Vietnam Journal of Earth Sciences, 46(4), 489-514, https://doi.org/10.15625/2615-9783/21075

Vietnam Journal of Earth Sciences
https://vjs.ac.vn/index.php/jse

Identification of the active faults and seismotectonic zonation of Laos territory

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Received 03 May 2024; Received in revised form 15 June 2024; Accepted 10 July 2024

ABSTRACT

In this study, the main active faults in the territory of Laos were identified by analyzing the spatial relationship between the distributions of neo-tectonic faults and earthquake epicenters. The map of neo-tectonic faults was built by integrating the results of neo-tectonic faults research using geological-geomorphological data together with the lineament map obtained from remote sensing analysis. Nontectonic lineaments were eliminated by correlating the spatial distribution of the lineament field with a topographic map, DEM, and geological-geomorphological data. The earthquake data, including 4416 events in Laos and its surroundings, were collected from different sources: the International Seismological Center (ISC), the earthquakes recorded by the local seismic network in Laos, the seismic data in Vietnam, and the earthquake catalog provided by the Thailand Meteorological Department (TMD). Among these, 820 events were located using the hypocenter method, and the local network recorded the data. The magnitude conversion was applied to get a unified scale Mw. The catalog of 1617 main shocks obtained after eliminating foreshocks and aftershocks using the declustering technique was used for a spatial correlation with the neotectonic fault distribution to identify active faults. A total of 14 main active fault zones in the Laos territory were defined. Most are also seismogenic faults with Mw ≥ 5.0 occurring along their trace. Considering the characteristics of seismic activity and the active and neotectonic faults, the territory of Laos can be divided into six seismotectonic zones according to the decreasing level of seismic activity: the Western, the Northeastern Samnua, the Phongsali, the South Truong Son, the North Truong Son, and the Khorat zones. Each zone is characterized by relative homogeneity in the seismic activity and the characteristics of active and neotectonic faults.

Keywords: Seismic activity, Earthquake, active fault, seismotectonic zonation, Laos, lineaments.

1. Introduction

Collecting earthquake data from different sources shows that the seismicity is quite active. During the period from 1925 to October 2021, there were 8 earthquakes with Mw = 6.0–6.6 and 47 earthquakes with Mw = 5.0–5.9, including main shocks and foreshocks, aftershocks mainly distributed in the northern part of Laos (Fig. 1). The most recent strong earthquake occurred on November 20, 2019, in Xayabouli Province with Mw = 6.1. In addition, 3 strong earthquakes with Mw = 6.1–6.9 were

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recorded outside Laos, but only from 6 to more than 20 km from the border. Given that in Laos, on average, every few years, there is an earthquake capable of damaging structures (Mw ≥ 5.0). It is necessary to identify the earthquake generation sources (active faults) and assess the earthquake hazard to provide the data for territorial planning and construction of Socio-Economic infrastructure in Laos To mitigate the losses caused by earthquakes in the future. However, the results achieved by this research direction in Laos so far are still minimal.

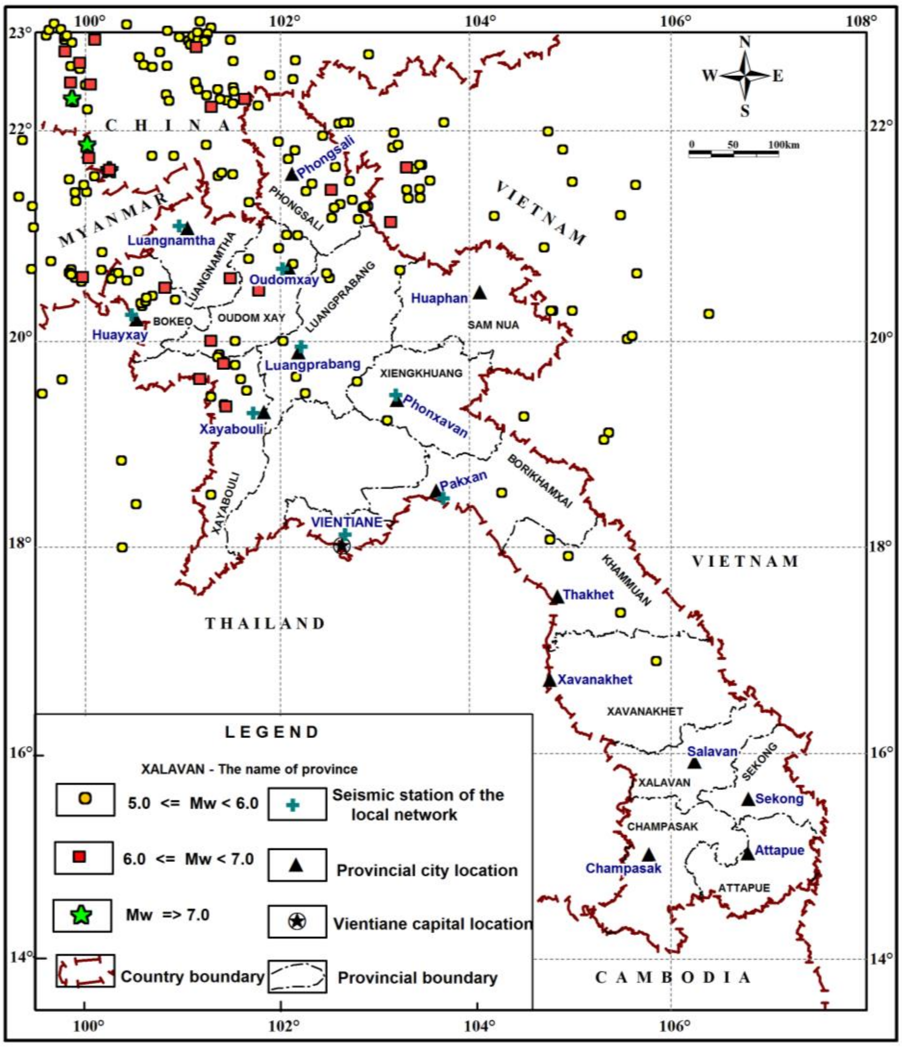

Figure 1. Distribution of earthquake epicenters Mw ≥ 5.0, including foreshocks and aftershocks

Most of them have come from foreign authors who have conducted earthquake hazard assessments in regional studies. In some cases, they were conducted mainly for Laos territory. In 2009, the results of the earthquake hazard assessment for Thailand (Pailpolee et al., 2009) and its surrounding areas, including a part of the northwestern Laos region in both deterministic and probabilistic directions, were published. In that study, several active faults were revealed partially by remote sensing data, including 6 faults of northeast-southwest trending: Nam Ma, Mae Chan, Mae Ing, Nam Peng, Dien Bien Phu, Loei Petchabun in the northwestern part of Laos, and Song Ma, Song Ca, the northwestern segment of Thakhek faults in the northeastern part. The earthquake generation sources accepted all these faults, and the maximum credible earthquake (Mmax) was estimated using fault length following the formula of Wells L.D. and Coppersmith (1994).

The evaluation of peak ground acceleration (PGA) from the deterministic approach reached very high values in some places in the northwestern region of Laos, approaching 3 g, which is not likely consistent with reality. There are different reasons leading to the above result. Among them, an overestimation of the maximum earthquake was probably generated by active faults located outside Thailand. It is more apparent that the faults in northern Vietnam, where the values of Mmax admitted in the study of Pailpolee S. et al. (2009) are much larger than those from the Vietnamese researchers (Nguyen D.X. et al., 2004; Nguyen H.P. and Pham T.T., 2015). Among the earthquake sources listed in Table 1, two faults, Dien Bien Phu and Song Ca, extend deeply into Laos territory. It should be noted that in the studies of earthquake generation sources carried out in Vietnam, a large amount of data such as geophysical, geological-geomorphological, remote sensing, seismological, and GPS has been used.

Table 1. The M_{max} estimated for the faults in Northern Vietnam by different authors

No	Fault name	Pailloplee S. et al. (2009) - Mw	Nguyen D.X. (2004) - Ms	Nguyen. HP and Pham TT (2015) - Mw
1	Cao Bang-Tien Yen	7.9	5.5	5.5
2	Dien Bien Phu	7.5	5.5	6.5
3	Dong Trieu	7.7	5.9	6.1
4	Red River	8.5	6.1	6.3
5	Song Ca	7.8	6.1	6.5
6	Song Chay	7.1	6.1	6.3
7	Song Da	7.0	5.5	5.3

Notation: Ms-Surface wave magnitude; Mw-Moment magnitude

The following products obtained solely from seismic data analysis are the maps of earthquake ground motion covering the whole territory of Laos. The first is the map of the earthquake intensity of a 250-year return period on the MMI scale, established by the United Nations Humanitarian Organization in 2010 (OCHA, 2010). The second includes the maps of peak acceleration (PGA) and the earthquake intensity on the scale MMI derived from the calculation, followed by the deterministic and probabilistic approaches (Pailoplee S. and Charusiri P., 2017). The ground motion values estimated in these studies are much less than those obtained from the previously mentioned research. For example, the maximum possible acceleration in some places of northern Laos reached approximately 0.4 g. However, a poor spatial correlation between the distributions of the ground motion intensity and earthquake generation sources caused by the lack of data on active faults is the limitation of the research results that prevent a practical application. A more detailed and improved study on active faults in the territory of Laos to provide the data for earthquake hazard assessment is essential.

During the period 2011–2014 in the cooperation between the scientists from the Vietnam Academy of Science and Technology and the Laos Academy of Science, numerous main neotectonic faults inside Laos territory were studied by using geologic-geomorphological investigations (Nguyen T.Y. et al., 2014; Bui V.T. et al., 2014; 2015). This data source provides more detailed information on the distribution of the main neotectonic faults in Laos. Since 2011, a local seismic network consisting of 8 Nanometric broadband seismometers which were provided by Taiwanese scientists under the three sides of cooperation between the Institute of Geological Sciences, Vietnam Academy of Science and Technology; the Institute of Earth Sciences, Academy Sinica, Taiwan and the Cabinet of Laos Academy of Science has been installed in Laos. Because the local network can record earthquakes of smaller magnitude than the network distributed outside Laos, it allows us to evaluate seismic activity in more detail in the northern part of Laos. In this study, the data source collected from the local network, combined with the earthquake data from the International Seismological Center (ISC) and the networks in neighboring countries, has been correlated to the research results on neotectonic faults, thereby initially determining the distribution of the main active faults in the entire territory of Laos. The outcome is expected to provide a more suitable data source for determining the earthquake generation sources and for the earthquake hazard assessment in more detail for Laos territory in the coming years.

