Did the $M_s7.0$ Lushan earthquake dynamically trigger earthquakes in the Datong volcanic region (Shanxi Province)?

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Abstract Immediately following the $M_s7.0$ Lushan earthquake on April 20, 2013, using high-pass and low-pass filtering on the digital seismic stations in the Shanxi Province, located about 870–1,452 km from the earthquake epicenter, we detected some earthquakes at a time corresponding to the first arrival of surface waves in high-pass filtering waveform. The earthquakes were especially noticed at stations in Youyu (YUY), Shanzizao (SZZ), Shanghuangzhuang (SHZ), and Zhenchuan (ZCH), which are located in a volcanic region in the Shanxi Province, but they were not listed in the Shanxi seismic observation report. These earthquakes occurred 4–50 min after the passage of the maximum amplitude Rayleigh wave, and the periods of the surface waves were mainly between 15 and 20 s following. The Coulomb stresses caused by the Rayleigh waves that acted on the four stations was about 0.001 MPa, which is a little lower than the threshold value of dynamic triggering, therefore, we may conclude that the Datong volcanic region is more sensitive to the Coulomb stress change. To verify, if the similar phenomena are widespread, we used the same filtering to observe

contrastively continuous waveform data before, and 5 h after, the $M_s7.0$ Lushan earthquake and $M_s9.0$ Tohoku earthquake in 2011. The results show that the similar phenomena occur before the earthquakes, but the seismicity rates after the earthquakes are remarkably increased. Since these weak earthquakes are quite small, it is hard to get clear phase arrival time from three or more stations to locate them. In addition, the travel time differences between P waves and S waves (S–P) are all less than 4 s, that means the events should occur in 34 km around the stations in the volcanic region. The stress of initial dynamic triggering of the $M_s9.0$ Tohoku earthquake was about 0.09 MPa, which is much higher than the threshold value of dynamic triggering stress. The earthquakes after the $M_s9.0$ Tohoku earthquake are related to dynamic triggering stress, but the events before the earthquake cannot be linked to seismic events, but may be related to the background seismicity or from other kinds of local sources, such as anthropogenic sources (i.e., explosions). Using two teleseismic filtering, the small background earthquakes in the Datong volcanic region occur frequently, thus we postulate that previous catalog does not apply bandpass filter to pick out the weak earthquakes, and some of the observed weak events were not triggered by changes in the dynamic stress field.

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1 Introduction

Since the preliminary study on the Landers earthquake (Hill et al. 1993; Hill 2008), the phenomenon of seismic dynamic triggering phenomena has been identified in many

parts of world, including associated with the 2002 M_w 7.9 Denali earthquake, in which six seismic networks along the east coast of the United States ($\sim 3,000$ – $4,000$ km from the epicenter), the small local earthquakes or swarm-like character of events were triggered by the surface waves (Prejean et al. 2004). Similar events also occurred after the 1999 M_w 7.1 Hector Mine earthquake in California, the 1999 M_w 7.0 Karluk Lake earthquake, the 2000 M_w 6.9 Kodiak Island earthquake, the 2000 M_w 7.4 Izmit earthquake in Turkey [Gomberg et al. 2001; Brodsky et al. 2000; Husker and Brodsky 2004; Kilb et al. 2002; Peng et al. 2010a; Tape et al. 2013], and the 2004 Sumatra M_w 9.0 earthquake (West et al. 2005)]. Some domestic scholars have also observed some dynamic triggering cases (Wan et al. 2002; Wu et al. 2009; Lu et al. 2006). For instance, the M_s 8.0 Sumatra earthquake in 2000 dynamically triggered the M_s 6.5 Burma earthquake, which was located 77 km away from the epicenter in Sumatra (Zhang et al. 2008, 2012). The Yunnan seismic network observed far-field dynamic triggering after several large earthquakes (Xie et al. 2010), and the triggered microearthquakes were found near Beijing by the Wenchuan earthquake (Peng et al. 2010b) and Peng's group have identified dynamic triggering by the Wenchuan earthquake in other regions in China (Jiang et al. 2010), and dynamic triggering by multiple teleseismic earthquakes near Beijing (Wu et al. 2011; Wu et al. 2012). In recent years, with the development of the Coulomb failure stress triggering theory, dynamical triggering phenomenon has attracted more and more attention. This field of study may provide new ideas for determining potentially hazardous areas after large earthquakes.

