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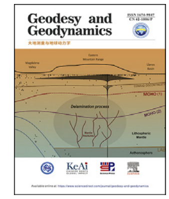

A review of tidal triggering of global earthquakes

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ABSTRACT

Earthquake prediction remains a challenging and difficult task for scientists all over the world. The tidal triggering of earthquakes is being proven by an increasing number of investigations, most of which have shown that earthquakes are positively correlated with tides, and thus, tides provide a potential tool for earthquake prediction, especially for imminent earthquakes. In this study, publications concerning the tidal triggering of earthquakes were compiled and analyzed with regard to global earthquakes, which were classified into three main types: tectonic, volcanic, and slow earthquakes. The results reveal a high correlation between tectonic earthquakes and tides (mainly for semidiurnal and diurnal tides; 14-day tides) before and after the occurrence of significant earthquakes. For volcanic earthquakes, observations of volcanoes on the seafloor and land indicate that volcanic earthquakes in near-shore volcanic areas and mid-ocean ridges have a strong correlation with tidal forces, mostly those with semidiurnal and diurnal periods. For slow earthquakes, the periodicity of the tremor duration is highly correlated with semidiurnal and diurnal tides. In conclusion, the tidal triggering of these three types of earthquakes makes a positive contribution to earthquake preparation and understanding the triggering mechanism, and thus, the prediction of these types of earthquakes should be investigated. However, there are still several inadequacies on this topic that need to be resolved to gain a definitiveanswer regarding the tidal triggering of all earthquakes. The main inadequacies are discussed in this paper from our point of view.

1. Introduction

The tidal triggering of earthquakes has been debated since the 17th century, when ocean tides were proposed as a cause of earthquakes [1,2]. The periodic activities of tidal forces have been proven to be the triggering force of earthquakes in many publications [3–6]; however, several publications have shown that there is no relationship between tides and earthquakes [7–11]. Due to the complexity of the seismic activity, the applicability of using tides, as a known quantity, to predict earthquakes has not been fully confirmed. The existence of a seismic gap demonstrates that earthquakes have a slow stress accumulation and rapid release process in underground rocks [12]. The periodic activities of tidal forces are supposed to play an important role during the stress accumulation stage, which has a confirmed relationship with earthquake preparation. The peaks of tidal stress are considered to be the final catalyst during the triggering of earthquakes. A rapid release of accumulated stress occurs when the stress on the fault reaches its maximum. After the earthquake occurs, a new round of stress accumulation-release starts and seismic gaps appear. In above description, tides are regarded as the dominant factor when the fault stress is in a critical state near the threshold during earthquake preparation and triggering. Previous studies have presented abundant observational evidence regarding the tidal triggering of earthquakes using different methods [1,6,13–22].

Based on the abundance of previous investigations, the three main methods of exploring the correlation between tides and

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earthquakes are as follows: The first method is to examine the relative positions betweenthe Earth and the other planetsin the solar system [13,23]. Celestial gravitation provides a comparatively large force that can triggerearthquakes when the Earth and the other planets are arranged in a straight line, such as the relationship of the lunar phase and seismicitydiscussed by many Chinese researchers [24–26]. The second method is to compute spectrum analysis through sequences which is usually used for slow earthquakes [27–29]. The third method, which is widely used, is to explore the correlation between earthquakes and tidal stress on the fault (including tidal coulomb failure stress, normal stress or shear stress) [21,30,31] through statistical tests, including Schuster's test [15,32], the permutation test [33], the Chi-squared test [34], Hi(s-togram)Cum (ulation) tests [19], and two-rate Poisson model [11,35]. Because the general opinion is that earthquakes occur at tidal peaks, the simplest test among these statistical tests is to look for correlations between tidal peaks and the occurrence of earthquakes. Other methods have seldom been used in research on the relationship between earthquakes and tides.