2. Brief about geological and tectonic features of Laos territory

The tectonic picture of Mainland Southeast Asia is shaped based on the amalgamation of several diversified tectonic structural blocks such as Sibumasu, Sukhothai, Lincang, and Indochina. (Fig. 2). These structural units have developed from pre-Mesozoic crustal blocks with some boundary and internal structure modifications during the Mesozoic time (Punya C. et al., 2022). In which, the Sukhothai structural block is essentially a part of the island arc system developed along the western margin of the Indochina block that was amalgamated into this block in the Late Triassic (Masatoshi S. and Metcalfe I., 2008; Dao V.C., 2015). In general, the tectonics of the study region continued to change when the northward collision of the Indian plate into the Asian plate started from the Middle Tertiary has, caused a large-scale strike-slip movement along the major regional faults such as Red River, Wang Chao, and Three Pagodas. Many shallow, strong earthquakes occurred in the eastern Asian continent. As a result, the Indochina block extruded southeastward approximately 800 km along the Red River fault and rotated clockwise 25° in the first 20–30 Ma since the collision (Tapponnier P. et al., 1986).

In the study and adjacent areas, many fault systems have also been developed, and the most common fault systems are in NW-SE and NE-SW directions. In contrast, the fault systems of the meridian and parallel ones are less common. Studies on neotectonic structures (from the Pliocene or from the Late Quaternary to the present) in Vietnam, Thailand, and Laos have all confirmed that the NW-SE and the NE-SW trending fault systems are chiefly characterized by right-lateral strike-slip and left lateral strike-slip movement respectively; while the movement along the faults of the meridian and parallel directions are mainly the normal and reverse, respectively (Charusiri P. et al., 1999; Fenton C.H. et al., 2003; Nguyen V.H., 2002; Bui V.T., 2002; Nguyen N.T. et al., 2005; Nguyen T.Y. et al., 2006, 2014; Pailoplee S. et al., 2009). These properties reflect the collision direction between the tectonic plates and the modern stress field in Mainland Southeast Asia.

As a part of the Indochina composite structural block (Tran V.T. et al., 2020; Masatoshi S. and Metcalfe I., 2008), the territory of Laos occupies some part of the area belonging to the higher-order structural units in this composite block. Based on geological-geotectonic features, including

Neotectonic characteristics in previous studies (Phan C.T. et al., 1991; Masatoshi S., and Metcalfe I., 2008; Phommakaysone K., 2012; Nguyen T.Y. et al., 2014) Laos territory can be divided into 4 central structural regions as follows:

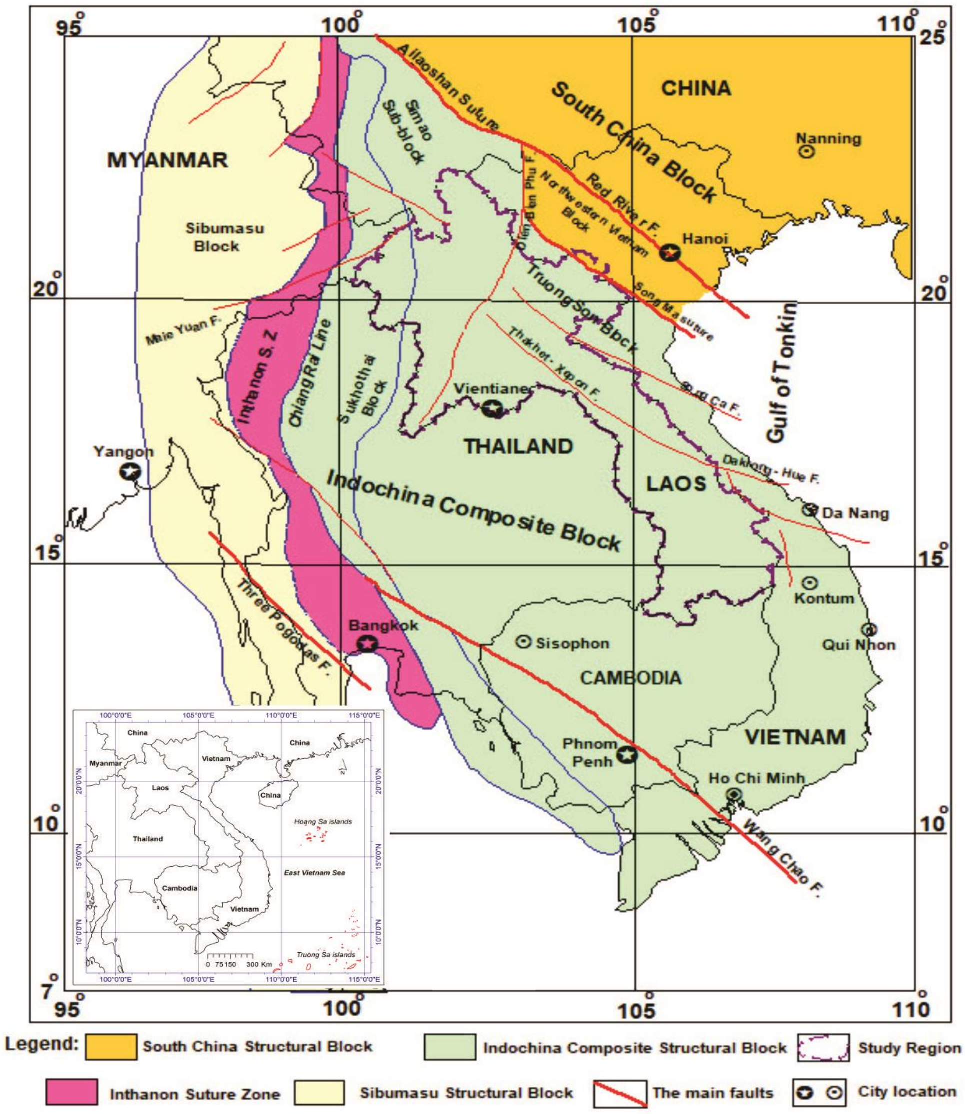

Figure 2. Tectonic map of Mainland Southeast Asia (Modified from S. Masatoshi, I. Metcalfe, 2008)

2.1. The Northwestern Laos structural region

Based on the differences in direction of the main neotectonic structures and the rock formations constituting this structural unit compared to the adjacent, the northwestern region of Laos is separated from the southeastern juxtaposition areas by the Dien Bien Phu fault. This is a sizeable regional-scale fault that runs from northwestern Vietnam along the meridian direction with a dominated left strike-slip movement mechanism (Zuchiewicz W. et al., 2004; Masatoshi S., and Metcalfe I., 2008), then changes direction to NE-SW cuts through the northern part of Laos territory and continues to Thailand with a total length up to approximately 700 km. The segment running through northern Laos is called the Luangprabang-Xayabouli fault (LPB-XYBL) in this study. This fault is also one of the most seismically active faults in the Indochina block. However, no sign of its pre-Cenozoic activity was found; the fault is also not a boundary between the plates because no evidence of collision was found between them (Masatoshi S. and Metcalfe I., 2008). According to the geological-geotectonic characteristics, this structural region can be divided into Phongsali and Western Laos sub-regions (Fig. 3).

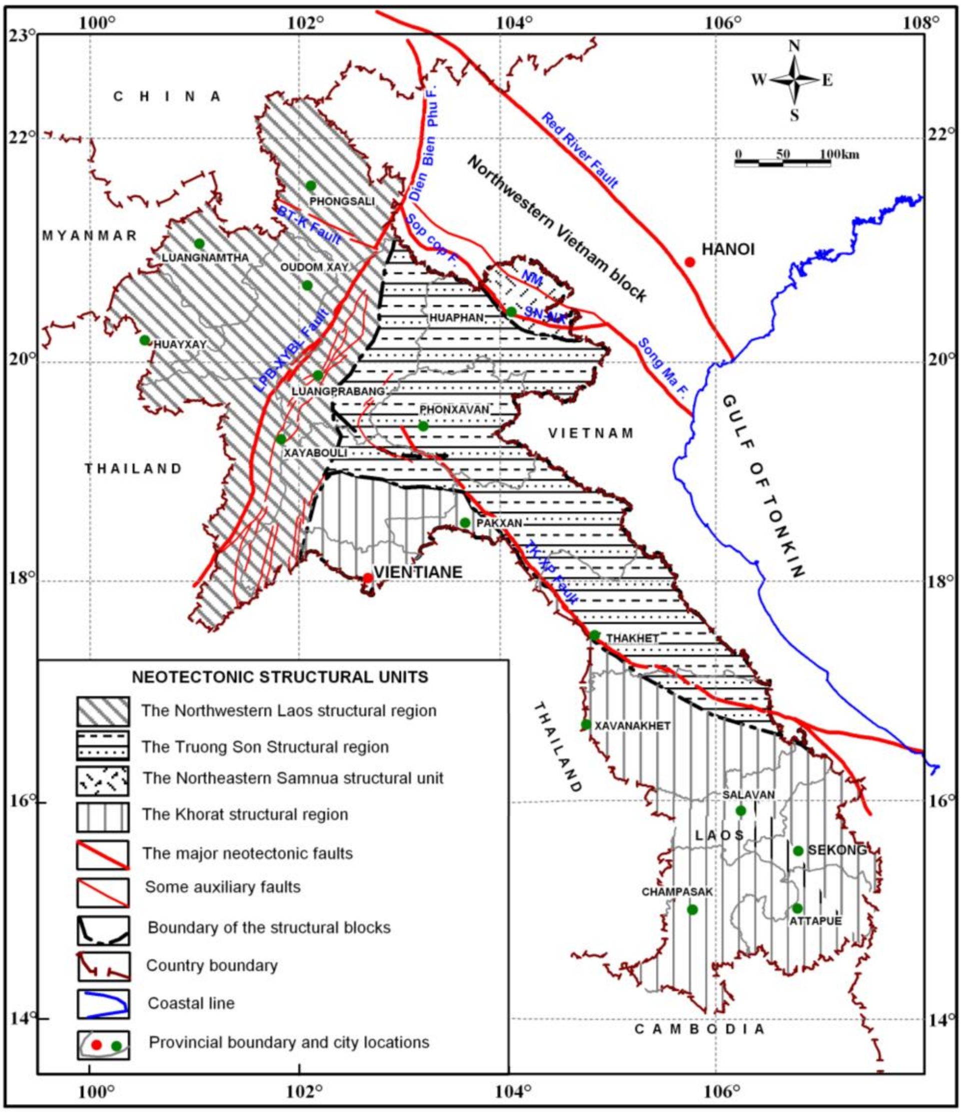

Figure 3. The main structural units in Laos territory (Modified from Nguyen T.Y. et al., 2014)

- *The Phongsali sub-region* is developed along the NW-SE direction in the northwestern part and then gradually changed to the sub-meridian direction in the southeastern segment. The rocks of carbonate formations with the late Paleozoic age (C-P) are constituting the sub-region. To the east and west are younger terrigenous sedimentary formations that overlap the Middle Mesozoic formation (J-K) (Phan C.T. et al., 1991; Phommakaysone K., 2012). The region's eastern boundary is bounded by a segment of the LPB-XYBL fault. The NWW-SEE trending Bontai-Khoa fault zone (BT-K) is accepted as the southern boundary of the structural unit. The region has many destructive structures of linear shape, mainly the NW-SE and sub-meridian direction faults.

