Mud volcanoes influences on the seismicity behaviors indicated from z and b value

Gege Hui [1, 2*] , Gangzhi Li[1, 2] , Chuang Sun[1, 2] , Yipeng Zhang[1, 2] , Pengcheng Wang[3] , Peizhen Zhang[1, 2]

[1] Guangdong Provincial Key Laboratory of Geodynamics and Geohazards, School of Earth Sciences and Engineering, Sun Yat-Sen University, Guangzhou, 510275, China

[2] Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), zhuhai, 519082, China

[3] Ocean University of China, Qingdao 266100, China

Corresponding author: Gege Hui (huigg@mail.sysu.edu.cn)

† Present address: *School of Earth Sciences and Engineering, Sun Yat-sen University (SYSU), Zhuhai Campus, Tangqi Road, Tangjiawan, Xiangzhou District, Zhuhai, Guangdong, 519082, P.R.China.*

Key Points:

- b-values in the SW Taiwan show the frequently periodicity fluctuations.
- z-values in the mud volcanoes area keep seismic quiescence before a big shock.
- A conjunct triggering relationships should exist between mud volcanoes and earthquakes.

Abstract

To explore the repeating mud volcanoes influences on the seismicity behaviors, we measured the spatial distribution z and b value changes with the time in the mud volcanoes developing area. We find a weak correlation between the b-z values and the mud volcanoes. Generally, the z-values anomalies of the mud volcanoes area show unchanged negative values and indicate the seismic quiescence before a strong earthquake, while the b-values show the frequently periodicity fluctuations around the value of 0.5. It may indicate the conjunct triggering relationships between the mud volcanoes and earthquakes stuck. We infered that the mud volcanoes eruptions help to partition and release part of the regional stress accumulation from the earthquake seismogenic structures, thus balanced the local stress in the strata.

Keywords: Mud volcano; SW Taiwan; coulomb stress change; b-z-value; conjunct triggering relationship

Plain Language Summary

Earthquakes caused subsurface fracture and stress perturbation are known to induce the earthquakes.While, the spatial and temporal distribution features of the seismicity activity before and after the mud volcanoes eruptions remain uncertain. This study analyzes the relationship between the strong earthquakes sequence including the SW Taiwan offshore December 26th, 2006 and June 5th,2016 earthquakes and the z and b values anomalies in the mud volcanoes developing area. Our results reveal the z-value in the offshore SW Taiwan shows the seismic quiescence before a big shock, but without many strong earthquake's occurrence. It may suggest a conjunct triggering relationships between the mud volcanoes and earthquakes stuck, the mud volcanoes eruptions would be an effective way to partition and release part of the regional stress accumulation from the earthquake seismogenic structures, thus balanced the local stress in the strata to mitigate large magnitude seismicity.

1 Introduction

Mud volcanoes are of particular interest for several reasons. The scientists have investigated it for a couple of decades, because it closely related to the gas hydrate accumulations and is important for the global carbon cycle, which have been used successfully to predicting the offshore oil and gas assembly (Etiope et al.,2004; Davies and Stewart,2005; Kopf and Deyhle,2006). Mud volcanoes can occur in different geological settings, especially the fore-arc basins on active continental margin, or in the petroliferous basins on the passive continental shelves (Planke et al.,2003). It presented and recognized as the specific phenomenon similarly to the magma volcanisms. Always, the mud volcano shows chaotic acoustically amorphous piercement structures (Dia et al.,1999; Martinelli and Panahi,2005) and the anticlines or the trust faults, to be the feeder channel, for the semi-liquid argillaceous material migrating directly along the narrow faults or fissures in the upper layer (Yusifov,2005).
Mud volcanism has a long history of investigation. A number of research papers have consoliadeted the strain and stress perturbations from large earthquakes would affect the mud volcanoes and ground water at a long distance (Delisle et al.,2002) and such instances are widely reported, such as the Pakistan, Romania, Sumatra and etc. Snead et al. (1964) has done the quantitatively study and examined effects of different magnitude thresholds and triggering distances on mud volcanoes. Following, many studies (Milkov et al.,2003; Mellors et al.,2007;

Maestrelli et al.,2013) have consolidated the hypotheses that whether the mud volcanoes are developed as the earthquake environmental effects. The recent example of the earthquake/mud volcano triggering occurred on the Arabian Sea, the new islands have been created during the process. Sedimentary analysis shows two islands are composed of pale bluish grey clay as well as grey mudstone blocks uplifted rapidly when the Mw7.7 earthquake occurred 180 miles away from coastlines of the Arabian Sea in 1945 (Dimitrov,2002). The similar situation occurred 16 km offshore in Gwadar west bay, and the islands with circular coned-shape encrusted with marine sediments, the gas eruptions and flames were also noticed in the vicinity of the new island (Sondhi,1947). All these new created islands were found kilometers away from the epicenter after the earthquake and only the coseismic uplift can rule out (Mellors et al.,2007; Rudolph and Manga,2010;2012; Bonini Hui et al., 2018;Hui et al., 2018).