The occurrence of earthquakes is not only related to external celestial forces but also to the geological conditions of everysingle earthquake. In order to investigate the relevance of the tidal triggering of earthquakes under different geological conditions, the publications concerning the tidal triggering of earthquakes are discussed according to the different geological types of earthquakes in this study. Based on their geological conditions, earthquakes are generally classified by seismologists into four main types: tectonic earthquakes, volcanic earthquakes, induced earthquakes, and slow earthquakes [36]. Induced earthquakes are mostly influenced by human activities, such as reservoir water storage [37], hydraulic fracturing [38], wastewater injection [39], and oil and gas exploitation [40]. For this reason, it is difficult to make a direct connection between tides and induced seismicity. Therefore, three types of earthquakes, i.e., tectonic earthquakes, volcanic earthquakes, and slow earthquakes, are discussed in this paper. The summary of previous studies on the correlation between tides and these three types of earthquakes may provide clues to fault ruptures and earthquake nucleation. Several new ideas for exploring the correlation between tides and earthquakes are discussed at the end of this paper.

2. Tectonic earthquakes and tides

Tectonic earthquakes, also known as fault earthquakes, are caused by tectonic movement in the lithosphere and account for more than 90% of the world's earthquakes. When the deformation exceeds the bearing capacity of the rock, the long-term energy accumulated during the tectonic movement is rapidly released, causing the rocks to vibrate and result in earthquakes. Research on the tidal triggering of earthquakes has demonstrated that the tidal stress caused by the Sun, the Moon, and other celestial bodies is superimposed on tectonic stress and plays a triggering role for earthquakes on seismogenic faults. Although the tidal stress varies within a comparatively small magnitude—with an order of 10^3 Pa, which is much smaller than the average stress drop of an earthquake (magnitude of 10^6 Pa)—the stress accumulation rate is much larger than the tectonic stress [1,41]. Earthquake rates may correlate directly with the stress rate (especially daily maximum stress rates) when the stress in the source area is close to the critical level, therefore, earthquakes are triggered by Earth tides [6,42]. In conclusion, tides play an important role in the nucleation and triggering of tectonic earthquakes, which has been proven in numerous studies [6,43–46].

Several researchers have used the global earthquakesto calculate the relationship between tectonic earthquakes and tides. According to the characteristics of their faults, tectonic earthquakes can be further divided into thrust earthquakes, normal earthquakes, and strike-slip earthquakes. For these different types of tectonic earthquakes, tidal triggering behaves differently [47]. For thrust earthquakes, the shear stress on the fault plane has a very high correlation with the tides [6], especially for earthquakes with depths of 0–40 km [45]. For normal fault types, there is a significant correlation between the stress tensors of shallow earthquakes and larger earthquakes [6]. However, for strike-slip faults, nearly no correlation with tides has been found. The reasonable explanation is that thrust and normal faults have larger tidal stress amplitudes than strike-slip faults [45]. For all the high-correlation situations, the occurrence of an earthquake is concentrated on the tidal phase that accelerates fault sliding, which indicates that the high correlation is not accidental and is reasonable from a physical point of view.

Several researchers have used regional data to investigate the relationship between earthquakes and tides. High correlations between earthquakes and tides have been found not only before but also after major earthquakes. Evidence for the foreshocks of major earthquakes has been found in many places around the world. Using Schuster's statistical test, Tanaka explored a series of megathrust earthquakes, including the M_W9.1 Tohoku-Oki earthquake in 2011 [15], the M_W9.0 Sumatra earthquake in 2004 [48], and the M_W7.5 South Tonga earthquake in 1982 [32], and it was found that the frequency of the tidal phase was near the peak where the tidal shear/normal stress could accelerate fault sliding before the occurrences of these major earthquakes [49]. Significant correlations between tidal stresses and earthquakes about 2 years before the mainshock in Tengchong, China, have been identified [43], indicating that tides may be a potential tool for forecasting earthquakes. Moreover, tides have a clear effecton triggering and/or accelerating the rupture of the mainshock-aftershockfault system. The aftershocks in the Ning'er area, China [44,50], and Jiaxian, Wutai, Taiwan region [51], were found to have been triggered by semidiurnal tides and diurnal tides. In the Hellenic Arc, Greece [52], and Taiwan region [53], it was found that these aftershocks were triggered during the period of lunar tidal variations.

