Ma fault is characterized by much sparser distributions of the earthquake epicenters in comparison with the southern segment. It is questionable whether the increase of the cracks resulted from the deformation process in the southern segment is related to its younger activity in comparison with the squeezing type of the deformation revealed in the northern segment?

The distribution of a large portion of the earthquake epicenters are closely related to the distributions of the active faults in the study area. However, a large number of earthquakes is unrelated to any fault, most of them are distributed in the area of the Thanh Hoa plain, which is covered by the thick Quaternary sediments, so the hidden faults are still undefined. Thus, a more detailed and more quantitative study of the seismotectonic sources as well as the continued and more detailed earthquake monitoring.

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### References

- Bui V.T., Nguyen V.H., Oneta S., Samsanith D., Southiphong V., Bounpaphan M., 2014. Active characteristics of Sam Nua fault zone during Neotectonic stage. *Vietnam J. Earth Sci.*, 36(2), 97-107 (in Vietnamese).
- Campbell K.W., 1997. Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra, *Seism. Res. Lett.*, 68, 154-179.
- Dinh V.T. et al., 2010. Study of the earth crustal structures of Northern Vietnam by using the deep seismic, magnetotelluric investigations and gravity data. Vietnam National project: KC08.06/06-10: Outcome report - 8/2010 (in Vietnamese).
- Dinh V.T. et al., 2012. Study in detail of the seismic activity of the Song Ma fault zone (Along the Thanh Hoa - Nghe An Section) and characteristics of several soil dynamic parameters in the social-economic important locations of the study area. Vietnam Academy of Science and Technology project (2010-2011), Outcome report - 5/2012 (in Vietnamese).
- Dinh V.T., Chen C.H., Wen S., Lai H.P., Tran A.V., Nguyen T.H.Q., Duong T.N., 2013. The preliminary results of earthquake observation by deployment of the local seismic network Guralp - 6TD in the region of Thanh Hoa province. *Vietnam J. Earth Sci.*, 35(1), 36-46 (in Vietnamese).
- Dinh V.T., Harder S., Huang B.S., Trinh V.B., Doan V.T., Lai H.P., Tran A.V., Nguyen T.H.Q., Nguyen V.D., 2018. An overview of northern Vietnam deep

- crustal structures from integrated geophysical observations. *Terr.Atmos.Ocean. Sci.*, 29, 1-16.
- Douglas J., 2011. Ground-motion prediction equations 1964-2010. Final Report BRGM/RP-59356-FR. Geoscience for a sustainable Earth.
- Lai H.P., 2016. The crustal structural model of Northern Vietnam based on seismic and gravity data. PhD. Dissertation, Institute of Geological Sciences, VAST (in Vietnamese).
- Lai H.P. et al., 2018. The detailed characteristics of seismic activity in the Thuong Xuan-Ba Thuoc fault zone and related geological hazards. Vietnam Academy of Science and Technology project VAST05.01/15-16, Outcome report-6/2018 (in Vietnamese).
- Langston C.A., 1979. Structure under Mount Rainier, Washington, inferred from teleseismic body waves. *Journal of Geophysical Research*, 84, 4749-4762.
- Lee W.H.K., J.C. Larh, 1972. HYPO71: a computer program for determining hypocenter, magnitude, and the first motion pattern of local earthquakes, USGS, Open-File report, 29pp.
- Lee W.H.K., C.M. Valdes, 1985. HYPO71PC: a personal computer version of the HYPO71 earthquake location program, USGS, Open-File report, 85-749, 43pp.
- Lee S.K., Kim H.J., Song Y., Lee C.K., 2009. MT2DinvMatlab - A program in MATLAB and FORTRAN for two-dimensiona magnetotelluric inversion, *Computers and Geosciences*, 35(8), 1722-1734.
- Mark R.K., 1977. Application of linear statistical model of earthquake magnitude versus fault length in estimating maximum expectable earthquakes. *Geology*, 5, 464-466.
- Nguyen D.X. et al., 2004. Earthquake and ground motion prediction in the territory of Vietnam. Vietnam National project (in Vietnamese).
- Nguyen D.X., 2009. Earthquakes in the territory of Vietnam. In the book: Cenozoic dynamics of Northern Vietnam for celebrating 10 years of the Vietnam-Poland cooperation (1999-2009), 165-177 (in Vietnamese).
- Nguyen H.P., Pham T.T., 2015. Probabilistic seismic hazard maps of Vietnam and the East Vietnam sea. *Vietnam J. of Marine Science and Technology*, 15(1), 77-90 (in Vietnamese).
- Nguyen N.T. et al., 2006. Detailed earthquake zonation of the Northwest Region. Vietnam National project: 2007-48-129 (in Vietnamese).
- Nguyen T.Y. et al., 1998. Study of the land cracking hazard of the Vietnam territory. Vietnam National project: DL-94, Outcome report (in Vietnamese).
- Nguyen T.Y. et al., 2014. Investigation and establishing Natural Hazard Maps of Lao DPR. Outcome Report of Vietnam-Laos cooperation research in framework of Vietnam-Laos Protocol Agreement 2011-2014, Institute of Geological Sciences, VAST, Hanoi (in Vietnamese).
- Nguyen V.D., Huang B.S., Le T.S., Dinh V.T., Zhu L., Wen K.L., 2013. Constrains on the crustal structure of northern Vietnam based on analysis of teleseismic converted waves. *Tectonophysics*, 601, 87- 97.
- Nguyen V.H., Nguyen N.T., Hoang Q.V., 1996. Some characteristics of the young NW - SE trending fault systems in the Vietnam Northwest Region. In the book: *Geology and Resources*, Hanoi. Science and Technique Pub. House, 1, 47-58 (in Vietnamese).
- Nguyen V.H., 2002. Characteristics of the neotectonic faults in the Northwest Region of Vietnam. PhD. Dissertation-Institute of Geological Sciences, VAST (in Vietnamese).
- Nguyen V.H., Hoang Q.V., 2004. About activity of the neotectonic fault zones in Northwest Region of Vietnam. *Vietnam J. of Geology*, 285, 38-48 (in Vietnamese).
- Nguyen V.H., Hoang Q.V., 2006. The main characteristics of the Son La - Bim Son fault zone in the Neotectonic stage. *Journal of Natural Science and Technology*, Hanoi National University, XXII(2A), 21-39 (in Vietnamese).
- Nguyen V.H., Hoang Q.V., 2009. The main characteristics of the Song Ma fault zone in the Neotectonic stage. *Vietnam J. of Geology*, 7, 21-39 (in Vietnamese).
- Pham N.D., Pham N.K., Lai H.P., Dinh V.T., Tran A.V., Duong T.N., Ngo T.L., 2018. The effectiveness of data analysis by using the differential magnetotelluric curves in the study of deep structures. *Journal of Geological and Mining Engineering Science*, 59(2), 18-26 (in Vietnamese).