The mud volcanoes in offshore SW Taiwan mainly distributed on the Kaoping slope (Figure1a; Chen et al.,2014; Chiang et al., 2020). Many submarine volcanoes, diapirs and deep-incised canyons have been recognized and mostly developed along the axis of the fold anticlines or the thrust faults deformation front. What's more, there are numerous earthquakes larger than Mw5.0 have been reported in the SW offshore Taiwan slope (Chen et al.,2014). Hui et al.(2018) have confirmed that the majority of mud volcanoes occurred immediately after the strong mainshock and confirmed to be perturbed by the stress change produced in the ground shaking.

Whereas, the mud volcano is symbolized with gashydrate and oil accumulation, it has multi-stage eruptions on the seismic profile indication and can be re-activated when the next earthquake stuck (Kumar et al.,2018). This process will rework or destroy the accumulation environment on the slope, even to trigger the seabed instability and change the local stress field. Thus, the further research is needed, such as to confirm how the mud volcanoes influences on the seismicity behaviors mud volcano eruption environment influences on the earthquakes behaviors in the multi-phase MV eruption zone.

Generally, the high b-value can indicate the small-scale earthquake event when the parameter a keeping constant (Wimer,2001; Leptokaropoulos and Lasocki,2020). In contrast, the low b-value indicating the relative high stress status in the crust would hold another earthquake event. Another seismicity parameter z describes the seismic rate (Scholz,1968). z-value varies in the specific regions, and show different seismic rates in different period before the mainshock. For decades, the seismic rate (z-value) has been used to obtain the precursory information of earthquakes. For example, Wiemer and Wyss (1994) has identified the seismic quiescence before the Landers (M=7.5) and Big Bear (M=6.5) 1992 earthquakes. Historical statistical results have demonstrated the law that the b-value decreases to negative when a mainshock approaching, and the seismic risk probability increases as the b-z-value becomes positive. Determining the crustal b-z values under which earthquake can occur is of tremendous importance to seismicity evaluation in our study area. Based on the regional geological condition, we applied the b-z value spatial scanning image and the abnormal area to conclude the precursory period prior to the occurrence of large crustal earthquake. Finally, we can ensure the multiphase mud volcanoes influence on the seismicity activity.

In this study, we took advantage of the Taiwan Telemetered Seismic Network (TTSN) and Global Centroid-Moment-Tensor (CMT) Project for compiling the seismic earthquake catalogue, and the important b- z-value in the precursory of the earthquake, which have been used to study the triggering relationship between the mud volcanoes and earthquakes offshore SW Taiwan. It would help us a better understanding of the resource and geohazard effect of MV, and provide new perspectives for the disaster prevention and mitigation, as well as the resources evaluation.

2 Data description

2.1 Earthquake and mud volcano catalogue

The earthquake catalogue in this study compromise tens thousands of historical seismicity activities,our study area is located in SW offshore Taiwan where seismic activity is the weakest and with the scarcely large magnitude earthquakes occurrence (Figure1a). While remarkably, 10 NE-NNE-striking elongated mud diapir belts have developed in the deeper water of the Kaoping Slope on SW Taiwan continental slope(Liu et al., 2000; Chen et al.,2003; Sung et al.,2010). Moreover, 60 mud volcanoes are recognized in the study area surrounded by the thrust faults, and the gas fluids migrated upward along the fractures (Yin,1986; Chen et al.,2003; Chiu et al.,2006). The majority of the mud volcanoes extend southward, mainly distributed along the NNE–SSW to N–S direction against with the canyon system (Chow et al.,2001; Lacombe et al.,2004; Hai et al.,2007). Previous study from the seismic reflections show the diapirs are almost exposed at the seafloor and covered only by thin sediments, indicating they are still active and growing (Chen et al.,2014; Hui et al.,2018). Submarine mud volcanoes are different from the onshore, which are much younger than onshore, and most active (You et al.,2004). Many of them are found at the water depths larger than 1000km.

The mud volcanoes catalog in this study is a compendium of events over 70 times in the former studies and includes historical as well as instrumentally recorded events, which showed the occurrence short time after moderate to large offshore earthquakes (M>5.0) (Wang et al.,1988; Kao and Chen,2001; Rau et al.,2000; Chuang et al.,2013). We have compiled the catalog ranging from the 2003 to 2016. According to the statistical results in FigureS1, it shows several moderate to strong earthquakes occurrences roughly been divided into three active seismic periods. In sequence, the first period *Mw* 5.2 26 December 2006 earthquake initiated in the SW offshore Taiwan was followed with 12 hours later by two strong mainshocks at 27 December 2006, the largest of which had the magnitude of *Mw* 6.7. The second seismic period started from 04 March 2010, and the seismic intensities gradually decreased with the *Mw* 5.4 earthquakes at 24 February 2012. The latest period strong earthquake is occurred at 05 February 2016 with the magnitude of *Mw* 6.11. All these events in the SW offshore stuck an approximately 10-30 km distance extending from the Taiwan Island, which have impressive coseismic effect in the epicenter and its vicinity area(FigureS2).