But even in the same region, diverse results of tidal triggeringearthquakes were found in some publications. For example, there are negative and positive results of tidal triggering of earthquakes using different time periods earthquake datarecorded in central Japan [34,54,55]. To a specific earthquake (M_W9.1 2011 Tohoku-Oki earthquake), Tanaka shows that tidal triggering occurs over a decade-long period preceding the Tohoku-Oki earthquake [15]. However, Wangfound that there was no correlation using 23-day foreshock sequence of the Tohoku-Oki earthquake [54]. There are also similar results found in southern California using different data sequences [56]. Results show that clustering of earthquakes in aftershock sequences, lower magnitude completeness levels, and insufficient number of sampling cycles of data sequences may lead to erroneous periodicities [56]. Another possible reason is that using the Coulomb failure criterion to compute Tidal Coulomb Failure Stress when calculating earth tidescan make statistics more physically meaningful [35]. In conclusion, both seismic data and physical mechanism of tidal triggering earthquakes are needed to be well understood.

Based directly on laboratory experiments, Dieterich obtained the mechanism of the model for the nucleation of earthquake slip [57] under periodic loads (earth tides as an example) [58]. Dieterich's model are further confirmed by actual seismic observations [59]. It indicates that the rate of seismicity influenced by tides is governed by three aspects: the amplitude of the earth tides, the normal stress acting on the fault, and the constitutive parameter that controls the direct velocity dependence of fault slip. Based on the constitutive parameter, it is believed that a correlation between seismic rate and Earth tides can be detected at normal stresses below around 8 MPa. Consequently, for a simple model of faults with instantaneous instability at the threshold, earthquakes will always be expected to occur near the tides' maxima when periodical tidal loading is shorter than earthquake nucleation time [42].

In conclusion, tides have different effects on the different types of tectonic earthquakes. Thrust and normal faults are influenced by tidal stresses, while strike-slip faults are not. Before and after the occurrence of major earthquakes, high correlations between the earthquakes and tides (mainly regarding the periods of semidiurnal, diurnal, and lunar tides) can be found.

3. Volcanic earthquakes and tides

Before the eruption of volcanoes, the movement of underground magma and/or groundwater usually generates earthquakes, which are often accompanied by phenomena such as surface deformation and the emission of gas and heat. There are currently five methods of monitoring volcanic activity: seismology, surface deformation, volcanic gas, image and/or thermal imaging, and infrasound analysis [60]. Among them, earthquake monitoring is one of the most widely used methods. According to their different seismic sources, volcanic earthquakes can be classified into two types: volumetric source earthquakes and shear or tensile source earthquakes. Volumetric source earthquakes are dominated by fluids, and the pressure changes induced by the movement of underground materials or fluid thermal dynamics generate earthquakes. However, shear or tensile source earthquakes are dominated by brittle fractures of the rocks. In addition, for the other classification of volcanic earthquakes, long-period (LP) events, very-long-period (VLP) events, and volcanic tremors are characteristic of volumetric source earthquakes, while volcanic-tectonic (VT) earthquakes are shear or tensile source earthquakes. Hybrid events have the characteristics of both these types of sources [61]. Ourstudy of the relationship between volcanic earthquakes and tides is based on these classifications. Previous studies have shown that tidal forces may trigger eruptive events [62–64].

