



Seismic activity in the continental shelf of South-Central Vietnam and adjacent regions from 2005 to 2020

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ABSTRACT

Since 2005, 10 seismic monitoring stations have been installed in the southern part of Vietnam. These stations can detail the earthquakes in the region and adjacent areas. In the past, there was an earthquake of magnitude 6.1 (1923) in the offshore South-Central Part related to the Hon Tro eruption, the largest observed earthquake magnitude in the 20th century. Between 2005 and 2020, 371 earthquakes were recorded with magnitudes ranging from 0.7 to 5.3. Most of events were distributed on some northeast-southwest direction faults in South Central offshore. The magnitude of the representative earthquake was relatively small, $M_c = 2.2$, so it is assumed that this research area was of weak activity. The epicenter is about < 20 km, and the majority concentration is at a relatively shallow depth of 5km and still located in the crust of Earth. The relationship between earthquake magnitude and frequency in this region is as follows: $\lg N = 4.063 - 0.694 * M$ for the entire catalog of 371 events and $\lg N = 3.826 - 0.704 * M$ after filtering 92 foreshocks and aftershocks of the earthquakes $M = 5.3$ on November 8th, 2005, and $M = 5.2$ on November 28th, 2007. So, the calculated average b -values before and after filtering foreshocks and aftershocks were approximately 0.7. These values are almost approximate to the b -value of 0.76 determined by Pham Van Thuc et al., (2004) based on the East Vietnam Sea earthquake catalog from 1903 to 2002 and smaller than the b -value of 0.92 for triggered earthquakes in the Song Tranh 2 hydropower region. In addition, oil and gas exploitation activities are still taking place in the South-Central continental shelf; it is necessary to continue collecting earthquake data to elucidate the causes of earthquakes in the study region.

Keywords: Earthquake, the 109° Meridian fault, East Vietnam Sea, South Central Vietnam.

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INTRODUCTION

Many Vietnamese and foreign scientists have been interested in the South-Central Vietnam continental shelf and adjacent areas for a long time. The geodynamic settings of the region are mainly driven by the 109° Meridian fault, extending from the mouth of the Gulf of Tonkin to the Vung Tau-Tu Chinh basin with a length of over 1,000 km. This fault system consists of three main and many minor faults in the NE-SW direction [1, 2]. The fault level 2 system running in the Northeast-Southwest direction controls and separates the area into the Cenozoic Cuu Long, Nam Con Son, and Tu Chinh-Vung May basins, and the Con Son uplift has a Northeast-Southwest direction. In addition, there is also a fault system in the Northwest-Southeast direction, but with weaker activity, consisting of the Hau river fault and the Vung Tau fault extending from the mainland to the sea [1].

This region's seismic activity has two different types of earthquake sources: volcanic-related activities and active tectonic origins. The first origin was the Hon Tro submarine earthquake, with a magnitude of 6.1 (1923). According to a recorded document, "before the eruption, many places in Phan Thiet, Cu Lao Hon,... were strongly shaken, houses tilted, people stood unsteadily. However, the sea level was not disturbed; these tremors lasted more than one week. Then, when the Japanese ship was passing by, they saw a cloud of black smoke standing up with a dense column of vapor emitted up to more than 2,000 m high, accompanied by strong explosions" [3]. The other related to tectonic activity was a swarm of earthquakes that occurred offshore the Vung Tau coast in 2005, which affected the coast of Southeastern Vietnam, such as Phan Thiet, Vung Tau, Ho Chi Minh city, and some other provinces. In this swarm, the earthquake with a magnitude of 5.1 at 14:09:33 (UTC) on August 5th, 2005, at 10.419°N and 108.430°E, shook some buildings in Ho Chi Minh city for a few seconds, causing people to panic. In Dong Nai, many people felt the strong vibration of the floor, and the light bulb on the ceiling swayed. The earthquake may have lasted only a few seconds, but it made everyone very scared and

went outside. The citizens living in the Vung Tau airport dormitory, in the Viet-Xo Petro joint venture dormitory, and in the Commercial Center of Ward 7 ran down the street. Many in Ward 3 and 5 felt the vibrating floor in a few seconds, causing some stuff hanging on the wall to fall [4]. However, in November 2005, two larger earthquakes with a magnitude of 5.2 and 5.3 occurred offshore South-Central Vietnam on November 7th and 8th, respectively. Seismic shakings were felt within a large area in Central and South Vietnam territory and offshore. In Ho Chi Minh city, the earthquake vibration shook the high-rise buildings, causing panic in public [5]. In addition, based on the estimation of frictional coefficients of faults in the Tuy Hoa-Vung Tau region [6, 7], some suspected that the seismic activity in this region for the 2002–2020 period might be induced by oil and gas exploitation activities.