The Shanxi rift zone is located at the intersection of the Indian, Pacific, and Eurasian plates, and is the largest Cenozoic continental rift found in China. There are a large number of volcanoes and basaltic rocks exposed to the east of the Datong fault basin and the river valley along the middle reach of the Sangganhe River (here after referred to as the Datong volcano group). The Datong volcano group erupted mainly in the middle Pleistocene, the latest extending to the early late Pleistocene (An 2008). They are distributed to the east of the Julebao station in the Jing-Bao railway—Chenzhuang of Datong, along the western boundary between the Shanxi and Hebei provinces, to the north of Xiashenjing of Yanggao County, in the southern foothills of the Liulengshan mountains. The length is about 30 km from east to west, and the width is about 20 km from south to north.

The M_s 7.0 Lushan earthquake occurred on April 20, 2013, and is an example of a strong earthquake that occurred after the M_s 8.0 Wenchuan earthquake along the Longmenshan fault zone. Studies have shown that the rupture length was about 20–40 km (Liu et al. 2013). Based on the rupture process, Shan et al. (2013) calculated the static Coulomb

failure stress caused by the Lushan earthquake, and proposed that the Coulomb rupture stress field mainly affected the earthquake hypocenter area and its surrounding regions. However, a large number of earthquakes were observed at the time of, or shortly after, the surface wave reached the volcanic area or subduction zone far away from the respective epicenters. Compared to the static triggering stress, the influence range and distance of dynamic Coulomb stress is much larger. The Shanxi rift zone is located to the north of the Longmenshan fault zone, and the rupture direction and the direction of fault plane are almost parallel to that of the Shanxi rift zone. According to the propagation characteristics of the dynamic Coulomb stress field, dynamic triggering is usually favorable in the direction of wave propagation, although there are some cases that the triggered events are not along the direction of the propagation. Considering that the Shanxi rift zone is an active area with high-frequency seismicity, the Datong volcanic belt in the northern part of the Shanxi rift zone has a high possibility of dynamic triggering. Therefore, it is worth studying whether the Lushan earthquake affects the seismicity of Shanxi region by dynamic triggering. However, few studies have been done on the remote dynamic triggering of Lushan earthquake so far. Thus, by collecting the change of seismicity before and after the Lushan earthquake, we calculated the change in the Coulomb stress field caused by seismic waves, and quantitatively analyzed the influence and triggering of seismicity in Shanxi region from Lushan earthquake. This study provides some necessary information for further understanding the process of strong earthquake dynamic triggering, and also for carrying out research on strong earthquake dynamic triggering in other volcanic areas.

2 Data

2.1 Source parameters of the Lushan earthquake

In order to analyze the dynamic triggering effect of the Lushan earthquake, we need to obtain the source parameters of this earthquake. According to the results obtained by Xie et al. (2013), and the seismic rapid report catalog of the China seismic network, the hypocenter parameters of the Lushan earthquake are shown in Table 1.

2.2 Seismograms collected in the Datong volcanic region

There are 31 stations in the Shanxi province (Fig. 1a). The Datong volcanic group is located to the east of the Datong basin in northern Shanxi province (Fig. 1b). The M_s 5.9 Datong–Yanggao earthquake occurred in this area on October 19, 1989, followed by one M_s 5.8 earthquake in

Table 1 The hypocenter parameters of Lushan earthquake

Epicenter	Date	Lat. (°)	Long. (°)	Depth (km)	M_S	Strike (°)	Dip-angle (°)	Slide-angle (°)
Lushan, Sichuan	2013-04-20	30.3	103	13	7	210	44	94

Showing data from Xie et al. (2013) and the rapid report catalogue of China seismic network

Fig. 1 **a** The path diagram of the epicenter of Lushan earthquake to each station in Shanxi seismic network. **b** The locations of Datong volcanic group and its surrounding stations. Black solid triangles show the locations of the broadband seismic stations, which the stars represent that locations of the volcanoes. Thick solid lines outline the faults at the boundaries of the basins. The gray regions show the basins in the studied area

1991 and one $M_S5.6$ earthquake in 1999, respectively. We collected waveform data from the 31 stations in Shanxi province, and another station in the Inner Mongolia network (Liangcheng station), to study the dynamic triggering phenomenon caused by the Lushan earthquake. Among these stations, six digital seismic stations are located in the Datong volcanic area and its surrounding region, including the Shanzizao station in the volcanic group, and the other five close to the volcanic zone. Recording instrument parameters are shown in Table 2. The length of the seismograms is 3,100 s long, which contains data 100 s before and 3,000 s after the P-wave arrival.