- *The Western Laos sub-region* occupies a large area in the northwestern part of Laos. This structural unit is limited to the northeast by the BT-K fault zone, to the southeast by the LPB-XYBL fault, and to the west and southwest boundaries extending beyond Laos's territory. All the primary faults in this unit are developed along the NE-SW direction.

The Late Paleozoic formations (PZ3) constitute the sub-region with carbonate and extrusive, intrusive rocks of (C-P) ages. They are exposed along the NE-SW direction and interspersed with younger Mesozoic formations of ages (T-J-K), mainly the rocks of terrigenous sediments.

2.2. The Truong Son structural region

This region has occupied a large portion of the Truong Son structural block, which is limited to the northeast by the Sop Cop-Song Ma suture zone, to the northwest by the LPB-XYBL fault zone, and to the southwest is the Thakhet-Xepon fault zone (TK-XP) separating this block from the Khorat plateau. The common point of the Truong Son region is that the major faults are developed mainly along the NW-SE direction, a large portion of them extending to the territory of Vietnam.

The rocks constituting the structural unit belong to the Truong Son block in the Laos territory, comprising a complex combination of rock formations from ancient times to the present. In the northern part, there are mainly PR, PZ, and MZ ancient rocks, along with intrusive rocks forming high mountain ranges. Further to central and southern Laos are terrigenous-carbonate PZ1 metamorphic sedimentary rock formations (S-D) and (C-P). Carbonate rocks are interlaced (T-J-K) terrigenous sedimentary formations. Particularly in the south, it is also covered by young basaltic extrusive rocks.

2.3. The Northeastern Samnua structural unit

This unit is distributed from the Samnua - Namxoi fault (SN NX) to the Laos - Vietnam border at the northeast. This unit is a small part of the Northwestern Vietnam structural block. The region has two main fault zones: SN-NX and Nam Ma (NM), both of which have the dominant NW-SE direction. However, the southeast segment of the SN-NX fault is partly shifted to sub-parallel. The two faults mentioned are the middle segments of the Sop Cop and Song Ma faults distributed in the Northwestern Vietnam region. The structure is constituted of geological formations of ages from Proterozoic to Mesozoic, including metamorphic rocks, schist, deep-sea sediments, intrusive magma formations, and volcanic sediments. Activities in the Cenozoic time had created in the SN-NX fault zone a small basin that accumulated terrigenous sediments of Neogene-Quaternary ages at the southeastern edge of the Huaphan administrative center of this province.

2.4. The Khorat structural region

Belonging to the Khorat block, it has occupied a small portion of the plateau, including its northwestern edge in Vientiane Province and a strip of land distributed to the southwest of the TK-XP fault zone. The density of faults in these areas is not as high as the Northwestern and Truong Son structural regions, and the sizes of the faults are not significant. Few faults are detected in the Vientiane area, and their strike is mainly in the sub-parallel direction. In contrast, some detected faults are distributed along NW-SE and sub-meridian directions in the southern part of Laos. The main geological formations distributed in these locations are the terrigenous Mesozoic (MZ) sediments with ages (J-K). A younger Neogene-age rock formation was observed in Vientiane, creating a step-shaped structure descending to the south.

3. Data and methods

3.1. Data

3.1.1. The data used for the construction of the neotectonic fault map

As mentioned above, the preliminary identification of the main active faults in Laos territory is based on the correlation of the spatial distributions of earthquake epicenters with neotectonic faults. The data were used for the construction of the neotectonic fault map as follows:

- The results of the neotectonic fault study were obtained from the geological and geomorphological investigations in the previous studies (Nguyen T.Y. et al., 2014; Bui V.T. et al., 2014; 2015). Among them, the geological data comprise distribution and deformation indications of geological formations along the fault zones. The deformation of geomorphologic objects, topographical morphology, terraces, alluvial deposits, scarp face, and straight drainage channel segments appearing along fault zones indicate the recent active faults' distribution and mechanism of motion. It is noted that all the investigations were carried out along all the main tectonic fault zones in several key locations. Many geologic-geomorphologic indications reflecting fault activity during Pliocene-Quaternary time were recorded.

- The results on neotectonic fault research in Eastern Laos by using only remote sensing analysis and results on active faults in Vietnam collected from the previous studies were additionally used (Nguyen D.X. et al., 2004; Nguyen T.Y. et al., 2006; Nguyen H.P. and Pham T.T., 2015). A number of the faults in Eastern Laos extend into Vietnam's territory.

- The spatial distribution of lineaments obtained in this study was also used. The data for this purpose include Landsat images with 30 m resolution, the topographic map on the scale 1:100 000, digital elevation model (DEM), and geological-geomorphologic data.

3.1.2. Earthquake data

- Since the local network was only installed in October 2011, the earthquake data used in this study were mainly collected from sources from international and neighboring countries. The long-term earthquake catalog from 1925 to 2021 was mainly collected from the International Seismological Center (ISC). The short-term collected data sources include the earthquakes recorded by the local Laos network, the network of the Thailand Meteorological Department (www.seismology.tmd.go.th/en) from 2011, and the networks in Vietnam: VBSN from 2005 (Huang B.S. et al., 2012) and SMSN from 2009 (Wen S. et al., 2015). Due to the data collected from different sources, some earthquakes were recorded by more than one network. In this case, the data recorded by the network with a closer distance was selected.

- Another type of data is the focal mechanism of 7 earthquakes with Mw = 5.2–6.9 that occurred during the period 1978–2011 from the International data source (www.globalcmt.org/CMTsearch). Although there are few, these data can be used to understand the present-day motion characteristics of faults where earthquakes occur. This provides information to understand better the motion mechanism of the recent active faults that are continuing.

3.2. Methods

- A group of spatial analysis methods was applied to investigate Laos's distributions of neotectonic faults. Among them, the remote sensing technique extracts the initial map of lineament distributions from satellite images. The elimination of nontectonic lineament from this map was conducted using a GIS tool to analyze the spatial correlation of the above lineament map with a topographic map, digital elevation model (DEM), and geological-geomorphologic data. On the other hand, a GIS tool is also utilized to analyze the spatial relationship between earthquake epicenters and neotectonic faults to identify active faults in the studied area.

- The HYPOCENTER method, including an adaptive damping technique in the Seisan Program Package was applied for earthquake location. The input data are the difference between S and P wave first arrival times (Fig. 4) and the seismic wave velocity model of the earth's crust (Barry R.L. et al., 1986). In this case, the velocity model of the Song Ma area in Vietnam, which is close to Laos's northern region, was selected from a recent study by Wen S. et al. (2015).

The local magnitude M_L was calculated by using the formula as defined for Southern California:

$$M_L=\log_{10}(A)+1.11\log_{10}(R)+0.00189R-2.09 \quad (1)$$

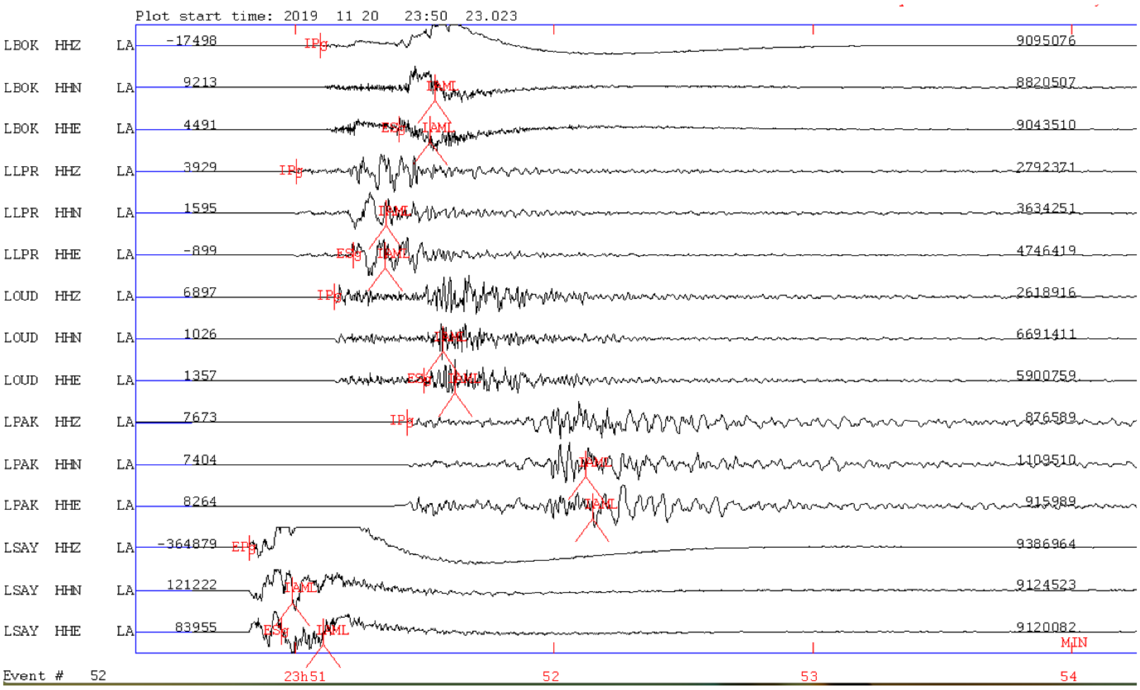

Figure 4. An example of an earthquake location for an event occurred on November 20 2019

Where maximum amplitude A is measured on a ground displacement trace (nm), filtered with the Wood-Anderson response, R is the hypocentral distance (Hutton L.K. and Boore D.M., 1987; Haskov J. and Ottemoller L., 2010).

- The earthquake magnitudes from the collected catalogs were defined by different scales, such as surface wave magnitude (Ms), body P-wave (Mb), and local magnitude (M_L). A magnitude conversion to obtain a single scale is needed to guarantee objectiveness for the estimation and comparison of the seismic activity level in different regions. This study chose the moment magnitude (Mw) as a single representative magnitude scale. The experimental formulae (2,3) and (4,5) obtained by Scodilis E.M. (2006) and Sipkin S.A. (2003) were used to convert the Ms and Mb scales to the Mw. The local magnitude M_L of the earthquakes collected from the local network and networks of neighboring countries: Thailand (Ornthammarat T. et al., 2010) and Vietnam with $M_L \leq 6.0$ are kept no change followed formula (6) (Heaton T.H. and Tajima F., 1986).

$$Mw = 0.67\ M_S + 2.07 \text{ with } 3.0 \leq M_S < 6.2 \quad (2)$$

$$Mw = 0.99\ M_S + 0.08 \text{ with } 6.2 \leq M_S \leq 8.2 \quad (3)$$

$$Mw = 0.85\ Mb + 1.03 \text{ with } 3.5 \leq Mb \leq 5.5 \quad (4)$$

$$Mw = 1.46\ Mb - 2.41 \text{ with } 5.5 < Mb \leq 7.3 \quad (5)$$

$$Mw = M_L \text{ with } M_L \leq 6.0 \quad (6)$$

- Eliminating foreshocks and aftershocks to attain statistically all events independent in the earthquake catalog is important for earthquake hazard assessment. This work was done based on the space-time window algorithm proposed by Gardner J.K. and Knopoff L. (1974), and the calculation was conducted using Zmap software (Wiemer S., 2001).