To have more information to help more accurately evaluate earthquakes in this region. From 1976–2005, two Nha Trang and Da Lat stations began operating in Khanh Hoa and Lam Dong provinces in the South Vietnam [8]. Since 2006, From October 2006 to 2008, according to the project of seismic observation in the southern part, four additional stations were established in La Nga (Dong Nai), Dau Tieng (Binh Phuoc), Ba Ria, and Chau Thanh (Tien Giang) (not available at present) [9]. In the following phase, the Institute of Geophysics (IGP) has been actively promoting the project "Strengthen Earthquake Prediction and Establish Seismic Monitoring Network" to expand the seismic monitoring network and collect earthquake data in Vietnam. Hence, a total of 6 broad-band monitoring stations with advanced technology have been gradually installed in southern continental Vietnam and adjacent regions, including Da Lat (2009); Nha Trang, Binh Thuan (2015); Buon Me Thuat, Con Dao, and Phu Quy stations (2017) (Fig. 1) [10]. The digital signals from various seismic monitoring stations have been transmitted directly to the Seismological Center in Hanoi. The detailed and reliable information on earthquake activity is recorded to understand of their origin. Furthermore, some seismologists have given different predictions of the

maximum earthquake magnitude, such as Nguyen Hong Phuong's studies [11, 12] suggesting $M_{\max} = 6.6$, and Le Tu Son [13] based on the assessment method of Johnson et al., [14], predicting the largest earthquake $M = 6.4$ that could occur on this fault. Thus, the research on earthquakes is not only utilized to understand the regional seismic activities but contributes to the assessment of earthquake hazards and risks.

TECTONIC SETTINGS AND PETROLEUM EXPLOITATION ACTIVITIES

Tectonic settings

The South-Central Vietnam continental shelf is situated on the Southwestern continental margin of the East Vietnam Sea (EVS). Based on magnetic anomaly identifications, the geological setting of the study area is generally controlled by the EVS evolution, which was characterized by Cenozoic rifting phases that are suggested to be related to the opening of the EVS seafloor around 32–15.5 Ma as a result of the India-Eurasia plate collision [15, 16]. In the Cenozoic, several different tectonic models explained the formation and evolution of the EVS [16–19]. Taylor and Hayes [16] considered that the EVS opened along the Eurasian continental margin during the Paleogene and early Neogene, resulting from the slab pull of the subducting proto-China Sea. The hypothesis of Taylor and Hayes implies the existence of right-lateral motion along the N-S Vietnam escarpment. Tapponnier et al., [18, 19] suggested the collision between the Indian and Eurasian plates in the Cenozoic caused the entire Shan Thai-Sundaland block to extrude southeast, creating a strong left-lateral strike-slip along the Ailao Shan-Red river fault in the NW-SE direction. A horizontal displacement of about 700 km is the primary cause of the Cenozoic oceanic crust of EVS (32–15.5 Ma), like a giant stretch structure (pull-apart). Robert Hall's model [17] indicated the 109° Meridian fault, continuous with the Red river fault, also has a left-slip pattern. Rangin et al., [20] recognized the role of triggering the opening of the EVS in the Red river fault system. However, in the later stages, the EVS

developed according to Hall's model [17], the 109° Meridian fault has a right-sliding pattern.