2.2 Correlation between the seismic sequence and mud volcano eruptions in SW offshore Taiwan

For an alternate estimate of the earthquake mud volcanoes, we use the eruption time-of-occurrence information (FigureS1). According to the graph in FigureS1, which has incorporated the Number-Time (N-T) histograms from the earthquakes and mud volcanoes, it can be seen that the earthquakes number sharply went up to the summit at each time the strong mainshock stuck. We can clearly see that the N-T fluctuation curves with the impulse-shake patterns with each strong earthquake, while the mud volcanoes show the platform signals with a long duration explosion. In the 12 years spanning from 2005 through 2016, the N-T chart shows a positive correlation between the mud volcano and the earthquakes occurrences. As is demonstrated in the red histograms, we can see a considerable number of mud volcano eruptions increases since from 26 December 2006, with the similar trend of the earthquake number and moment magnitude. Except this, there are the same situations occurred at the year of 2010 and 2016, when there are two strong earthquakes stuck. The overall process like years between eruptions show the exponential Poisson expected shape. Besides, what calls for special attention is that there has a small transient gap and eruption time delay between the earthquakes and the mud volcanoes. Generally, the eruption of MV occurred one or two days subsequential to one mainshock and can even last for several years, or the reposed MV even been re-activated.

3 Materials and Methods

3.1 Analysis on the seismic data catalogue

The seismic observation technology development in the vicinity of Taiwan has multi-phase, and was initiated from the year of 1897. The third period development was happened during the 1973 to 1990, and the TTSN was set up. The recent network can document the earthquakes magnitude smaller than 1.0, and acquire more accurately recording of the earthquakes in Taiwan. In this study, we have compiled the earthquake catalog from 1980 with at least 15000 events. According to the focal mechanisms difference, the seismic activities have been divided into four seismic zones (A,B,C,D in Figure1a, Wang and Shin, 1998). The SW seismic zone activity is most weak in the Taiwan area and the earthquakes show the shallow centroid focal depth less than 20km.

From the Magnitude-Time (M-T) diagram (FigureS3), we can see three to four seismic reoccurrences, there are the years of 2000, 2000-2010 and 2015, respectively and the average reoccurrence interval is about five years. In addition, the four M-T histograms show the average seismicity activity of the moderate-strong earthquake in different area, the observed earthquakes number increased with the time when the magnitude is larger than 5.5.

To estimate the earthquakes catalog completeness and discuss the data dependence on the seismic network, we calculated the Minimum Magnitude of Completeness (Mc) which reflected the advancement of the seismic monitoring and analysis methods (Figure1b). This calculation is relying on the integrated study on frequency-magnitude distribution (FMD) of the seismic activities. The FMD is calculated as follow function:

$$R(a,b,M_i) = 100 - \left(\frac{\sum_{M_i}^{M_{max}} |B_i - S_i|}{\sum_i B_i} 100\right)$$

B_i is standing for the accumulation number for every strong earthquake; S_i stands for the assumed accumulation number, this process is to confirmed the fitting degree between them. We evaluated the Mc value of the earthquakes ranging from 1995 to 2020 by the open source software ZMAP5.5 software in MATLAB (Wimer,2001; Leptokaropoulos and Lasocki,2020). The result shows that the Mc has fluctuations within a narrow range since the year of 2000, and show an overall descending trend. The Goodness of FMD fit to power law displays the Mc at 90% confidence to 3.9 (Figure1c). Based the Mc value above, we select the reasonable and homogeneous seismicity, removed the inadequate and explosions from earthquake catalog for calculation.

3.2 z-value statistical method

Generally, the z-value is widely used to testify and quantitatively calculating on the seismic rate of the seismic activity, two aggregate functions $AS(t)$ and $LTA(t)$ have been employed in the calculation (Wimer,2001). z-value is aim to evaluate and make comparisons of the seismic rate in different time intervals approaching to a main shock. In other words, if we set four different times with equal intervals before one earthquake event, and the z-value will be defined to be positive when the accumulative seismic occurrence between t_1 and t_2 is larger than that between

t_3 and t_4. In this case, the positive z-value can indicate the decreasing seismic rate. $AS(t)$ Function is often simplified as:

$$Z(t) = \frac{(R_1 - R_2)}{\sqrt{\frac{{\sigma_1}^2}{n_1} + \frac{{\sigma_2}^2}{n_2}}}$$

where the R_1, R_2 represent the average seismic activity rate obtained by using a certain time interval as the sampling interval in period 1 (from t_0 to t_e) and period 2 (from t to t_e), respectively; σ_1 andσ_2 are the standard deviation of seismic activity rate in the corresponding period; $n_1$and n_2 are the number of samples in the corresponding period. $AS(t)$ Function is used to resolve on a very crucial question: when is the maximum single seismic rate change occurred between two specific ends on the timeline? It is useful to identify one anomaly at the end of a time series, but it cannot detect two or more seismic rate change anomalies in the time series.