4. Results and discussions

4.1. Lineament distribution characteristics

The structure of the lineament field, in many cases, reflects the correlation closely with the distributions of neotectonic fault systems. It sometimes reflects a relatively straightforward relationship with seismic activity characteristics (Ahmed M.H. et al., 2013). In this study, the high-density lineament strips generally exhibit a good consistency with the distribution of the main neotectonic faults and certainly reflect the distinct characteristics among the tectonic structural blocks in the study area (Fig. 5). Lineaments primarily consist of a set of numerous separated segments that follow each other, creating clear structures of linear shape with the NW-SE, NE-SW, sub-meridian, and sub-parallel directions. The NW-SE and NE-SW segments usually last longer than the sub-meridian and sub-parallel directions.

In the Western structural unit of Laos, the lineaments formed 5 main linear strips extending in the NE-SW direction: the Mienxing-Mienglong, Luangnamtha-Bokeo; Namo-Phaudom, Udomxai-Pakbeng and Luangprabang-Xayabouli strips. In the Phongsali structural unit, the lineaments appeared along the NW-SE direction in the northwestern part, then gradually changed to the meridian in the southeastern part.

A lower lineament density distinguishes Laos territory's northern part of the Truong Son block from the Western or Phonsali structural sub-regions. The sub-meridian direction Viengkham-Viengthong reflected the fault zone of the same name, which is the most apparent lineament strip. The other strip distributed along the NW-SE direction reflects the Kham-Nonghet faul (K-NH). This fault is a northwestern segment of the Song Ca fault in Vietnam. The remaining locations in this region have relatively low lineament density.

In the central part of Laos, many high-density lineaments with great lengths run along the NW-SE direction. The lineaments relate to two main faults: Thatthon-Nakay and Thakhet-Xepon, which are more clearly reflected. The lineament field in the Northeastern Samnua area is reflected by two high-density strips along the NW-SE direction, i.e., SN-NX and NM fault zones. Particularly in the areas of the Khorat plateau, short lineaments with higher density running along the sub-parallel direction are pretty standard in the Vientiane area. In the southern part of Laos, the lineament field most clearly reflects high-density strips of the NW-SE and sub-meridian directions.

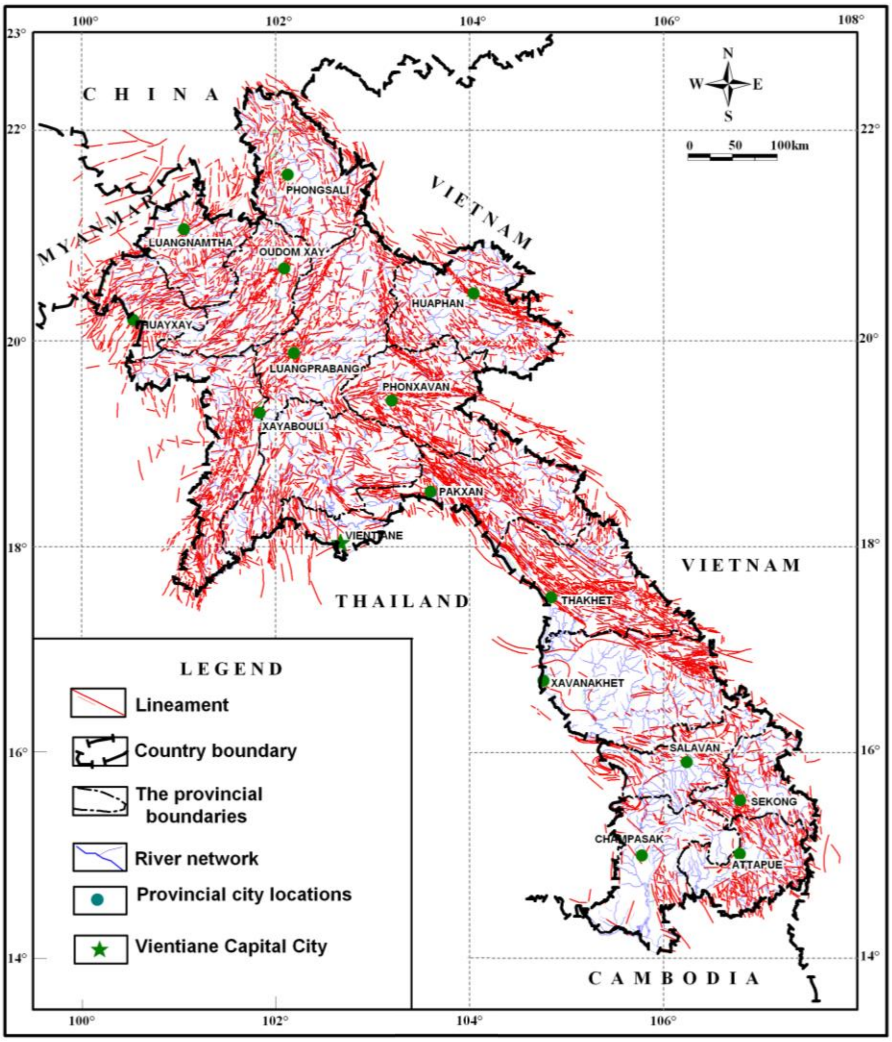

Figure 5. The distributions of lineaments in Laos territory

4.2. The main Neotectonic faults in the territory of Laos

The activity of many old structures probably has continued to the present day (Ntokos D., 2018), so finding neotectonic faults is essential in identifying active faults. By correlating the lineament map and the results of the recent study on neotectonic faults in Laos (Nguyen T.Y. et al., 2014; Bui V.T. et al., 2014, 2015), a more completed map of the main neotectonic faults throughout the territory of Laos was constructed. The spatial distribution and movement mechanism of the faults during Pliocene-Quaternary time are indicated (Fig. 6). It was found that the Phongsali sub-region was characterized by the development of tectonic faults in the NW-SE and sub-meridian directions. All the NW-SE trending faults are continuously extended to China. In addition, the Gnotou-Phongsali (GO-PSL) and Phoudendin-Mai (PDD-M) faults have changed to the sub-meridian direction at their southeastern segments. The NW-SE trending BT-K fault restricts the southern margin of the region. The geologic-geomorphologic data have shown the suitable lateral strike-slip motion along these faults during the Late Cenozoic time in association with a normal component in several locations dominantly (Nguyen T.Y. et al., 2014; Bui V.T. et al., 2014; 2015).

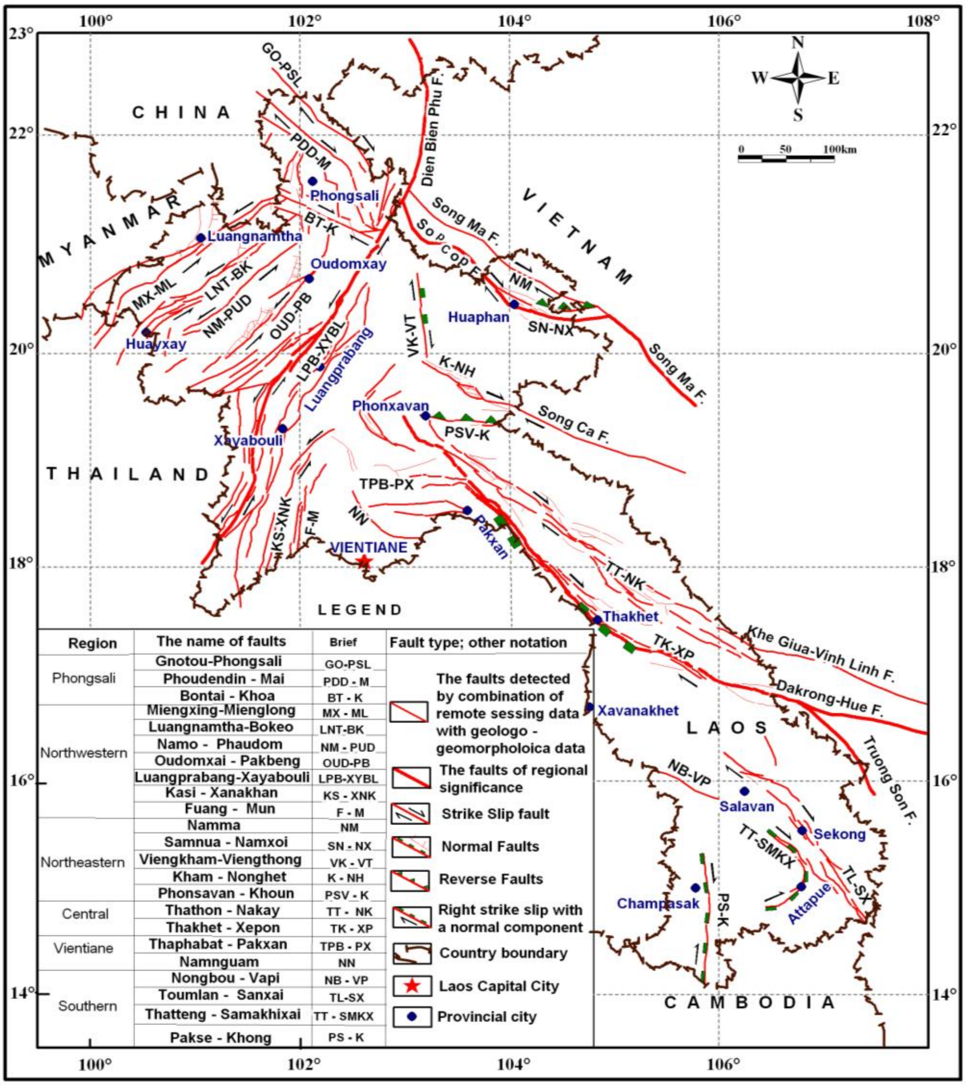

Figure 6. Distributions of the main neotectonic faults in Laos

The Western Laos structural sub-region stretches from the LPB-XYBL fault zone to the northwest border. The main faults in this structural unit including Dien Bien Phu, Loei Petchabun, Nam Ma, Mae Chan, Mae Ing, Nam Peng in the northwestern part of Laos (Pailpolee et al., 2009) which are re-named into Luangprabang-Xayabouli, Fuang-Mun (F-M), Miengxing-Mienglong (MX-ML), Luangnamtha-Bokeo, Namo-Phaudom (NM-PUD) and Oudomxai-Pakeng (OUD-PB) in this study, respectively are distributed along the NE-SW direction. Therein, the LPB-XYBL fault divides the northern part of Laos into two regions with relatively similar areas and continues to extend to the Thailand territory (Nguyen D.X. et al., 2004; Zuchiewicz W. et al., 2004; Nguyen T.Y. et al., 2014).