According to the tectonophysics analysis data [21], the mainland and the islands of South-Central Vietnam show a strong expression of shear displacements along the strike-slip faults in the NW-SE direction. These faults can be considered as representations of the southward Red river shear zone. They can extend and penetrate as far as the Malaysian island of Borneo, contributing to the ease of opening the crust and spreading the seafloor of the EVS Cenozoic. In the Southwest sub-basin of the EVS basin, some faults in the NW-SE direction also act as transformation faults. Among these faults, a fault system plays a role as the southwestern boundary of the Southwest sub-basin with the shape of a V-shaped wedge. The activity of the North-South fault system is also found in some places, although it seems to be less than the NW-SE fault system. The North-South fault system illustrates more substantial activity in the depths, along with the East Vietnam Slope fault system, triggering the appearance of horizontal sliding surfaces beneath the geoblocks, which contribute to significant sinkhole-type gaps behind geologic blocks, such as the Phu Khanh Basin. Manifestation right-lateral slip of the sub-meridian fault system was recorded at a series of survey points, such as Tuy Hoa, Deo Ca, and Vung Tau.

From the field observations, Tapponnier et al., [19] reported that the most recent displacements on the Red river Fault are right-lateral, meaning that the sense of movement on it has reversed in a comparatively short time concerning the one in the Middle Tertiary. The right-lateral motion along the Red river Fault [18, 19] is interpreted to be more recent, of Plio-Quaternary age, and caused by the extrusion of the South China block. The recent displacements on the Red river Fault exhibit deformation compatible with NS shortening and EW extension [22]; a similar stress field has been confirmed by modeling and observations in Vietnam and regionally in Southeast Asia [23–26]. Under the effects of such a stress field, the NW-SE or sub-latitudinal faults are right-lateral, and the NE-SW or sub-longitudinal ones are left-lateral.

Petroleum exploitation activities

Hydrocarbon exploitation activities are mostly located in offshore southeast Vietnam, where the Cuu Long Basin accounts for 80% of the country’s crude oil production, and the remaining 20% is in Nam Con Son, Ma Lay-Tho Chu, and the Phu Khanh Basin [27]. The petroleum exploitation production of the Vietnam National Oil and Gas Group experienced an increase from 1.8 million tons in 1989 to approximately 20 million tons in 2004. However, crude exploitation output decreased from 2005, averaging output still gaining over 16 million tons/year. Between 2006 and 2011, the petroleum exploitation output saw a slight rise to 16.5 million tons in 2009, then a continuous decline to 15 million

tons in 2010. The next five-year period also witnessed a rising trend, from 15 million tons in 2011 to 18.75 million tons in 2015, apart from the gas exploitation also went up gradually from 8.6–10.6 billion m³ during this time [28, 29]. At the start of 2016, crude oil and natural gas production dropped until 2020. However, the oil and gas yield still gained at approximately 17.2 million tons and 11.5 billion m³ in 2016. Then in the following years, hydrocarbon exploitation activities tended to decline to 11.47 million tons of crude oil and 9.16 billion m³ of natural gas at the year-end of 2020 [30]. Petroleum exploitation activities continue on the continental shelf of South-Central Vietnam until now.