Thus the $LTA(t)$ function is introduced, it is more effective for the unbiased statistical test and the detection of multiple anomalies in a time series. The formula for the $LTA(t)$function is defined as follows:

$$Z(t) = \frac{(R_{all} - R_{W_t})}{\sqrt{\frac{{\sigma_{all}}^2}{n_{all}} + \frac{{\sigma_{W_t}}^2}{n_{W_t}}}}$$

where the R_{all},R_{W_t} represent the overall average seismic activity rate and the average seismic activity rate within the time window with a length of W_t. Moreover, the seismic catalogue aftershocks clusters elimination and integrity analysis should be completed before using the above function to calculate the z value.

We used the earthquakes background through the entire Taiwan Island and its vicinity area. The calculation used the minimum latitude as 20°and the maximum latitude as 26°, the longitude ranges from the 118°to 124°. The spatial scanning distance increment of longitude and latitude is 0.02 degrees. The starting time T_0 is set as 1985, and the end time T_e is the year of 2005. The starting time window T_c is 1997, and the average window length Tw is 5 years. In the calculation, the earthquakes magnitude constraint is the Mc greater than or equal to 2.0, and the focal depth is less than or equal to 50 km. In addition, we adopted the sampling parameters such as the time step to be 30 days. And as a rule of thumb, we successfully use ni = 20 as the calculation lattice. Then we select the LTA function under "time-cut" mode and plot the latitude/longitude map of z-values at a specific time T (Figure5 a-n). We take the time of half a year before and after each main shock as the statistical time window, the number of earthquakes within a radius of 10 km is captured spatially with each main shock epicenter. Generally, the negative z-value within 10 days before an earthquake can indicate the probability of the earthquake risk is becoming higher (Wyss and Martyrosian,1998). Therefore, we can confirm the statistical effects of earthquakes with different spatial scales, from observing the near field z-value changes before the occurrence of large earthquakes.

3.3 b-value statistical method

b-value plays an important role in Gutenberg-Richter (GR) earthquake frequency-magnitude relationship. Similar to the z-value discussed above, estimation of the b value is crucial for evaluation of the earthquake occurrence probability. The G-R relationship put forward by Gutenberg and Richter (1944) can be described as follows:

$$\log N = a - bM$$

where b in the function stands for the slope and are measured as a function of depth in a wide variety of tectonic regions; N is the accumulative number of seismic activities having magnitude larger or equal to *M*; *M* is the magnitude of the event. The cumulative frequency - magnitude has a linear distribution.

Changes of b-values as a function of time would provide a signal for evaluating the regional crustal stress accumulation status before or after the mainshock (Scholz,1968; Shi and Bolt,1982; Rao et al.,2005). When the number of large earthquakes is large, the b value will be relatively small, so the area with small b value is often considered to have a relatively large chance to occur on a large magnitude (Smith,1981).

In the previous study, there several methods like WLS (weighted least squares method) and max L (maximum likelihood) are offered for the calculation on the changes of b-values, but both methods of estimating b-values show the similar results.

z-maps from a to n shown in the Figure2 have been calculated with the time increment of 5 years, and the z-values were plotted in each slide with different colors representation for assessing the outstanding anomalies. In addition, the b value changes with the time (Figure3a) and map of the maximum z values of all LTA functions with a window length of 3 yr have been plotted (Figure3b). Particularly, several significant strong earthquakes have also been taken account into the calculation. The objective of the study is to determine whether there was the significant rate decrease prior to the big shock in this area, and what might occur at the mud volcanoes developing area.

4 Results

As mentioned in the last paragraph in the last section, b-z-value changes are the significant earthquake precursor signals, which can possibly provide the valid information like the location, time and magnitude for a big shock. Many previous studies have worked on the b-z-value changes before the mainshock. Wu et al. (2006,2008) have conducted the b-z-value changes research and the distribution maps were drawn for the half year, one year and two years separately before the big earthquakes. According to the statistical data, when approaching to a big earthquake, the b value at the epicenter decreases gradually and even presents negative. Different b value changes with time before the earthquake have different indications. According to the historical observation, b value in the epicenter present the negative accounted for only 47.0% two years before earthquake (16negative, 18positive, three zero, three has no obvious data). While to half a year before the earthquake, negative b value of the epicenter rate up to 71.4% (25 negative, 10positive, five zero), and b values in most of the earthquake epicenter show the decreasing phenomenon (Wang et al.,2004). What's more, they indicated that the z-value have the similar trend to the b-value, it would decrease as well when approaching a big earthquake (Wyss and Martyrosian,1998; Wyss et al.,1996).