Seven volcanoes (the Miyake-Jima volcano, Axial volcano, CampiFlegrei volcano, Stromboli volcano, Ruapehu volcano, Aso volcano, andOldoinyoLengai volcano) were investigated in this study to determine the correlation between volcanoes and tides (Table 1 and Fig. 1). Studies on the CampiFlegrei volcano [7], Stromboli volcano [63], and Ruapehu volcano [65] have revealed that these volcanicactivities have a lunar period. Although it is uncertain which of the external triggers (e.g., rain, pressure, and tides) is the dominant factor, monitoring the temporal changes in these phenomena and their correlations with earthquakes and volcanic activity can help us assess risk scenarios. The relationship between volcanic earthquakes and tides is affected by a variety of factors, such as changes in magma properties and plumbing systems [59]. After careful consideration of the level of the background noise, which is modulated by the local wind and meteorological conditions, no evidence of tides, air pressure, or temperature modulation was found to trigger the VLP events at the Aso volcano [9]. Another example is the lack of correlations between the thermal data and the semidiurnal and fortnightly solid Earth tides at the OldoinyoLengai volcano [10]. A reasonable explanation for this is that the obtained tidal periods depend on the length of the observation dataset used. For example, a semidiurnal and fortnightly tidal period may be detected using several months of observations. However, the annual tidal period is undetectable in data with such a short observation duration.

Investigation of the activities of Miyake-Jima volcano [66] and Axial volcano on the Juan de Fuca Ridge [14,18,20,59,64,67] shows that the seabed pressure changes caused by ocean tides and the peaks in seismic activity are strongly correlated, and a semidiurnaltidal periodicity is detected inspectrum analysis of the seismic activity. It should be noted that these volcanic earthquakes are preferentially triggered during low tides, but earthquakes should be triggered at tides' peaksaccording to the theories of rate-dependent and state-dependent friction [58]. It can be explained by the complex interplay between magma chamber expansion and periodic tidal loading. As the magma chamber expands/deflates in response to tidal stress, Coulomb stress of opposite sign to tides is correspondingly generated on the fault [59].

In summary, observations of volcanoes on the seafloor and land indicate that earthquakes in nearshore volcanic areas and mid-ocean ridges have a strong correlation with tidal forces, mostly exhibiting semidiurnal and/or diurnal periods. The fortnightly cyclic behavior of several events may be influenced by Earth tides, temperature, and/or atmospheric pressure variations, but researchers have not definitively determined which is the dominant factor.

4. Slow earthquakes and tides

Slow earthquakes were considered a rare phenomenon in the 20th century because it was difficult for ordinary seismograph instruments at the time to record them. In recent decades, a new generation ofdensely spaced and highly sensitive earthquake monitoring networks (including high-sensitivity borehole seismometer arrays and continuously recording global positioning system networks) has made it possible to monitor slow earthquakes [68]. Using data from earthquake monitoring networks, Obara and Kato [69] identified the various types of slow earthquakes: low-frequency earthquakes (LFEs), very-low-frequency (VLF) earthquakes, deep-low-frequency earthquakes, slow slip events (SSEs), episodic tremors and slips (ETS), and non-volcanic tremors (NVTs) [70]. Slow earthquakes mostly occur in the subduction zone. Previous results have revealed that tremor activities are found in the following regions: Taiwan region, Nankai, Cascadia,

Table 1
Representative publications concerning volcanic earthquakes and tides.

No.	Volcano	Tidal period	Publications	Eruptiontype
1	Ruapehu volcano	fortnightly	Girona et al., 2018 [65]	eruptions
2	Stromboli volcano	fortnightly	Sottili and Palladino, 2012 [63]	explosive events
3	CampiFlegrei volcano	fortnightly, monthly, semiannual, annual	Petrosino et al., 2018 [7]	volcano tectonic seismicity
4	Miyake-jima volcano	semidiurnal	Kasahara, 2002 [66]	volcanicactivity
5	Axial volcano	semidiurnal	Sahoo et al., 2021 [64]; Wilcock et al., 2016 [18]; Tolstoy et al., 2002 [20]; Wilcock, 2001 [14]	volcanic activity
6	Aso volcano	none	Niu and Song, 2021 [9]	VLPs
7	OldoinyoLengai volcano	none	van Manen et al., 2010 [10]	variable eruptive activity