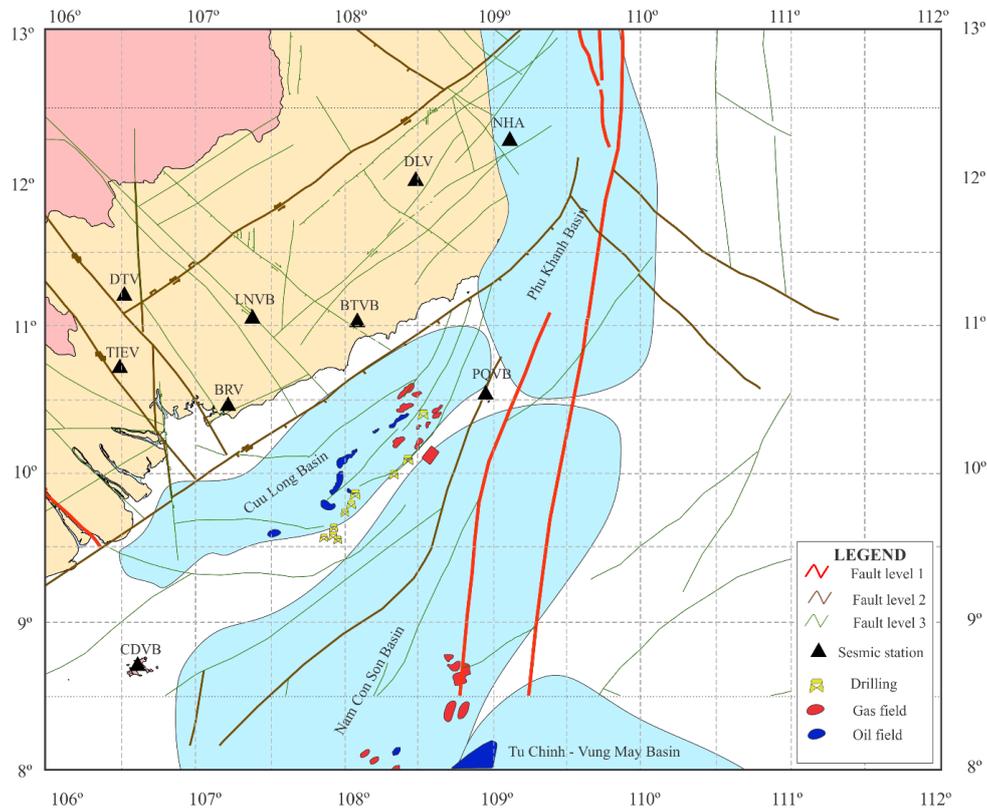


Figure 1. Petroleum exploration activities and seismic monitoring network in study region

DATA AND PROCESSING METHODS

Data

The earthquake catalog in the study regions bound by 8°00’–12°00’N and 106°00’–112°00’E was recorded by the seismic

observation station network in the period from January 1st, 2005, to December 31st, 2020. During this period, we obtained 371 earthquakes with magnitudes ranging from 0.7 to 5.3 from the Earthquake catalog of the

Earthquake Information and Tsunami Warning Center, IGP; 68 events were collected with a magnitude ranging from 1.9 to 5.5 from the Bulletin of the International Seismological Centre (ISC Bulletin) catalog [31]; and 10 shocks with a magnitude of 4.0 from the USGS United States Geological Survey website (USGS) [32] in the rectangle as mentioned above area. Based on the above data, we filtered these events at the same time and location. The IGP obtained the majority of all earthquakes. Therefore, the obtained catalog consists of a total of 371 events. Note that the magnitude in the catalog is on the local magnitude (M_L) scale. There was one largest event with a magnitude of 5.3; 3 shocks with moderate magnitudes ranging from 5.1 to 5.2; 21 quakes ranging from 4.0 to 4.9; 345 tremors with a magnitude less than 4.0; and 2 small shocks with a magnitude of 0.7 and 0.9. Most earthquakes have focal depths ranging from 5–17 km.

Application of the algorithm for allocation of foreshocks and aftershocks

To investigate the seismic characteristics of the study area in more detail, we applied the algorithm for the allocation of foreshocks and aftershocks in an earthquake with a magnitude greater than 5.0 by using a “space-time window” [33, 34]. For the earthquake with a magnitude of 5.3 that occurred on November 8th, 2005, using a space-window of 50 km and a time-window of 242 days, we have filtered 41 foreshocks, of which two events, $M = 5.1$ on 5/8/2005 and $M = 5.2$ on November 7, 2007, and 27 aftershocks. Similarly, for the earthquake with a magnitude of 5.2 at 08:16:08 UTC on November 8th, 2007, using a space-window of 45 km and a time-window of 120 days, we have filtered eight foreshocks and 16 aftershocks. Thus, after filtering both foreshocks and aftershocks of two events with a magnitude of 5.3 and 5.2, the earthquake catalog contains only 278 events.