Next to the northwest are the faults along the same direction: OUD-PB, NM-PUD, LNT-BK, and MX-ML, respectively. All the above fault zones extend to Myanmar or Thailand. Their segments distributed in Laos have ranged from 160 to more than 200 km long, and all of them are terminated by the Bon Tai-Khoa fault zone at the northeast. In addition, at the southeastern edge of the Western Laos sub-region, there are two smaller fault zones in the same direction: Kasi-Xanakhan (KS-XNK) and F-M, which continue to extend to Thailand. All the mentioned above faults are characterized mainly by the left strike-slip movement mechanism, and in some locations, they are linked to the normal or reverse components. The activity during the Late Cenozoic and Quaternary times is revealed in different locations along all the fault zones (Nguyen T.Y. et al., 2014; Bui V.T. et al., 2014; 2015).

Within the Truong Son and Northeastern Samnua structural regions, there are 5 main neotectonic faults in the NW-SE direction, which extend to the territory of Vietnam. The NM and SN-NX faults are located at the Northeastern Samnua structure of the Northwestern Vietnam structural block. The three remaining faults in the Truong Son structural region include the Kham-Nonghet fault (K-NH) with a segment extending to Vietnam called the Song Ca fault; the TT-NK fault slightly changed its direction to the sub-parallel when the fault entered into Vietnam as named Khe Giua-Vinh Linh; and the last one is the TK-XP with a segment entering Vietnam called Dakrong-Hue).

The activity during the Late Cenozoic-Quaternary times along all the faults is reflected by the geologic-geomorphologic data in several locations, and the exposed hot water springs are also detected. The dominant right strike-slip displacement is a motion mechanism for all the faults in Late Cenozoic-Quaternary times. However, the thrust component associated with the strike-slip movement mechanism is found in different locations along the NM and SN-NX faults. In contrast, the normal component is more prevalent along the Thatthon-Nakay and TK-XP faults. In addition, one smaller size Viengkham-Viengthong (VK-VT) sub-meridian fault revealed in the northern part of this region is characterized by a normal movement mechanism in association with the suitable strike-slip component (Nguyen T.Y. et al., 2014; Bui V.T. et al., 2014; 2015).

The density of tectonic faults has considerably decreased in the areas that come from the Khorat plateau region. Just two main faults were revealed in the Vientiane area, namely the Namnguam (NN) fault with the NW-SE direction in its northwestern segment, which gradually changed to the parallel direction in the southeastern one, and the sub-parallel direction Thaphabat-Pakxan (TPB-PX) fault. The Toulan-Sanxai (TL-SX) and Thatteng-Samakhixai (TT-SMKX) faults were observed in the remaining southeastern part of Laos. Both have stretched along the NW-SE direction and reflected dominantly the suitable strike-slip movement mechanism. In the southwesternmost area, the Pakse - Khong (PS-K) sub-meridian fault is also encountered with the predominant normal movement mechanism accompanied by the suitable strike-slip motion component (Nguyen T.Y. et al., 2014).

4.3. Seismic activity in the territory of Laos

By aggregating the various data sources, 4416 earthquakes have been collected in the territory of Laos and its surrounding areas. Among them, 820 events were located using the data recorded by at least 3 stations in the local Laos network. The decluttered catalog encompassing 1617 earthquakes obtained from the calculation is accepted as the mainshocks. This is the number of earthquakes considered to be independent events that happened in the territory of Laos and adjacent areas within 96 years, from 1925 to 2021. A map of the distributions of neotectonic faults and the earthquake epicenters was constructed to investigate the seismic activity level in different neotectonic structural regions and the relationship between earthquake epicenter distribution and neotectonic faults in Laos. Here, the neotectonic data encompass the neotectonic faults presented in Fig. 5 and ones revealed by only remote sensing data in Eastern Laos's region in other previous studies (Nguyen D.X. et al., 2004; Nguyen T.Y. et al., 2006). Besides, several major active faults in the territory of Vietnam obtained from other studies (Nguyen D.X. et al., 2004; Nguyen T.Y. et al., 2006; Nguyen H.P. and Pham T.T., 2015) were also added, mainly the faults extending from Laos to Vietnam, to clarify their size. The earthquakes on this map are independent events. In addition, because the recorded earthquakes with Mw < 2.0 are mainly distributed in the territory of Vietnam, this map shows solely the earthquakes with Mw ≥ 2.0 (Fig. 9).

4.3.1. Magnitude frequency, earthquake depth distribution, and seismic activity in different structural regions

The magnitude of the declustered catalog is varied from Mw = 1 to 7.2, and a large portion of events is manifested by the magnitudes in a range of 2.4 ≤ Mw ≤ 4.3 (Fig. 7). All the recorded earthquakes are shallow with a maximum focal depth less than 50 km, a large proportion ones are concentrated in the upper crust of the Earth H ≤ 20 km (Fig. 8).

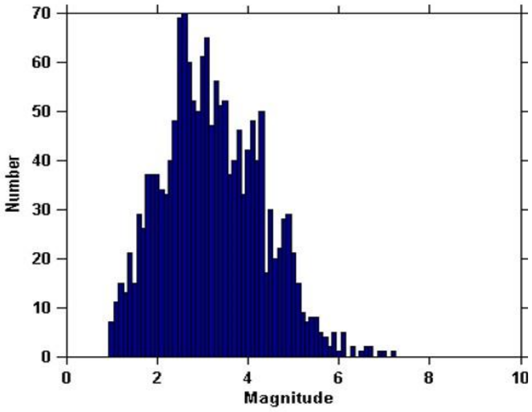

Figure 7. The number of earthquakes Vs. Mw

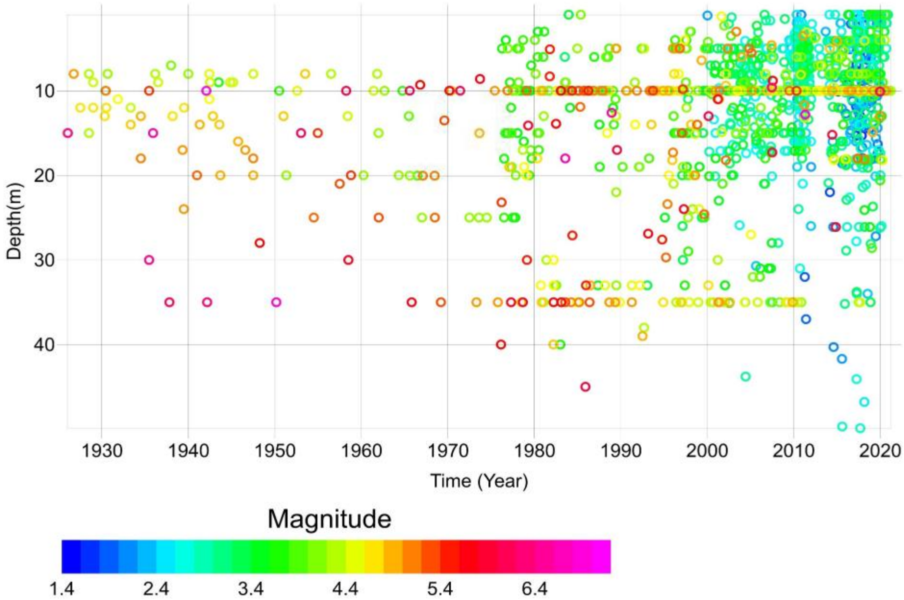

Figure 8. Distribution of earthquakes vs. depth

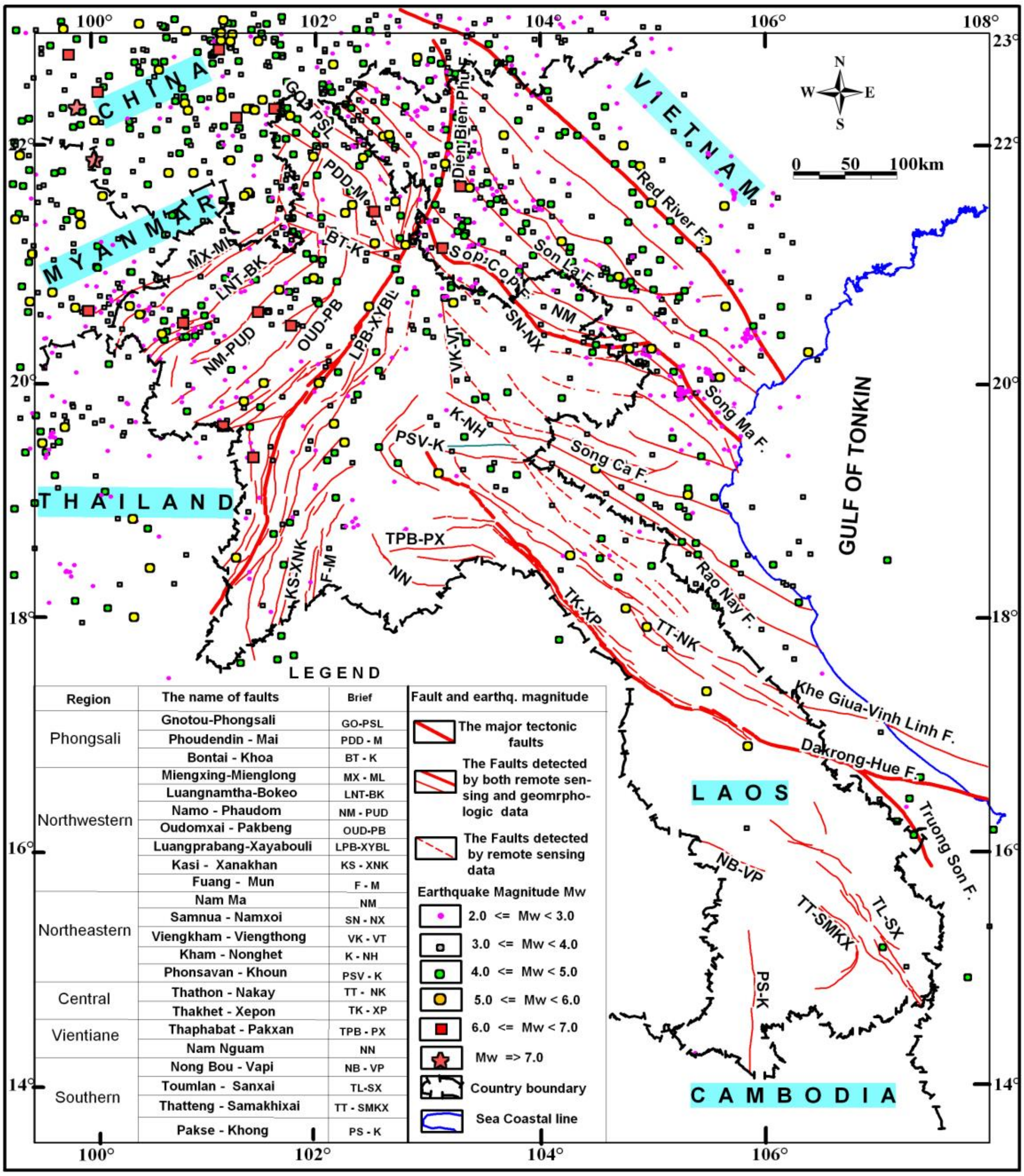

Figure 9. The relationship between the spatial distributions of earthquake epicenters and neotectonic faults

Considering the distribution of the earthquake epicenters on the map (Fig. 9), it is seen that the level of seismic activity in the Northwestern Laotian structural region is much stronger than the rest. Here, 19 mainshocks with Mw ≥ 5.0 have been recorded, of which 6 events have magnitude 6.0 ≤ Mw ≤ 6.6.