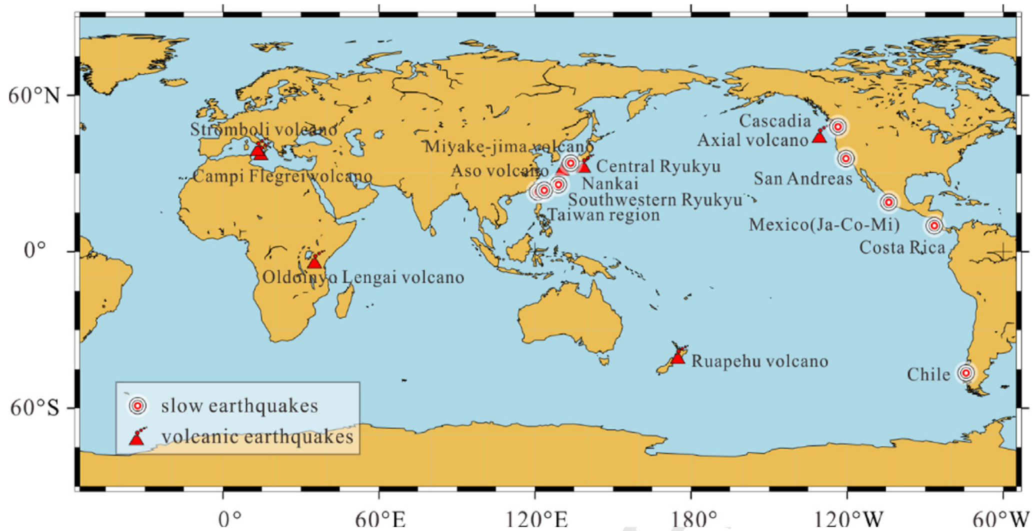

Fig. 1. Distribution of the volcanic earthquakes and slow earthquakes discussed.

Costa Rica, Chile, the San Andreas Fault, Ryukyu, Mexico, Alaska, and New Zealand (Fig. 1) [69,71]. Fig. 2 shows the locations of various types of slow earthquakes in the cross-section of a subduction zone. The LFEs, shallow VLFs, and NVTs are located shallower than the megathrust earthquakes, while the SSEs and ETSs are located deeper than the megathrust earthquakes.

Slow earthquakes that have occurred in Cascadia [72,73], the Nankai Trough [16,74], Costa Rica [75], Taiwan region [27], Chile [29], San Andreas [76], and Ryukyu [28] exhibit a high tidal sensitivity, and the periodicities of the durations of the tremors in these regions are strongly correlated with the semidiurnal and diurnal tides (Table 2). In Mexico, the tidal sensitivity is not uniform along the subduction interface, and the tremors in Ja-Co-Mi are more sensitive to the tidal shear stress than those in Guerrero and Oaxaca [77]. It has been found that the LFEs along the San Andreas Fault were modulated by a tidal stress with a 14-day cycle, and the highest LFE rate occurred during the waxing fortnightly tide [78]. Not all tectonic earthquakes and volcanic earthquakes are triggered by tides, but almost all slow earthquakes have been found to be triggered by tides. Slow earthquakes are believed to occur on faults in the vicinity of the brittle–ductile (seismic–aseismic) transition, and they preferentially occur when subjected to tidal shear stresses, which promote failure. Very small stress perturbations from solid Earth tides have been found to be responsible for significant increases in the tremor rate [79].

Tidal period of S2 (M2, N2, K1, P1, O1, fortnightly, Mm, and semiannual) is 12.000 h (12.421 h, 12.658 h, 23.934 h, 24.066 h, 25.819 h, 13.661 days, 27.555 days, and 182.626 days).

Tidal deformations can generate shear stress rates as high as ~10 kPa/day at plate interfaces, resulting in a strong triggering potential [16]. Because the frictional coefficient along a plate boundary is relatively small (<0.1) [80], the shear strength of the fault is very weak [81]. According to the friction theories of rate- and state-dependent friction [58], semidiurnal and diurnal tides can trigger SSEs when tidal stress fluctuations are superimposed on the plate boundary of a subduction zone.