4.1 spatially distribution of the z-value

The first prominent variations in the seismicity pattern can be identified in 1990 (Figure2d), it can easily identify the high z values in Figure2c decreased and even transited from positive to negative (declined to -2.0) in an area 15 km north of the epicenter, along the rupture of the 1990 *Mw* 6.7earthquake. Similarly, it has been noticed in this map (Figure2d), the z-value have a

drastically decline two or three months before another two earthquakes with magnitudes of 6.0 and 6.1. Except this, the z-values have the similar trend have been detected, for instance, the *Mw* 6.8 earthquakes in 1995 (Figure2e), the *Mw* 6.4 earthquake in 2000 (Figure2f), the *Mw* 7.06 earthquake in 2005 (Figure2g) and so on. The z-map coloring pattern show an overall decreasing with the time approaching to the strong earthquakes, and the z-value of the epicenter changes even gradually changes from positive to negative (on the map, it changes from red to blue). Particularly, on the z-value map of the 2019 Hualian earthquake (Figure2n) and another December 26th,2006 (Figure2h) event, z-value displays with the sharp decline and it even shows negative values spreading the whole study area hours before a big earthquake.
Obviously, all the z-value results indicate that there was the significant rate decrease prior to the big shock in the study area consolidated the previous study. However, there are exceptions that the z-values in the offshore SW Taiwan keep negative since from 1980 until now and seems to retain the seismic quiescence before a big earthquake. But only two historical strong earthquakes (with magnitude larger than 6.0) have been recorded in this mud volcanoes developing area. It seems violate the observation and is inconsistent with theories that the negative z-value are almost always occurred before a strong earthquake.

4.2 b-z value changes with time

To the further study of the b-z-values distribution in the mud volcanoes area, we have also calculated the temporal variation in b-value (Figure3a) and the maximum z values (Figure3b) in the LTA function. The cumulative number change with time is shown (blue line in Figure3). We selected the earthquake catalogue with the longitude ranges from 120° to 121° and the latitude from 21.5° to 23°. According to the b-values in Fig. 3a, it can be recognized that in the one-year period before the December 26th,2006 *Mw* 6.75 earthquake in our mud volcanoes developing area, the b-values are higher than in most other periods, and show a brief decline after the earthquake. Compared with the 2006 *Mw* 6.75 earthquake, the b-values before and after the 2010, 2012 and 2016 big earthquakes have shown the same b changes in time (green stars in figure 3a). Based on the previous study, the b value of the epicenter should decrease even to negative at the interval of two years till to half a year before the earthquake. But the overall earthquakes characteristics in SW Taiwan mud volcanoes area show the positive low b-values and frequently fluctuations.

5 Discussion and Conclusion

Traditionally, there are many controlling factors on the b-value change. One is the stress redistribution accommodate by the faulting activity, which is characterized by the earthquakes or the other eruptions (Hsu et al.,2008; Lacombe et al.,2001). Another one is because of the underground random fissures or ruptures, large rupture would result in decrease of b-value, while small fissures would increase the b-value (Ghosh et al.,2008; Scholz,2019). Through the analysis on the b-z-values of the mud volcanoes area in SW Taiwan, we can find that the b-values of earthquakes between 1995 and 2020 show the frequently periodic fluctuations and lacking of the big earthquakes, only with five to six moderate-strong earthquakes. Especially, only the December 26th,2006 *Mw* 6.75, *Mw* 6. 54 earthquakes occurred offshore and the February 5th,2016 *Mw* 6.11 earthquake occurred onshore in SW Taiwan (A and B in the Figure 3b). According to the b-value distribution, it has the average value around 0.5 and fluctuations with small amplitude, it may demonstrate the relatively high seismic rate in this study area due to the slowly stress redistribution and accommodation by small fissures.

In a more complex scenario, the regional subduction- accretionary geological settings in this study area are particularly susceptible to the neotectonic activity, it is likely triggering numerous small-scale fissures and the small earthquakes. These small earthquakes ruptures can be acted as the feeder dikes for the deep argillaceous rocks ascending to the upper layer, thus causing the mud volcanoes eruptions (Chen et al.,2003; Wu et al.,2005; Yin et al.,2015). In addition, the Taixinan Basin have received with great thickness of marine facies sediments since the Pliocene, which can provide with the favorable overpressure uncompact onshore shale formation and offshore marine facies mudstone formation deposits. The crustal stress might potentially disturb by the earthquakes induced local ground water equilibration, regional stress filed redistribution and accommodation (by mud volcanoes eruptions), thus showing the relative high b-value (that is, the stress would slowly release by the small fissures when the local stress accumulative to a considerable amount and show the negative z-value).

On the basis of observations of the b-value, we can conclude the mud volcanoes eruptions and earthquakes promote and restrain each other and induce the periodic crustal stress accumulation and release. This influenced the b-z-values distribution indicated the conjunct triggering relationships between mud volcanoes and earthquakes. Among them, the mud volcano eruptions can help to allocate and release part of the regional stress accumulation in the study area from the earthquake seismogenic structures, thus prevented the stress accumulation for a strong earthquake. Therefore, it can well demonstrate why the z-value in the offshore SW Taiwan always show the seismic quiescence before a big shock, but without many strong earthquakes occurred. Moreover, the conjunct triggering relationships between the mud volcanoes and the earthquakes give good explanations on the b-value in the mud volcanoes area keeping steady and showing periodicity fluctuations.