Frequency-magnitude relation

Gutenberg and Richter [35] introduced a formula for the frequency-magnitude distribution as follows:

$$\log_{10}(N \geq M) = a - b * M$$

where: M : earthquake magnitude; N : is the number of events having a magnitude $\geq M$; a and b are constants. The a -value represents the seismic activity and is determined by the event rate, and for a particular region, it depends upon the volume and time window considered. The parameter b is a tectonic parameter that represents the properties of the seismic medium, which may vary significantly from region to region or over time. In general, Gutenberg and Richter [35] suggested the parameter b changes from 0.45 to 1.5, while Miyamura [36] found that b -values vary from 0.4 to 1.8 depending on the geological age of the tectonic area. For global seismicity, Mogi [37] computed high b -values of 1.0–1.8 in oceanic areas, including mid-oceanic ridges and island arcs of tiny islands; 0.7–1.0 in orogenic zones; low b -values of 0.6–0.7 for continental rift zones and platform block zones; and very low b -values of 0.6–0.4 for shield zones. In addition, Gupta [38] suggested that the foreshock b -values for the reservoir-induced earthquakes in the Kariba, Kremasta, and Koynaare sequences be 1.18, 1.41, and 1.87, while the aftershock b -values correspond to 1.13, 1.12, and 1.28, respectively. These values are generally higher than the regional b values of 0.53, 0.82, and 0.47 for Africa, Greece, and the Peninsular Shield of India, respectively.

RESULTS AND DISCUSSIONS

Characteristics of earthquake activity

The distribution of earthquake magnitude over time

In Figure 2a, the bar chart illustrates earthquake magnitude distribution over time between January 2005 and December 2020. In general, the number of events occurred at its highest in 2010, with 79 earthquakes. However, the maximum observed tremor was 4.2, and the majority of observed tremors had a magnitude of $M \geq 2.0$, with 152 events during this time. Although there were only two seismic stations in 2005, they recorded 81 quakes, including the largest earthquake with

$M = 5.3$ on November 8th, 2005. The following year, there was a declining trend significantly by one-third, with a maximum earthquake $M = 4.0$. In 2011 and 2012, two and three events recorded in the research region, respectively. However, these earthquakes are

assessed as slight events with a magnitude of 4.6 to 4.75. From 2013 to 2018, the seismic monitoring network did not record any earthquakes in this region. There was only one earthquake with a magnitude of 3.2 in 2019.