5. Other types of earthquakes and tides

The relationships between tides and tectonic earthquakes, volcanic earthquakes, and slow earthquakes have been discussed above. However, in addition to the classification based on the cause of their occurrence, there are other classification schemes for earthquakes. Two preliminary schemes adopted by many researchers are the classification based on the magnitude of the earthquake and the classification based on the depth of the

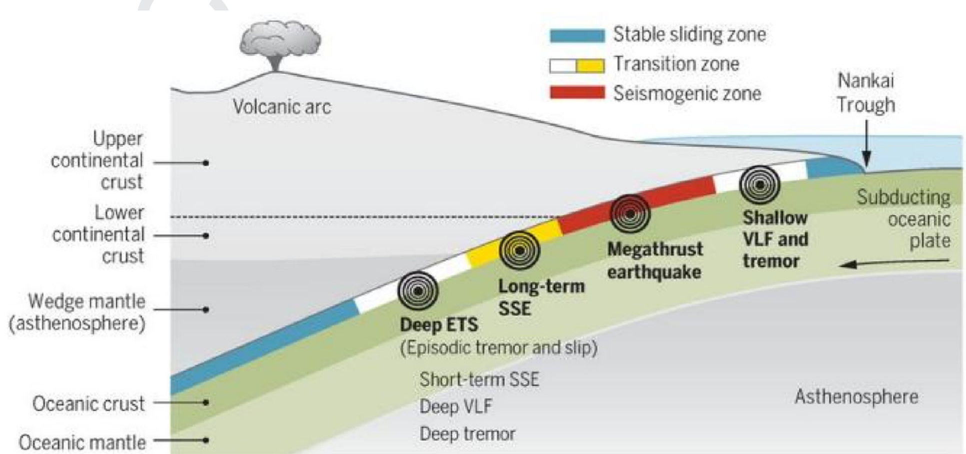

Fig. 2. Cross-section of a subduction zone and the locations of the various types of slow earthquakes (an example based on the Nankai subduction zone, from Obara and Kato [69]).

Table 2
Representative publications concerning slow earthquakes and tides.

No.	Location	Tidal period	Publications	Type
1	Taiwanregion	Semi-annual, 12 h, 24 h	Chen et al., 2018 [27]	Tremor events
2	Nankai	12 h, 24 h	Yabe et al., 2015 [74]; Nakata et al., 2008 [16]	non-volcanic tremors; slow slip events
3	Cascadia	12.4 h, 24–25 h	Royer et al., 2015 [72]; Rubinstein et al., 2008 [73]	episodic tremors and slips
4	Costa Rica	12 h	Walter et al., 2013 [75]	Tremors; very-low-frequency earthquakes
5	Chile	M2, N2, K1, O1, P1, Mm	Gallego et al., 2013 [29]	non-volcanic tremors
6	San Andreas	12 h, Fortnightly	van der Elst, 2016 [78]; Delorey et al., 2017 [76]	low-frequency earthquakes; non-volcanic tremors
7	Ryukyu	S2, M2, K1, O1	Nakamuraand Kakazu, 2017 [28]	very-low-frequency earthquakes
8	Mexico	Unknown	Mauryet al., 2018 [77]	slow slip events

hypocenter. Accordingly, the relationships between tides and these two classification schemes are summarized here, but other types of earthquakes are not discussed in this paper.