3 Data processing and result analyses

3.1 Data processing

There are two major methods to study the far-field dynamic triggering stress phenomena. One method is to analyze the earthquake catalog directly to identify whether the seismicity has been significantly strengthened. However, based on the earthquake catalog from the Shanxi seismic network, there was no obvious change in seismicity in the Datong volcanic area after the Lushan earthquake. This finding may mean that there was no seismicity change in the studied areas, since the catalog mainly focuses on relatively large earthquakes, thus no data process has been executed to

Table 2 Stations in the Datong volcanic group

No.	Station code	Station name	Frequency band of the seismometer	Recording system
1	SHZ	Shanghuangzhuang	Broadband	Continuous recording
2	HSH	Hengshan	Broadband	Continuous recording
3	SZZ	Shanzizao	Broadband	Continuous recording
4	YUY	Youyu	Broadband	Continuous recording
5	ZCH	Zhenchuan	Broadband	Continuous recording
6	LCH	Liangcheng	Broadband	Continuous recording

check smaller earthquakes or tremors. Therefore, in this study we have adopted the second method: using high-pass filtering of the original waveform to indentify the seismicity change before and after the main event.

Firstly, in order to indentify the weak earthquakes from the seismograms, we removed the instrument response from the broadband velocity waveforms of the 31 stations from the Shanxi digital network and the Liangcheng station from the Inner Mongolia network. Then, we rotated the data into $Z-R-T$ components, and finally filtered them by different filters to identify the small earthquakes from the waveforms. We not

only received the surface waves of the Lushan earthquake, but also eliminated the effects of long period surface waves and high-frequency noise from the Lushan earthquake without affecting the recognition of a possible dynamic triggering event. Based on trial and error, we eventually adopted the range 0.01–0.1 Hz as a low-pass filter and 4–20 Hz for high-pass filtering.

3.2 Result analysis

3.2.1 Identified Earthquakes in three components of seismograms from a single station

Take the SHZ (Shanghuangzhuang) station for example. Its high-pass filtering waveforms and low-pass filtering in tangential, radial, and vertical directions do not have large differences (Fig. 2a, b). However, due to the movement characteristics of Rayleigh waves, strong earthquake-triggering should be found in the radial and vertical components, few in the tangential direction. This puzzle may be related to polarization shifts in provincial bureau stations, which have been identified by Niu and Li (2011). Thus, the radial and tangential components of level signals after rotation are not taken to be the accurate tangential and radial movement. Therefore, in the following context, we used the filtering results of the vertical direction to discuss possible dynamic triggering. Another reason may be related to the scattering effect of the volcanic zone, due to the strong heterogeneity in the volcanic zone, Love wave and Rayleigh wave may couple together so that both the Rayleigh wave and the Love wave can trigger small earthquakes.

3.2.2 Earthquake triggering of stations near the Datong volcanic group

We processed waveform data with the length of 100 s before and 3,000 s after the Lushan earthquake from some

stations in Shanxi province (nine stations in northern Shanxi: Liangcheng, Shuanghuangzhuang, Shanzizao, Youyu, Zhenchuan, Yanmenguan, Yangyuan, Hengshan, Lingqiu; five stations in south central Shanxi: Yangquan, Zuoquan, Yongji, Yangxing). The results show that only four stations close to the Datong volcanic group (Shanghuangzhuang, Shanzizao, Youyu, Zhenchuan) (Fig. 1b) were found dynamic triggering phenomena. The high-pass and low-pass filtering results of the vertical component of the four stations SHZ, SZZ, ZCH, YUY are shown in Fig. 3a, b. At 720, 1,200, 1,900, 2,200, 2,350, and 3,150 s after the occurrence time of the Lushan earthquake, all of these seismograms contain obvious earthquake signals (Fig. 3a). This may indicate that a series of earthquakes were triggered in the Datong volcanic area by the surface waves of the $M_S7.0$ Lushan earthquake. After high-pass filtering, these earthquakes were found during the passage of the maximum amplitude of the Rayleigh wave, but they hadn't been recorded in the Shanxi earthquake catalog. Moreover, there were not recorded any local earthquakes about 7 h after the Lushan earthquake in the Shanxi seismic network either. These findings are consistent with traditional remote dynamic triggering in volcanic areas after strong earthquakes (Brodsky et al. 2000; Husker and Brodsky 2004). No similar events were recorded in the stations far away from volcanic area.