- Phung V.P., Vu V.C., 2002. The dynamic characteristics of the Ninh Binh-Thanh Hoa region. The proceedings of the Workshop on Earthquakes and several other natural hazards in the Northwest Region of Vietnam. Pub. of Hanoi National University, 155-165 (in Vietnamese).
- Shuka J., Choudhury D., 2012. Estimation of seismic ground motions using deterministic approach for major cities of Gujarat. *Nat. Hazards Earth Syst. Sci.*, 12, 2019-2037.
- Su C.M., Wen S., Tang C.C., Yu L.Y., Chen C.H., 2018. The variation of crustal structure along the Song Ma Shear Zone, Northern Vietnam. *Tectonophysics*, 734-735, 119-129.
- Thorne L., Terry C.W., 1995. *Modern global Seismology*. Academic Press. Inc., San Diego, California, 521pp.
- Tran T.H. et al., 2002. Study and assess all types of geohazards in the Vietnam territory and measures of prevention (First Stage for Northern part of Central Region ). Vietnam National project (2000-2001), Outcome Report-2002, Institute of Geological Sciences, VAST (in Vietnamese).
- Tran T.H. et al., 2004: Study and assess different types of geohazards in the mountainous provinces of Northern Vietnam and solutions of prevention, Vietnam National project (2002-2003), Outcome Report-2004, Institute of Geological Sciences, VAST (in Vietnamese).
- Tran V.T. et al., 2011. Study the relationship between different types of geohazards and modern activity of the sub meridian fracture zones in the Northwest region of Vietnam. Vietnam Academy of Science and Technology project (2009-2010), outcome report-2011, Institute of Geological Sciences (in Vietnamese).
- Wells D.L., Kevin J.C., 1994. New empirical relations among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, 84(4), 974-1002.
- Wen S., Tang C.C., Yu L.Y., Lai H.P., Dinh V.T., Chang W.Y., Chen C.H., 2015. The Tectonic Structures of the Song Ma Fault Zone, Vietnam. *J. of Asian Earth Sciences*, 107, 26-34.
- Wu W.J., Wen S., Tang C.C., Yu L.Y., Lai H.P., Dinh V.T., Chen C.H., 2018. Seismogenic structures in the Ma River Fault Zone, Vietnam: Insights from Focal Mechanisms of Microearthquakes and local stress state. *Bulletin of the Seismological Society of America*, 108(6), 3260-3269.