Many publications have discussed the relationship between tides and the classification according to the magnitude of earthquakes in the last few decades since it is a simple and easy way to classify earthquakes. The results of previous studies have revealed that regarding the tidal triggering of earthquakes of various magnitudes, the degree of tidal influence varies [6,53]. For volcanic earthquakes, micro-earthquakes ($M < 2.5$) exhibit a strong correlation with tidal lows [20]. For tectonic earthquakes, before the occurrence of a major earthquake, the foreshocks have been found to primarily oscillate with the tides during the stress accumulation on the fault. In addition, small earthquakes ($2.5 < M < 4$) have been found to be triggered by short-time-scale stress changes [5]. The aftershocks are not only influenced by the tides but also by external stress such as stress changes related to recent seismic activity (e.g., aftershocks) [82] and/or surface loads [83], which makes it difficult to obtain the relationship between the tides and aftershocks. Except for reverse faults, for which a relationship has been found between the shear tidal stress and earthquakes, the relationship between earthquakes ($4 < M < 7$) and tides was not clear until recently [5,6]. It has been found that very large earthquakes ($M \geq 7$), such as the 2004 Sumatra earthquake, the 2010 Maule earthquake, and the 2011 Tohoku-Oki earthquake, often occur near the maximum tidal stress amplitude [84,85]. The reason for this is that the possibility of small rock fractures expanding into huge ruptures increases as the tidal stress increases [86].

To investigate the focal depth of tidal triggered earthquakes, earthquakes need to be classified according to their focal depths. Generally, earthquakes are classified into three types according to their focal depths. Shallow earthquakes have focal depths of less than 70 km, and account for about 85% of global earthquakes. Intermediate earthquakes have focal depths of 70–300 km and account for about 12%of global earthquakes. Deep earthquakes have focal depths greater than 300 km and account for about 3%of global earthquakes [87]. The category that accounts for the largest percentage, i.e., shallow earthquakes, has been used by most researchers to investigate the relationship between tides and earthquakes. The results of these studies demonstrate that the correlation between earthquakes and tides is significant for shallow earthquakes [5,6,14,45]. Earthquakes (focal depths ≥70 km) exhibit indistinct correlations with tides, but some relevance between shear tidal stress and earthquakes has been found for normal faults and reverse faults [5,6]. One reasonable physical explanation for this is that the confinement stress of the fault becomes greater than that of the tide as the depth increases, and thus, shallow earthquakes are easily triggered by tides [5,42].

It should be noted that the classifications of earthquakes based on the magnitude of the earthquake and the depth of the focal source are slightly different for different regions, which is mainly related to the local tectonic background. Completeness of the magnitude and randomness of the earthquakes' occurrence is other two key factors in the tidal triggering. This is the reason why we focused on the relationships between tides and tectonic earthquakes, volcanic earthquakes, and slow earthquakes in this study.

6. Discussion and conclusions

In this study, the effect of tides on tectonic earthquakes, volcanic earthquakes, and slow earthquakes was investigated. For tectonic earthquakes, thrust and normal faults are more easily influenced by tidal stress than strike-slip faults. Before and after the occurrence of major earthquakes, there is a high correlation between these earthquakes and tides (semidiurnal tides, diurnal tides, and lunar tides). For volcanic earthquakes, observations of volcanoes on the seafloor and land indicate that earthquakes in nearshore volcanic areas and mid-ocean ridges have a strong correlation with tidal forces, mostly with semidiurnal and diurnal periods. The fortnightly cyclic behavior on several time scales may be influenced by Earth tides, temperature, and/or atmospheric pressure variations. However, researchers have not been able to definitively determine which is the main factor. For slow earthquakes, through the stress fluctuations at the plate boundary in a subduction zone, the tidal sensitivity is affected by the fluid in the fault. If the physical properties of the weak part of a large fault change due to long-term fluid migration and the shear strength in the fault is very weak, then tidal forces will trigger an SSE. Inconclusion, not all earthquakes are triggered by tides, but based on numerous statistical investigations, tides play an important role when the tectonic background is in a high-stress state; so, monitoring the changes in tides and their correlation with earthquakes can help assess risk scenarios. The research results can also provide us with physical data for analyzing fault ruptures and clues to the mechanisms and can serve as a powerful constraint for future mechanics models.