In addition, 2 strong earthquakes with Mw = 6.1 and 6.9 appeared outside of Lao but close to the border at Phongsali and west of Luangnamtha provinces, respectively, which still belong to this structural region in the part extending to foreign territory. The most recent strong earthquake occurred at Xayabouli on November 20, 2019, with Mw = 6.1 is also a part of this region. Earthquakes of smaller magnitude also have a higher density than other regions.

In the Truong Son structural region, the earthquake density is much lower than that in the Northwestern region, and no earthquake with an Mw ≥ 6.0 magnitude has been recorded. It should be noted that in its northern part, from the Phonsavan-Khoun (PSV-K) fault to the north and northeast, the level of seismic activity in the northern part is lower than in the southern one, not only the density of earthquakes but also the most significant magnitude which has reached only Mw = 5.0. In contrast, 6 earthquakes with magnitude Mw = 5.0–5.7 were recorded in the southern part.

The Northeastern Samnua area recorded 12 earthquakes with magnitude Mw = 2.8–4.6 and has a higher earthquake density than Truong Son. Although no earthquake with Mw ≥ 5.0 has been detected yet, this area is a part of the Northwestern Vietnam structural block, where 2 earthquakes (Mw = 6.7, 6.8) and 10 events with Mw = 5.1–5.8 had been recorded and recognized the most seismically active region in the territory of Vietnam. (Nguyen D.X. et al., 2004; Nguyen H.P. and Pham T.T., 2015; Nguyen. HP et al., 2019). Since then, the Northeastern Samnua area has been considered a seismically active region. The remaining area in the Khorat structural block is relatively stable, including an area in the south of the Vientiane Province and the region distributing to the southwest and south of the TK-XP fault zone. There are only 4 earthquakes in the Vientiane area with 2.0 ≤ Mw < 3.0, while in the southern part, 3 earthquakes with magnitude Mw = 3.4–4.2 were recorded.

4.3.2. The focal mechanism of several earthquakes and its relation with the fault motion

A correlation between the focal mechanism of these earthquakes and the distribution of main neotectonic faults in the territory of Laos shows that 7 earthquakes all occurred in the fault zones within the Northwestern structural region, of which 5 earthquakes occurred along the 4 fault zones of NE-SW direction in the Western sub-region and 2 others along the NW-SE trending GNO-PSL and PDD-M fault zones belonged to the Phongsali structural unit (Fig. 10). The above inference results are based on the distributions of earthquake epicenters close to the fault trace, in these locations were also not detected the faults of other direction and especially one from two sets of the focal mechanism parameters for each earthquake is reflecting the motion mechanism consistent with the research results using geological and geomorphological data. The parameters of the earthquake focal mechanism appropriated to the mentioned faults are listed in Table 2. Among the fault plane solutions defined from 5 earthquakes in the Western sub-region, 2 events have been related to the LNT-BK fault. A predominant left lateral strike-slip associated with a slight reverse component of this fault motion is revealed for earthquakes 1 and 6. The slight change in the dipping direction of the fault plane from the northwest in the provincial town area Huayxai (earthquake numbered 1) to the southeast in the location of the earthquake numbered 6 is probably related to the separation into different segments of this fault.

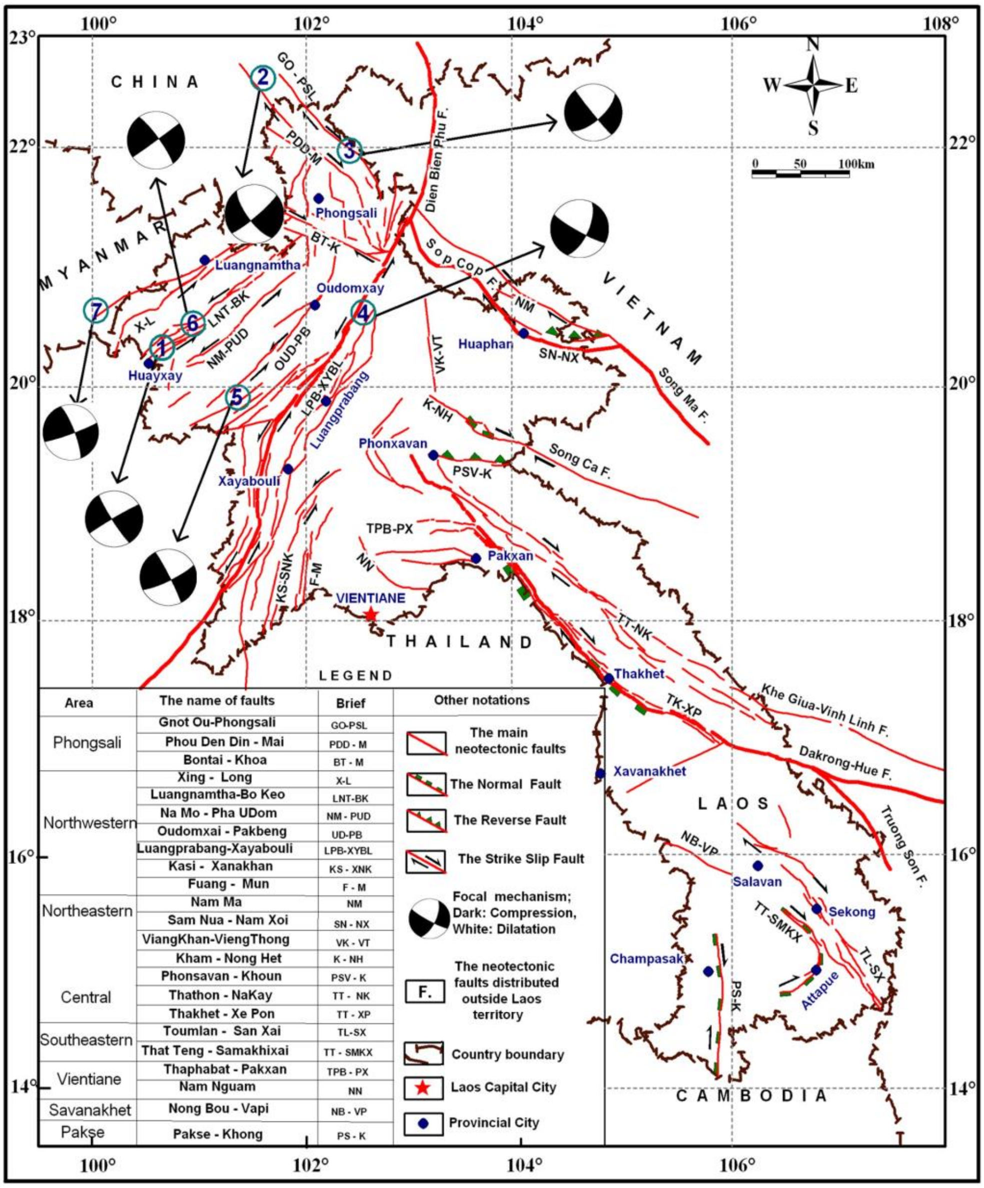

Figure 10. Fault plane solutions of 7 earthquakes in Laos territory

Table 2. The fault plane solutions of the earthquakes collected from the CMT catalog

No.	Latitude (Degree)	Longitude (degree)	Mw	Depth (Km)	Month/ Date/Year	Strike/dip/ rake (Degree)	Type of motion
1	20.26	100.51	5.2	15	8/2/1978	239/87/6	Left strike-slip in asso. with reverse
2	22.74	101.54	5.3	10	9/19/1981	143/71/-172	Right strike-slip in asso. with normal
3	21.97	102.36	5.5	10	6/1/1982	141/87/-156	Right strike-slip in asso. with normal
4	20.61	102.61	5.6	15	6/16/1989	25/65/-9	Left strike-slip in asso. with normal
5	19.92	101.33	5.4	15	1/19/2000	64/80/4	Left strike-slip in asso. with reverse
6	20.52	100.89	6.3	12.6	5/16/2007	54/89/9	Left strike-slip in asso. with reverse
7	20.62	100.02	6.9	13.2	3/24/2011	70/85/11	Left strike-slip in asso. with reverse

Remark: *asso. - association*

A predominant left-lateral strike-slip movement has indicated a good agreement with the motion type of this fault obtained by the geologic-geomorphologic data (Nguyen T.Y., 2014). The focal mechanism of earthquake numbered 4 that occurred along the LPB - XYBL fault zone depicted the dipping direction to the southeast and motion, the dominant left-lateral strike-slip associated with a normal component. The earthquake of number 5 related to the OUD-PB fault is characterized by the southeast dipping direction of the fault plane and the predominant left lateral strike-slip in connection with a slight reverse component. The same type of motion and dipping direction of the X-ML fault plane was defined by the focal mechanism of the Myanmar earthquake numbered 7. The fault plane solutions of the two remaining earthquakes numbered 2 and 3, are indicated by a predominant right-lateral strike-slip motion in the company of a normal component along the PDD-M and GO-PSL faults, respectively, in the Phongsali structural unit.

A good consistency of all the collected fault plane solutions with the fault movement mechanism obtained from the geologic–geomorphologic data has fortified the confidence about continuing the movement mechanism of the recent active faults to the present day. The continuation of a predominant strike-slip motion to the present day on a regional scale is also revealed by the focal mechanism of earthquakes from different research, such as earthquake Mw = 6.2 in Chang Rai, Thailand 2014 (Pananont et al., 2017), or Moc Chau and Muong Te earthquakes 2020 with Mw = 5.0 and 4.9, respectively in Vietnam (Nguyen et al., 2022a; 2022b).

4.4. Preliminary identification of active faults in the territory of Laos

The preliminary identification of active faults in the territory of Laos was accomplished based on a relation between the spatial distribution of neotectonic faults and seismic activity. In this study, young faults are considered active faults if they have several features, such as cutting through Quaternary formations in some locations and having several earthquake epicenters distributed along the fault zone (Charusiri P. et al., 1999; 2022) or the fault along with the earthquakes Mw ≥ 5.0 occurred (Charusiri P. et al., 1999), that called the seismogenic fault (Hanson K.L. et al., 1999).