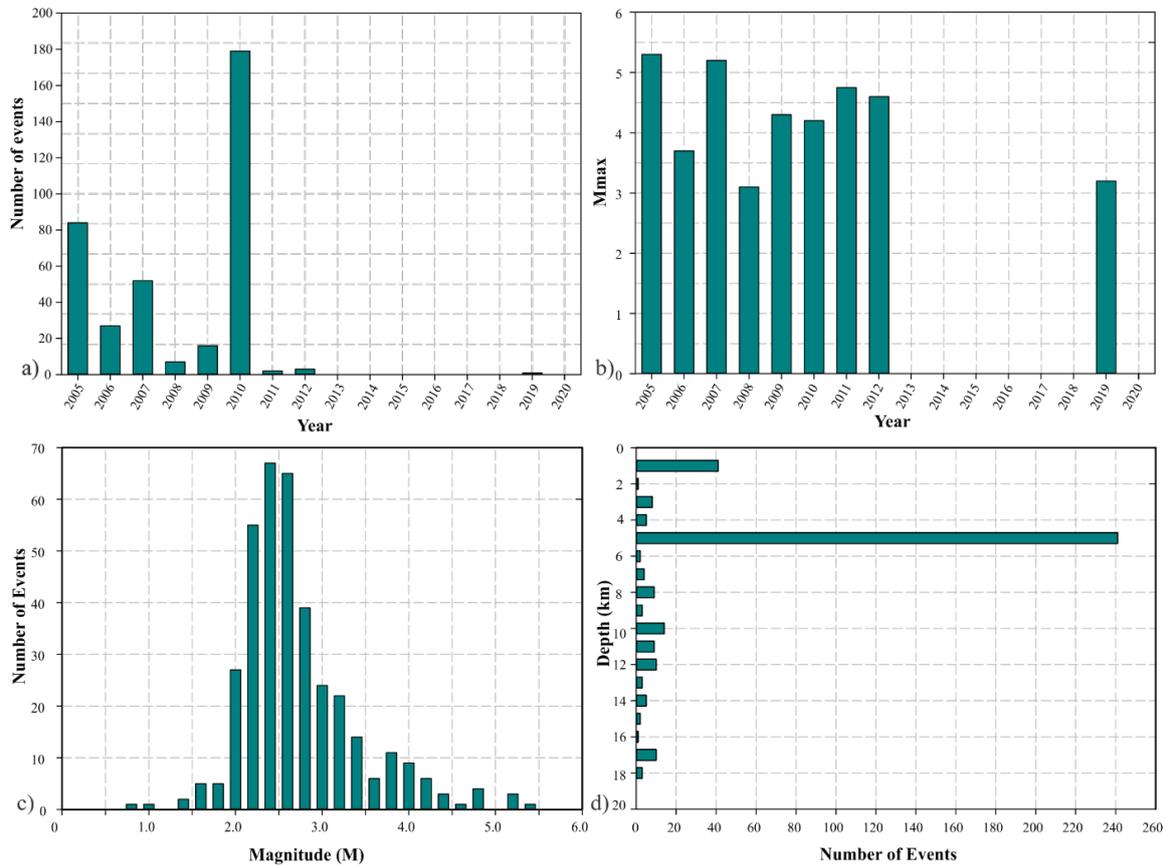


Figure 2. The distribution of earthquake magnitude a) Over time; b) By maximum earthquake; c) By magnitude; d) By depth

The statistical distribution of earthquake magnitude

Figure 2c presents the statistical distribution of earthquake magnitudes from 2005 to 2020. Most of the observed earthquakes in this region were minor events with a magnitude of 2.2 to 2.6. Concerning the number of earthquakes with $M = 5.0$ above, there are only four events. The representative earthquake in the study area has a relatively small magnitude of $M_c = 2.2$, so it can be said that the research area has weak activity.

The statistical distribution of earthquakes by the focal depth

The focal depth of all earthquakes recorded since 2005 in the study region is less than 20 km and is mainly concentrated at about 5 km (Fig. 2d). According to Nguyen Nhu Trung et al., [39], the continental margin area of central and south-eastern Vietnam has the thickness of the Earth’s crust varying drastically from 30 km in the continental shelf part to 10 km in the offshore area of the Phu Khanh and Tu Chinh-Vung May Basins. The continental crust has a

thin thickness of only 10–12 km from the Phu Khanh Basin to the Tu Chinh-Vung May Basins. The almost entire area of the Tu Chinh-Vung May Basin and most of the Phu Khanh Basin are located on this thin continental crust.

The Earth’s crust in the Nam Con Son Basin has a thickness varying from 28–12 km and 24–28 km at the Cuu Long Basin. Thus, the focal depth of these earthquakes is still located in the Earth’s crust in the Cuu Long Basin.

Table 1. Results from the moment tensor inversion of 4 earthquakes [Source: USGS]

M_L	Time (UTC)	Location	Depth (km)	Principal Plane			P -axis		T -axis	
				Strike	Dip	Rake	Plunge	Azimuth	Plunge	Azimuth
5.1	2005-11-07 17:15:50	9.959°N- 108.389°E	10	23°	79°	-22°	23°	339°	7°	71°
55.3	2005-11-08 07:54:38	9.973°N- 108.287°E	12	27°	82°	-22°	21°	342°	9°	75°
5.2	2007-11-28 15:16:10	10.12°N- 108.26°E	12	22°	82°	-19°	19°	337°	7°	70°
4.75	2011-01-26 07:24:27	9.888°N- 108.242°E	10	16°	85°	-21°	19°	330°	11°	64°

Focal mechanism

Analyzing the earthquake source mechanism is very important to know the fault characteristics and direction. The focal mechanisms of four events with a magnitude of > 4.5 obtained by the tensor moment inversion process from the National Earthquake Information Centre (NEIC)-US Geological Survey [32] are listed in Table 1 and presented in Fig. 3. It shows that these focal mechanisms are relatively similar, with a large dip (δ) angle varied from 79° to 85°, with the dip angle plugging in the ESE direction. The compression stress field is in the meridional direction (azimuth ~338°), and the dilatation one is in the latitudinal direction (azimuth ~68°), expressing left-lateral strike-slip fault along with the NE-SW orientation. These results are consistent with the present-day tectonic characteristics of the Central and South Vietnam regions [20].