Acknowledgments, Samples, and Data

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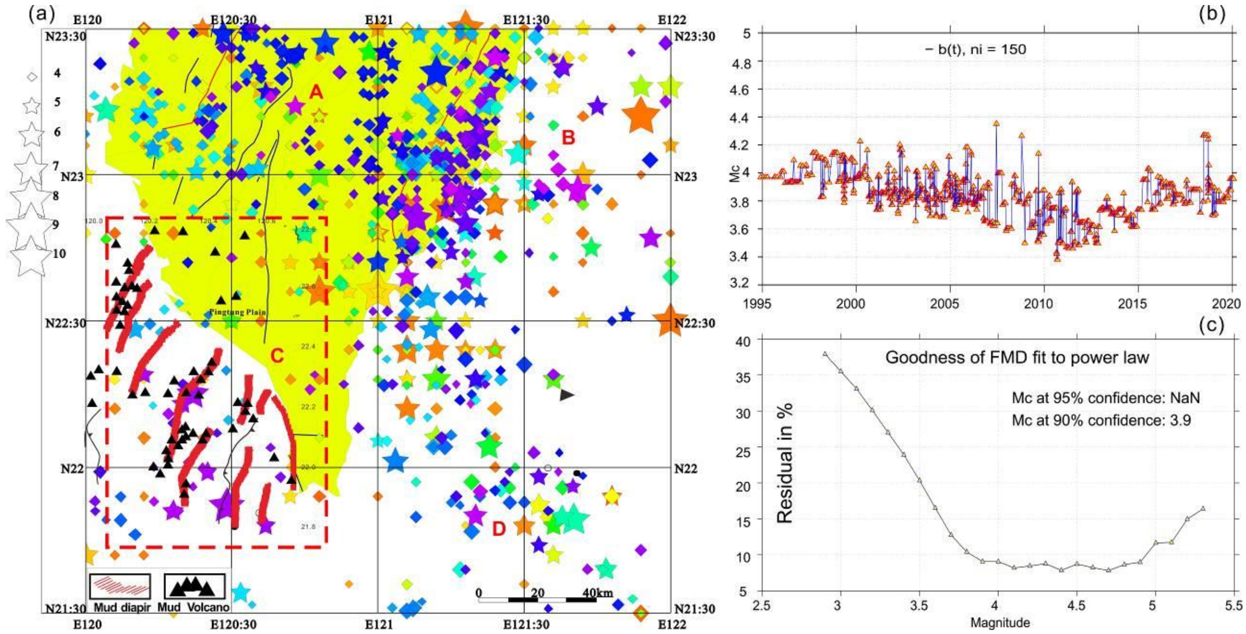
481 
(a)
E120
E120:30
E121
E121:30
E122
N23:30
N23
N22:30
N22
N21:30
A
B
C
D
Pingtung Plain
Mud diapir
Mud Volcano
0 20 40km
(b)
– b(t), ni = 150
Mc
(c)
Goodness of FMD fit to power law
Mc at 95% confidence: NaN
Mc at 90% confidence: 3.9
Residual in %
Magnitude

Figure 1. (a) Seismicity zone divisions (A to B) of the Taiwan Island (Wu et al.,2006) and the mud volcanoes and mud diapirs distribution characteristics in the offshore and onshore SW Taiwan. Black triangles in the map demarcated the history mud volcanoes (MV) between the year of 1995 and 2020, while the shadow belt show the directional mud diapirs distributions with NEE-striking (Chen et al.,2014).The colorful marks show the locations of the historical earthquakes with the moment magnitude. (b)-(c) The Minimum Magnitude of Completeness (Mc) and the Goodness of FMD distribution in the SW Taiwan.