Based on results from laboratory experiments [58] and actual seismic observations, influences of tidal triggering earthquakes have three dominant aspects: the amplitude of the earth tides, Tidal Coulomb Failure Stress (including friction coefficient), and the constitutive parameter of the fault. Earthquakes will always be expected to occur near the tides' maxima for a simple model of faults with instantaneous instability at the threshold when periodical tidal loading is shorter than earthquake nucleation time [27,59], which is highly related to the local geological tectonic background [59,88]. The smaller the coefficient of friction (<0.1), the earthquakes are more likely triggered by tides (eg. slow earthquakes). The irrelevant between seismicity and tides can be explained by the constitutive properties of faults. A detectable correlation between earthquakes and tidal stress can generally be expected if the constitutive parameter for natural faults is significantly smaller than those observed for laboratory faults [80]. Based on the constitutive parameter, it is believed that a correlation between seismic rate and Earth tides may be detected at normal stresses below around 8 MPa.

Classification of earthquakes should adopt new methods. Large and small earthquakes, and shallow and deep earthquakes can be accurately distinguished and classified through the construction of a modern seismic network and precision seismic relocation technology. However, for tectonic earthquakes, it is more complicated to accurately determine the fault types of a series of earthquakes. Many scholars have used statistics to determine the type of fault, but there will inevitably be differences. For example, Tanaka [6] defined $-120° \le$ rake $\le -60°$ as a normal fault, while Xu [89] defined $-135° \le$ rake $\le -45°$ and $45° \le$ dip $\le 90°$ as a normal fault. Several scholars [90,91] have used machine learning to identify tectonic earthquakes and explosions, and their results have been preliminarily verified. Perhaps, in future research, machine learning methods can be used to identify the fault types of tectonic earthquakes.

A great deal of attention should be paid to the completeness of the earthquake sequence. A comprehensive, detailed, and in-depth study of earthquake sequences can help determine the development trend of seismic activity after an earthquake event or a major earthquake. This could deepen our understanding of earthquake processes and ensure the scientific nature and stability of research [64,92]. There is an intense debate regarding tidally triggered earthquakes, which is due to the inadequacy of earthquake catalogs [93]. Regarding the completeness of the catalogue, Tang et al. [51] used the matched-filter technique to detect the early aftershocks after the M_L 6.4 Jiaxian earthquake in 2010 and the M_L 6.4 Wutai mainshocks in 2012, and they detected approximately three times more early aftershocks than are listed in the Central Weather Bureau's catalog in southern Taiwan region. Tang's results have shown that small early aftershocks frequently occur near or in areas where negative Coulomb and shear stress changes are induced by Earth tides. If we ignore this part of the information, it will be difficult to explore tidally triggered earthquakes. Therefore, when exploring the correlation between tides and earthquakes, a complete discussion of earthquakes is indispensable.

Different research methods have been used to obtain different results regarding tidally triggered earthquakes. There are many methods of studying the correlation between tides and earthquakes, such as the tidal stress and statistical testing methods mentioned in the reviews conducted by Li and Jiang [94]and Chen [95]; however, we found that the results obtained using different methods may be different. For example, different scholars have conducted calculations for the Mygdonian Basin [19], the Ionian Islands [96], the Greek arc [52], Santorini Island [97], and other placesusing the Hi(stogram)Cum (ulation) superposition analysis method [98]. It was found that the earthquakes in these places were clearly triggered by lunar and semidiurnal tides. However, Schuster's test has also been applied to these regions, and the conclusions reached were not as clear [19]. Schuster's test and the Hi(stogram)Cum (ulation) method are statistical testing methods, and using different methods may provide different conclusions; thus, the physical mechanism urgently needs to be investigated.

Tide can be a potential way for earthquake early warning and probabilistic forecasting. A long-standing question is whether we can estimate the eventual size of earthquakes when small cores undergo dynamic rupture, tidal stress may be a potential solution. Previous results indicate that there are frequent similarities between different-sized subduction-type earthquakes [99,100]. Large earthquakes are more probable during periods of high tidal stress according to the previous investigations [86]. It is an approach using small quakes and tidal stress to infer the possibility of a major earthquake in the future. Consequently, knowledge of the tidal stress state in seismic regions can be used to improve probabilistic earthquake forecasting and short-term earthquake prediction, especially for extremely large earthquakes.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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