In addition, the oil and gas fields and operating offshore drilling rigs are concentrated mainly in the Cuu Long and Nam Con Son Basins (Fig. 3). The focal depth of earthquakes almost coincided with the region where the oil and gas drilling rig was located, suggesting that these seismic activities were related to oil and gas exploitation activity in this area. Allison and Mandler [40] showed that any activity that significantly changes the pressure on or fluid content of rocks has the potential to trigger

earthquakes. The fluids include geothermal energy production, water storage in large reservoirs, groundwater extraction, underground injection of water for enhanced oil recovery, and large-scale underground disposal of waste liquids. For example, in Oklahoma, wastewater disposal rates tripled from 1 million barrels per day in 2010 to almost 3 million in 2014. Before 2008, there were only a few earthquakes larger than magnitude 3 ($M > 3$) per year in Oklahoma; after that, the number of earthquakes increased to 579 and 903 events ($M > 3$) in 2014 and 2015, respectively. These earthquakes clustered in areas with many large-volume disposal wells, strengthening the link between underground water disposal and induced earthquakes. In 2015, underground water disposal began to decline, and in 2016, the number of $M > 3$ earthquakes decreased to 623. This decline in underground disposal of produced water reflects both reduced production and state regulations. However, the oil and gas production in the South-Central Continental Shelf of Vietnam fluctuated slightly from 2005 to 2020, as described above. In addition, analysis results showed that the shear stress changes could induce earthquakes of 1.8–3.7 magnitude [7] due to oil and gas exploitation activity in the study area. However, the maximum earthquake observed from 2005 to 2012 was greater than 3.7 (except in 2008, $M_{max} = 3.1$); there was one recorded event from 2013 to 2020 with a

magnitude of 3.2 (2019). Therefore, it is challenging to consider that oil and gas exploitation activity is the main source of

earthquake activity, and it is necessary to continue collecting earthquake data to elucidate the causes of earthquakes in the study region.

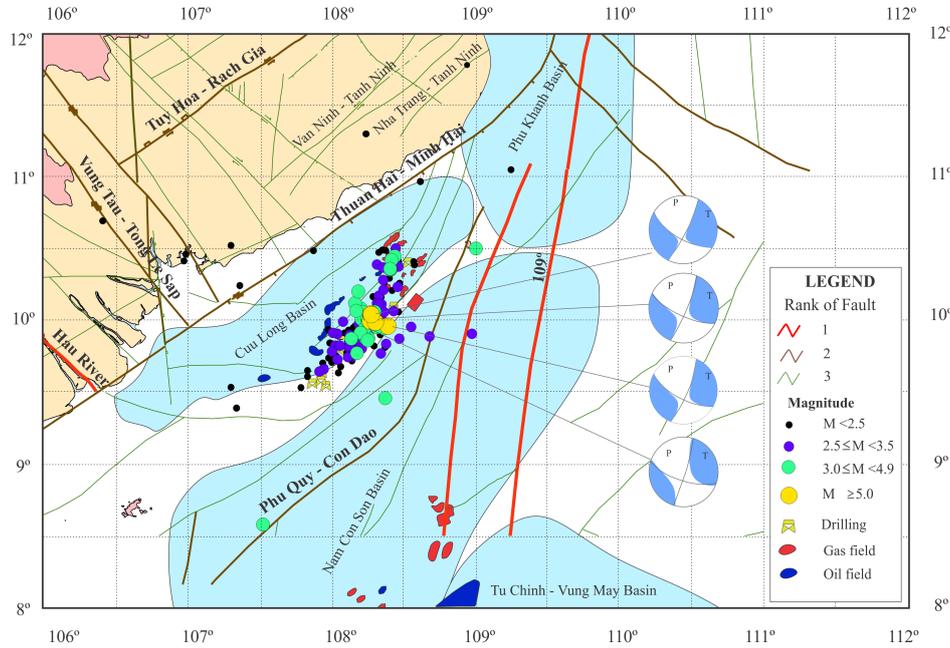


Figure 3. The distribution of epicenters of 371 earthquakes used in this study

Gutenberg-Richter relationship

We consider the Gutenberg-Richter relationship from the catalog of 371 obtained events, and the results are shown in Figure 4. Figure 4 illustrates that $M \leq 2.1$, the graph is almost horizontal. From the $M = 2.2-5.2$ segmentation, the graph has an almost linear decrease: $\lg N = 4.063 - 0.694 * M$. Therefore, the obtained b -value is 0.694.