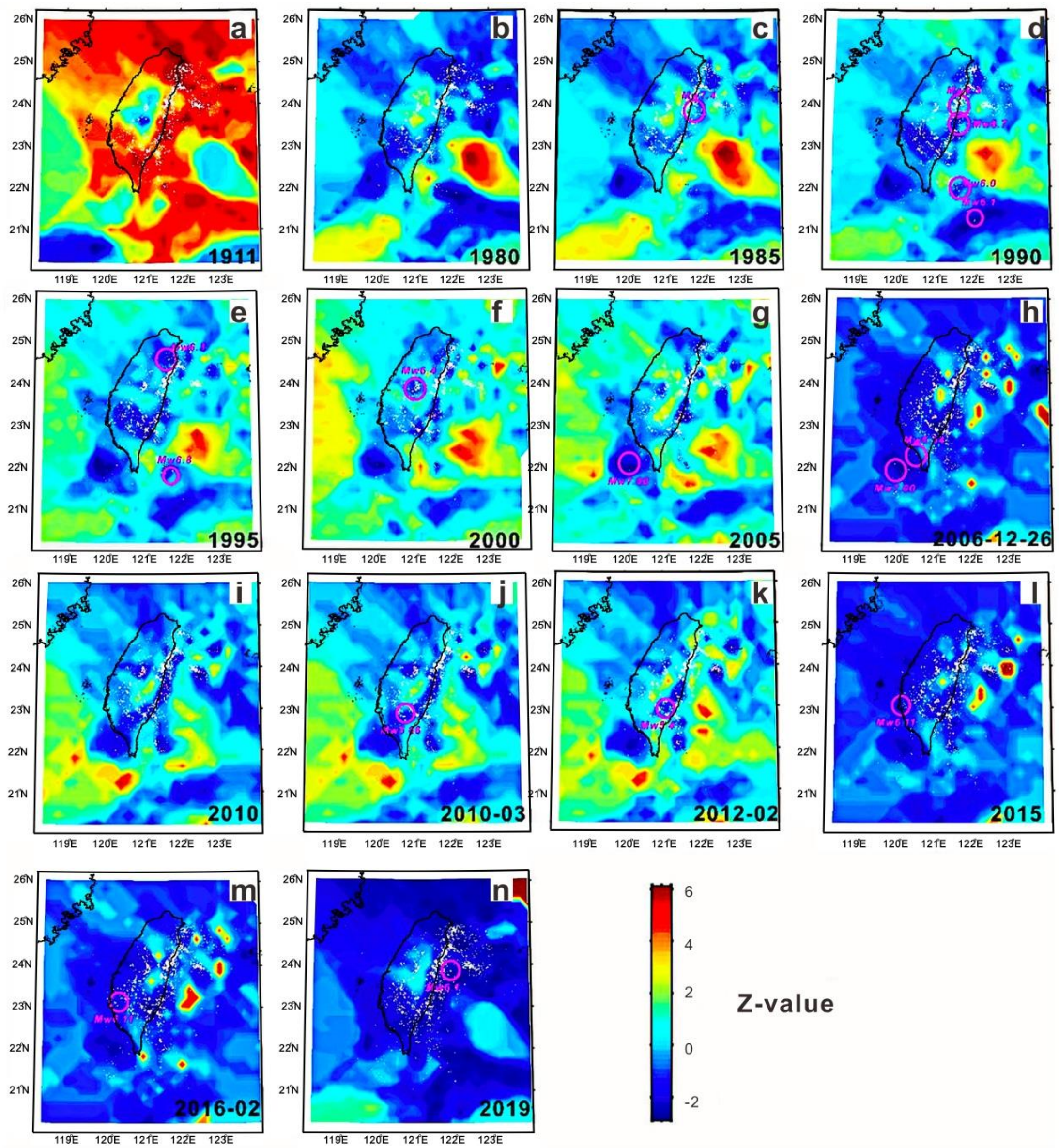


Figure2 (a)-(n) The seismic rate distribution (z-value) with the time window of 5 years after the significant earthquakes stuck in the vicinity of the Taiwan Island between 1995 and 2020. The blue area stands for the two or three days before a big earthquake events (The December 26th2006, February 2016 and 2019 Hualian earthquakes) and the z-value show decreasing when

approaching a big earthquake. The z-value in the offshore SW Taiwan keep the seismic quiescence status.