4.4.1. Identification of the active faults in the Northwestern structural region

In the Phongsali structural unit, which occupied the northern part of the Northwestern structural region, there are 3 main faults: GO-PSL, PDD-M, and BT-K cutting through the Quaternary formations in some locations (Nguyen T.Y. et al., 2014). Along the GO-PSL fault zone, 2 earthquakes, Mw = 5.5 and Mw = 5.2, were recorded in 1982 and 1983, respectively, and the epicenters of some more minor magnitude earthquakes are distributed along the fault. Two other strong earthquakes manifested in 1958 and 1965 with Mw = 6.0 and 6.1 belong to the PDD-M fault zone. An earthquake of Mw = 5.1 occurred in 2002, and several epicenters are also distributed along this fault trace. Not many earthquake epicenters were detected along the BT-K fault zone, including the Mw = 5.0 earthquake that occurred in 1979 (Fig. 9). Thus, the above faults can be considered active. In the Western Laos structural unit, the earthquakes Mw ≥ 6.0 were manifested along all of the 5 primary NE-SW direction fault zones. In the largest fault zone, LPB-XYBL, many earthquake epicenters are allocated to the primary and minor branches. Among them, 4 earthquakes with magnitude Mw = 5.3, 5.4, 5.9, and 5.6 appeared in the main branches in 1935, 1979, 1989, and 2001 respectively. Along two auxiliary branches located southeast of the main branch, 2 earthquakes with Mw = 5.0 and Mw = 5.5 were measured in 1948 and 1983, respectively. The most recent strong earthquake, Mw = 6.1 on November 20, 2019, happened in one auxiliary branch distributed to the west of the main fault branch in Xayabouli Province. Next to the northwest is the OUD-PB fault zone, consisting of several separated segments and several earthquake epicenters distributed along this fault. Among them, the strong earthquake that happened in 1937 with Mw = 6.1 was recorded in its middle segment and 2 events with Mw = 5.0 and 5.9 occurred in 1930 and 2000 years, respectively, belonging to the southeastern branch of this fault zone. Along the trace of the MN-PUD fault, two earthquakes, Mw = 6.6 and 5.1, occurred in 1925 and 1985 in its middle and northeastern segments, respectively. Many epicenters, including an earthquake Mw = 5.1 (1979) in the southeastern flank, likely belonged to this fault since the fault indicates the southeastern dipping direction along this section. The LNT-BK fault zone distributes further to the northwest and is almost parallel to the NM-PUD fault. At its northeastern and southwestern segments, some auxiliary branches have been developed. The density of earthquake epicenters is too high in the southwestern and less dense in the northeastern segments. The events with magnitude Mw = 5.2 and Mw = 6.3 that occurred in 1996 and 2007, respectively, can be seen in its southwestern segment. The last fault in this structural region, the MX-ML fault, has two branches running from the southern part of China territory, then through Laos and to Myanmar. Similar to the LNT-BK fault, the density of earthquake epicenters along this fault zone is much higher in the southwestern segment than in the rest. Also, in this segment, 2 earthquakes with magnitude Mw = 5.7 and Mw = 5.1 happened in two branches in 1977 and 2017, respectively. In addition, the earthquake Mw = 6.9 occurred in Myanmar on March 24, 2011, is only more than 20 km from the Laos border, it is still located in the extension segment of the MX-ML fault to Myanmar (Pailoplee S. and Choowong M., 2012; Feng W. et al., 2013). In the area between the LNT-BK and MX-ML faults, several earthquake epicenters with magnitudes from 2.0 to < 4.0 are unrelated to any fault. Thus, the main neotectonic faults in the Northwestern structural region, related to the spatial distribution of seismic activity, are all reflected as active faults.

4.4.2. Identification of active faults in the Truong Son structural region

Most of the primary faults in this structural region are northwest-southeast trending, and several faults extend to Vietnam. In the northern part of the region, from the PSV-K fault to the north, the fault systems have not been studied in detail. The density of earthquake epicenters here is low, and their spatial correlation with the neotectonic faults is not good enough. Along the VK-VT sub-meridian fault zone, not many earthquake epicenters were distributed. However, its northern segment detected the earthquake with Mw = 5.0 in 2003. Therefore, the fault could be recognized as a seismogenic fault. Only a few earthquake epicenters were observed along the K-NH fault zone, and no earthquakes with Mw $\geq$ 4.0. However, the segment extending to Vietnam, called the Song Ca fault, is relatively active, exemplified by earthquakes of magnitude Mw = 5.2 and Mw = 5.1, recorded in 1957 and 2005, respectively. In addition, the historical earthquake Mw = 5.4 observed in 1821 also belonged to the mentioned segment (Nguyen D.X. et al., 2004). With the above characteristics, the K-NH fault is active. In this region, there are also some faults detected by remote sensing data only, where quite a few earthquake epicenters were distributed, reflecting a poor spatial relationship with faults. Hence, these faults need to be studied more thoroughly in the future.

In the southern part of the Truong Son block, two main faults, TT-NK and TK-XP, stretch along the NW-SE direction approximately 400 km in Laos territory. Both of them extend to the territory of Vietnam with the names Khe Giua-Vinh Linh and Dakrong-Hue, respectively. These faults also have cut through Quaternary sediments in different locations. According to statistics, earthquakes linked to the TT-NK fault were recorded more often in 1968, 1982, 1985, and 2004, with Mw = 5.0, 5.0, 5.5, and 5.1, respectively. In addition, some more minor earthquakes were also distributed along the fault. The above indications reflect that this fault is active. Although the seismic activity level of the TK-XP fault zone is lower than the TT-NK one, 2 earthquakes with magnitude Mw = 5.1 and Mw = 5.7 were recorded in 1996 and 1997 in its northern and southern segments, respectively. The above sign allowed us to accept this fault as a seismogenic fault. However, several faults were detected by only remote sensing analysis. They appeared in separated segments at different locations, demonstrating a poor spatial relationship with the earthquake epicenters, which are scatteredly distributed in this southern part and need further study.

In general, the main neotectonic faults identified by remote sensing and geological-geomorphological data in the Truong Son region are all seismogenic and can be considered active. Although seismic activity is lower than in the Northwestern region, the potential to generate moderate to solid earthquakes as those segments extend to Vietnam may be possible along the segments of these faults in Laos.

4.4.3. identification of active faults within the Northeastern Samnua structural unit

7 earthquakes with magnitude Mw = 3.0–4.6 were detected along the SN-NX fault zone. The spatial distribution of the earthquake epicenters is closely correlated with the fault trace. In addition, the SN-NX fault is also the middle segment of the Sop Cop fault in the Vietnam territory, which is accepted as a strong seismically active fault. In the territory of Vietnam, the earthquake Mw = 6.8 in 1935 was revealed in the northern segment of this fault. Mw = 5.5 and 5.8 were recorded in 1948 and 1958, respectively, situated in the southern segment with their epicenters distributed only ≤ 20 km from the southern end of the SN-NX fault (Nguyen D.X. et al., 2004; Nguyen T.Y. et al., 2006; Nguyen H.P. and Pham T.T., 2015; Duong T.N. et al., 2021). Therefore, the SN-NX fault is considered a seismically active fault. Located about 35–40 km to the northeast of the SN-NX fault is the NM fault. This fault zone reflects relatively low seismic activity, with 5 earthquake epicenters with magnitude Mw = 2.8–4.2, which are placed away from the fault trace from 8 to more than 12 km. The low seismic activity and a not good correlation between the spatial distribution of earthquake epicenters and the fault trace do not prevent the recognition of the NM fault as an active fault since, along the segments extending to Vietnam called the Song Ma fault, there are many earthquakes epicenters distributed along the fault trace (Wen S. et al., 2015; Nguyen H.P. et al., 2019; Duong T.N. et al., 2021) including the earthquake of magnitude Mw = 5.4 occurred in 1954.

4.4.4. Active fault identification in The Khorat structural region

The Khorat structural region reflects a much lower seismic activity than other regions. Here, only a few earthquakes with magnitude 2.5 ≤ Mw ≤ 4.2 were recorded in the northwestern and eastern margins of the block. At its northwestern margin in the Vientiane Province, 4 earthquakes from Mw = 2.5 to 2.9 were recorded during

2017–2020, and one more Mw = 2.8 occurred to the north of the fault PTB-TX in 2019. In southern Laos, 2 earthquakes, Mw = 4.2 and Mw = 3.4, were noted in 2017 and 2018, respectively. These events were detected along the TL-SX fault zone. One another earthquake with magnitude Mw = 3.8 in 2016 is unrelated to any fault. Thus, the Khorat unit is the quietest region in terms of seismic activity in the territory of Laos. According to the criteria for identifying active faults in this study, no active faults have been detected in this region. Thus, from the spatial correlation between the distributions of neotectonic faults and earthquake epicenters, 14 main active faults were defined in this study, most of them are also seismogenic faults (Fig. 11).