Similarly, as mentioned above, we also computed the the relationship between Gutenberg and Richter for the catalog of 278 earthquakes after filtering foreshocks and aftershocks, as mentioned above. The results are presented in Figure 4. Results of approximately linear for the $M = 2.2-5.3$ segment have the following form: $\lg N = 3.826 - 0.704 * M$.

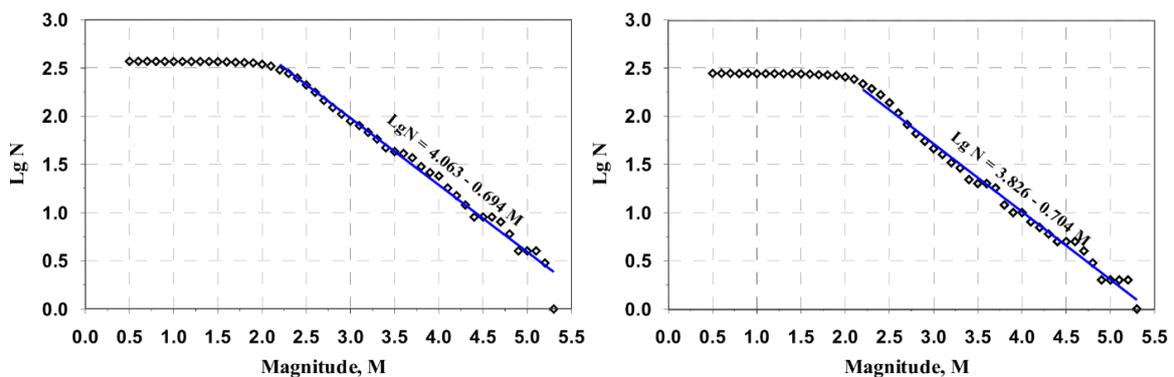


Figure 4. Earthquake frequency-magnitude distribution for a) The entire earthquake catalog; b) After filtering foreshocks and aftershocks

Therefore, the obtained b -value of 0.704 is very close to the b -value of 0.694 for the entire catalog of 371 events. The obtained b -value of approximately 0.7 was approximately equal to the b -value of 0.76 [41] for the East Vietnam Sea from 1903 to 2002; these b -values are smaller than the obtained b -value of 0.92 for stimulating earthquakes in Song Tranh 2 hydropower reservoir in Bac Tra My, Quang Nam province [42]. Thus, it is supposed that the tectonic origins have caused the earthquake activity in the research area.

CONCLUSIONS

1) In the South-Central Vietnam continental shelf and adjacent areas from January 2005 to December 2020, there were 371 earthquakes with four events of $M \geq 5.0$, of which the largest event, with a magnitude of 5.3, occurred in November 8th, 2005. The representative earthquake in the research area has a relatively small magnitude of $M_c = 2.2$.

2) The epicenters of earthquakes are mainly distributed in a Northeast-Southwest fault direction. A few earthquakes located on the Phu Quy-Con Dao and Thuan Hai-Minh Hai faults. Some of the remaining earthquakes occurred on the 109° Meridian fault.

3) In the study area, most earthquakes have a focal depth of about 20 km, with the majority concentrated at 5 km depth. Therefore, the focal depth is still in the Cuu Long Basin.

4) Using the “space-time window” with two earthquakes, $M = 5.3$ and $M = 5.2$, we filtered 92 events considered foreshocks and aftershocks of these earthquakes. The Gutenberg-Richter relationship calculation for the entire catalog of 371 earthquakes and the catalog of 278 events after filtering foreshocks and aftershocks obtained the b value of approximately 0.7.

5) Although the oil and gas exploitation activities have taken place continuously since 1989 up to now, and the epicenters of earthquakes in the study area are mainly located in the area with oil and gas exploitation activities in the Cuu Long Basin, it is difficult to consider that the oil and gas exploitation activity is the main source of the earthquake activity. Thus, it is necessary to continue

collecting earthquake data to elucidate the causes of earthquakes in the study region.

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