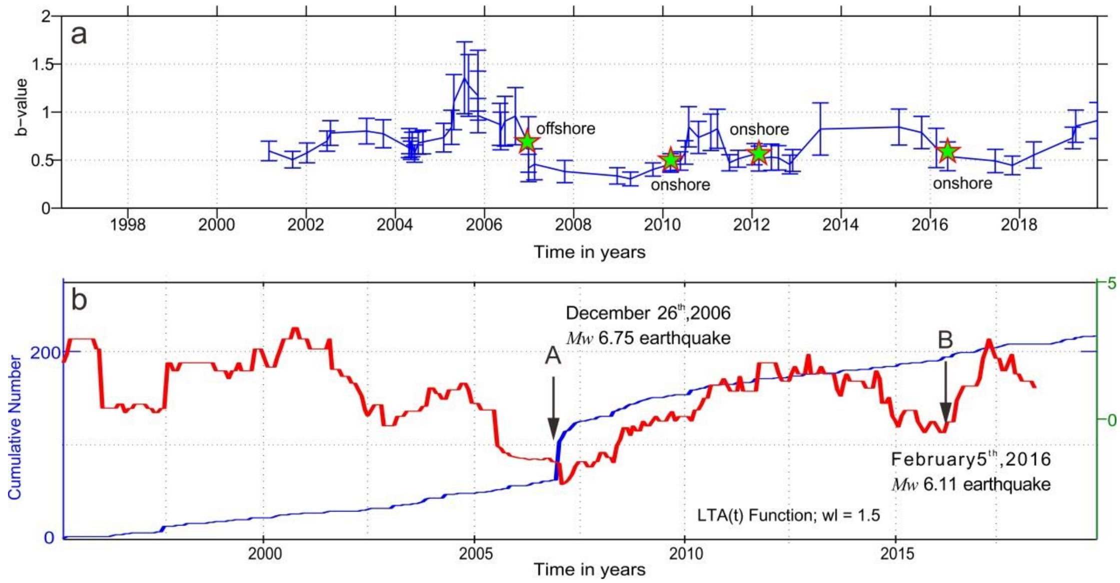
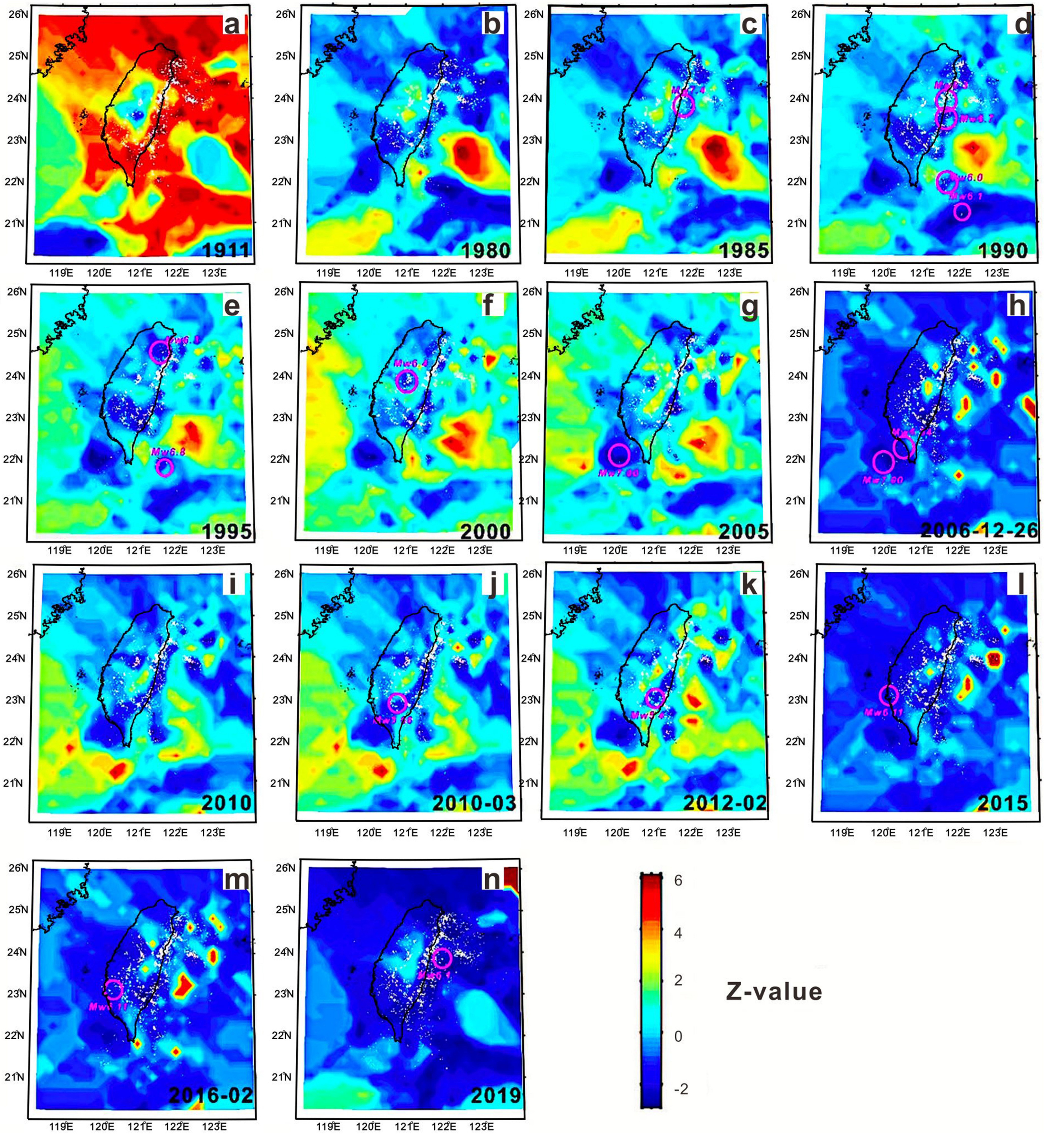


Figure3 (a) b-value changes with time with periodicity fluctuations in the SW Taiwan. Green stars represent the b-values of the four strong earthquakes in 2006,2010, 2012 and 2016, respectively. (b) z-value (red line) and the cumulative number (blue line) changes with time in the SW Taiwan. A and B stand for two abrupt decrease of the z-value subsequent to the two strong earthquakes.

Figure1.

(a)
E120
E120:30
E121
E121:30
E122
N23:30
N23
N22:30
N22
N21:30
A
B
C
D
Pingtung Plain
Mud diapir
Mud Volcano
0 20 40km
(b)
− b(t), ni = 150
Mc
(c)
Goodness of FMD fit to power law
Mc at 95% confidence: NaN
Mc at 90% confidence: 3.9
Residual in %
Magnitude

Figure2.



a
1911
b
1980
c
1985
d
1990
Mw6.7
Mw6.0
e
1995
Mw6.8
f
2000
g
2005
h
2006-12-26
i
2010
j
2010-03
k
2012-02
l
2015
m
2016-02
n
2019
26N
25N
24N
23N
22N
21N
119E
120E
121E
122E
123E
6
4
2
0
-2
Z-value

Figure3.


a
b-value
offshore
onshore
onshore
onshore
Time in years
b
December 26th,2006
Mw 6.75 earthquake
A
B
February5th,2016
Mw 6.11 earthquake
LTA(t) Function; wl = 1.5
Cumulative Number
Time in years