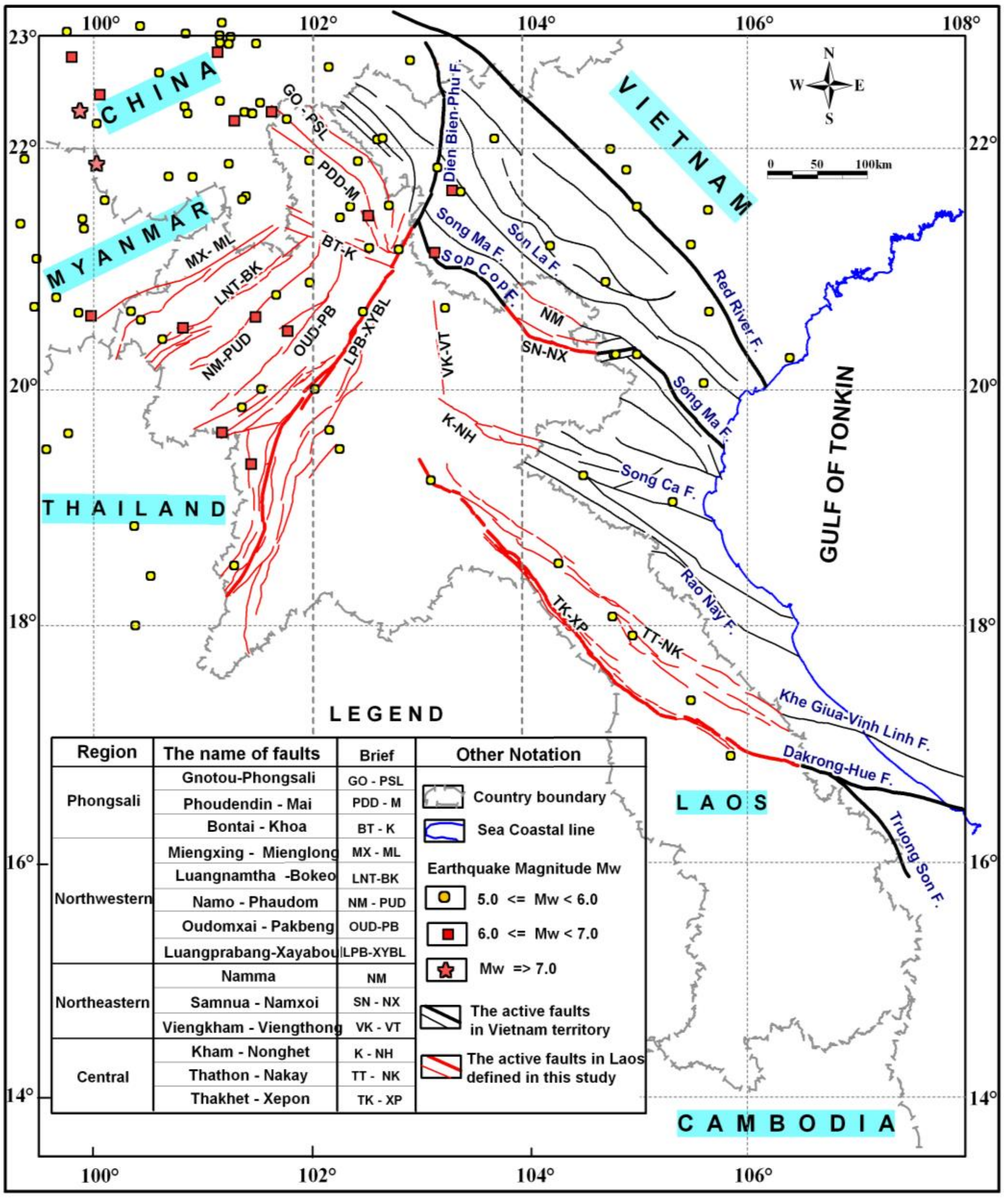

Figure 11. The main active faults in Laos territory are defined in this study

Among them, 5 faults are distributed in the Northwestern, 3 in the Phongsali, 2 in the Northeastern Samnua and 4 in the Truong Son regions, respectively. The results of active faults presented in this study should only be considered preliminary results because the study of active faults also requires using many other data, such as crustal structures, paleoseismic activity, historical earthquakes, and modern activity manifestation, according to GPS data. In addition, several areas still do not have enough geological-geomorphological data to study neotectonic faults in detail. Many earthquake epicenters were detected in different locations, but their distribution is unrelated to any faults. There are many reasons for this phenomenon, such as some blind faults that cannot be detected by the geological-geomorphological data used in this study and significant errors in locating the earthquakes, especially for small earthquakes. Another phenomenon is the difference in seismic activity rates at different segments of many fault zones. To achieve a more comprehensive feature of the relationship between faults and seismic activity, these objects must be further implemented in more detail in the upcoming time.

4.5. Preliminary seismotectonic zonation of Laos territory

The seismotectonic zonation has been done based on recognizing the characteristics of seismic activity and the relatively homogeneous tectonic regime in each region (Vamvakaris D.A. et al., 2016; Monique T.S. and Didier B., 2021). From the mentioned research results on seismic activity and active and neotectonic faults, it can be seen that the Northwestern structural region has the most robust seismic activity, both in magnitude and frequency. This region can still be divided into two zones corresponding to the two structural sub-regions: Western Laos and Phongsali (Fig. 12).

As mentioned above, the number of earthquakes with Mw ≥ 6.0 recorded in the Western sub-region is higher than in the Phongsali, and the most significant observed earthquake magnitude also occurred here. According to the seismic activity, all the primary faults in this structural unit are the sources of strong earthquakes, so that this area can be the highest earthquake risk zone. Regarding tectonic activity, the predominantly left-lateral strike-slip movement mechanism characterizes all the main neotectonic and active faults in this unit stretched along the NE-SW direction.

Although the Phongsali sub-region also has a high seismic activity, the number of earthquakes with magnitude Mw ≥ 6.0 and observed maximum earthquake magnitude were also smaller than the Western sub-region. The NW-SE direction of the primary faults and the predominant suitable strike-slip displacement mechanism are different from the Western sub-region, so this area could be indicated as a separated zone with relatively seismic solid activity. Within the Eastern region of Laos, a part of the Truong Son structural block from the fault zone PSV-K to the north and northeast up to the SN-NX fault zone reflects lower seismic activity than the southern part, as mentioned above. The feature is similar to the area between the Song Ca and the Song Ma faults in the territory of Vietnam (Fig. 9). Except for the distinction in seismic activity, the density of neotectonic and active faults in the northern part is lower than the value in the southern part, and the size of the primary faults in the southern part is also larger. Given the mentioned indications, the area belonging to the Truong Son structural block in the territory of Laos can be divided into 2 seismotectonic zones temporarily called North Truong Son and South Truong Son.

The next area in the Eastern region is the

Northeastern Samnua structural unit. Although the observed seismic activity here is not too high, this is a part of the Northwestern Vietnam seismically active region. Thus, the Northeastern Samnua can be considered a potentially seismic solid activity area in this case. The remaining part of the Laos territory includes the area belonging to the Khorat block in Vientiane province, the strip of land distributed to the southwest of the TK-XP fault zone, and the southernmost part of Laos is characterized by the sparse distribution of the neotectonic faults and low seismic activity, temporarily called the Khorat zone, and can be considered a relatively stable seismotectonic zone.

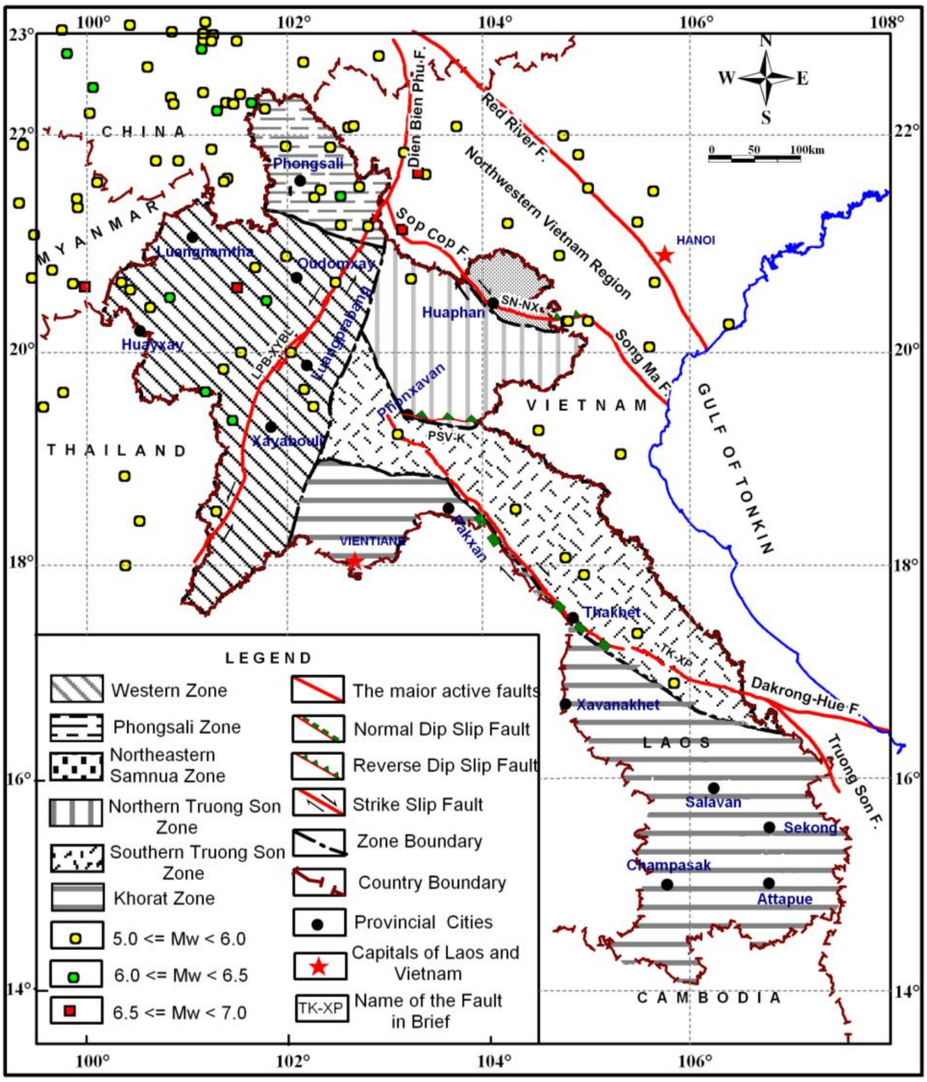

Figure 12. Seismotectonic zoning map of Laos territory

Thus, according to the characteristics of the seismic activity as well as neotectonic and active faults presented in this study, the Laos territory can be roughly divided into 6 seismotectonic zones, of which the most seismically active zone is the Western sub-region of Laos. The second most robust seismic activity potential zone is the Northeastern Samnua structure since this area belongs to the Northwestern Vietnam seismotectonic zone, where the observed maximum earthquake and frequency of solid earthquakes are only after the Western sub-region. The Phonsali sub-region can be regarded as having the third seismic solid activity. The North Truong Son and the South Truong Son zones are recognized as having moderate seismic activity; however, the Southern Zone is indicated by a more substantial level of seismic activity than the Northern one. The last zone accepted as relatively stable includes the remaining areas mentioned above.

5. Conclusions

In this study, the active faults in the territory of Laos are preliminarily identified as neotectonic faults cutting the Quaternary formations in different locations along their traces, and at the same time, they are the seismogenic faults with Mw ≥ 5.0 or with several earthquake epicenters distributed along them. All 14 main active faults were defined. Among them, 8 faults: MX-ML, LNT-BK, NM-PUD, OUD-PB, LPB-XYBL, B-TK, PDD-M and GO-PSL; 4 faults: VK-VT, K-NH, TT-NK, and TK-XP; 2 faults: NM and SN-NX are distributed in the Northwestern, Truong Son and Northeastern Samnua regions, respectively. The results show that all the immense sizes of neotectonic faults identified using remote sensing and geomorphological data are recognized as active faults.

- By considering the characteristics of the spatial distribution, the movement mechanism of the main active and neotectonic faults, and the seismic activity level in different locations, the territory of Laos can be divided into 6 seismotectonic zones. The regions are ranked in order of decreasing seismic activity: Western Laos, Northeastern Samnua, Phongsali, Southern Truong Son, Northern Truong Son, and Khorat zones.

- The simultaneous use of remote sensing data, data on seismic activity, and research results on neotectonic faults derived from geologic-geomorphological data allows the results obtained in this study to move a step forward in identifying active faults compared to previous studies that relied solely on remote sensing data. These results can be considered a more suitable data source for more profound studies on active faults, seismotectonic sources, and improving the quality of earthquake hazard assessment in Laos territory soon.

Acknowledgments

The authors would like to express sincere thanks to the Institute of Earth Sciences-Academia Sinica-Taiwan, the Institute of Geological Sciences-Vietnam Academy of Science and Technology, and the project with codes CSCL11.02/23-24 for the technical and financial support for our study. We also thank the International Seismological Center (ISC) and the Thai Meteorological Department (TMD) for providing the earthquake data online.

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