For instance, we analyzed data from the SHZ station, including the earthquake-triggering signal in detail. There were 14 signals with high signal-to-noise ratio 50 min after the $M_S7.0$ Lushan earthquake, with a duration of 3–30 s (Fig. 4). Comparing the amplified triggering signal with the surface wave signal of the corresponding period shows a correspondence between the peaks of the surface waves. The above results are a little difference with results obtained after the $M_w9.0$ Sumatra earthquake in 2004, when the Alaska Wrangell volcanic area (11,000 km from the epicenter) found multiple triggering earthquakes lagging behind by

Fig. 2 The waveform obtained from the SHZ station of the $M_S7.0$ Lushan earthquake on April 20, 2013 after filtering (Tangential T , radial R , and vertical V component are in turn from top to bottom). **a** 4–20 Hz high-pass filtering. **b** 0.01–0.1 low-pass filtering

Fig. 3 The waveforms of the $M_S 7.0$ Lushan earthquake on April 20, 2013, after filtering (four stations). All of the waveforms are in vertical component. **a** 4–20 Hz high-pass filtering. **b** 0.01–0.1 low-pass filtering

about $\frac{1}{4}$ cycle of a period-peak of a surface wave of the main event (West et al. 2005). The records from four stations indicated that these events did not originate from a single hypocenter but were scattered in different locations within a volcanic area. Waveform characteristics, amplitude, and the records of different stations, indicate that many events were distributed within 34 km around the stations in the volcanic region. It looks that some of the events shown in Fig. 5 occurred before the arrival of the peaks, including event 2, 4, and 9. However, event 2 actually occurred just after the arrival of one peak of surface wave which are not shown in the subplot. For event 4 and 5, things are a little different, event 5 may be one event triggered by the peak wave of a cycle of surface, but the uncertainty is quite high. Event 4 is a little too small, it could be a small event which belongs to the background earthquake. Event 9 is quite weird, it occurred just before the arrival of the surface wave peak. There are two possible reasons for this phenomenon: first, event 9 is triggered by previous peak of surface wave which is not shown in the subplot; second, It is not a triggered event. Anyway, in the total 14 events shown in Fig. 5, 3 events might not be triggered events. But anyway, the other 11

events are highly potential to be dynamic triggered by the surface waves of the Lushan earthquake.

Since some of the events are quite small, it is hard to get clear phase arrival time from three or more stations to locate the earthquakes. Fortunately, since the distances between stations are less than 50 km, if the event is detected by less than three stations in around evenly distributed azimuths, and the stations are inside or close to the Datong volcanic zone, the events should occur in the volcanic region. For the events with record number more than three stations, We carefully checked the events which looks like recorded by more than three stations, however, based on the relationship between travel time T_p and difference of arrival times between P wave and S wave (S–P), the records are not belong to the same events, actually they are independent small earthquakes which are very close to the recorded stations. In order to further identify the characteristics of the events, we analyzed the records of SZZ stations with magnitude around $M_L -0.3$. After the processes which have mentioned in the article, we made sure that all of the events are earthquakes. The biggest amplitude recorded by high-pass filtering at SZZ stations is

Fig. 4 The record from the SHZ station (the *top panel* is low-pass filtering, the *bottom panel* is high-pass filtering)

around 0.2 m/s (Fig. 6). From Fig. 5 we can find that all of the peak amplitudes of the events recorded at SHZ are smaller than 0.2 m/s, furthermore, the S–P travel time differences of these events are less than 2.5 s, so all of these events should be small earthquakes which occurred inside the circle with radius smaller than 22 km with the center at the SHZ station. Since the volcanic zone is surrounding SHZ station with radius around 50 km, we can make sure that all of these small events occurred in the volcanic zone. Since these earthquakes are very weak, they can only be observed through high-pass filtering from the waveforms.

3.2.3 The relationship between transient stress and triggered events

This article has estimated the far-field dynamic transient stress caused by the target earthquake based on the magnitude and epicentral distance using the method provided by Peng et al. (2010b), and has discussed the possible influence on the records in volcanic areas caused by the $M_S7.0$ Lushan earthquake.

The far-field dynamic transient stress observed at the SHZ (Shanghuangzhuang) station caused by the Lushan earthquake was about 0.001 Mpa. According to the results of previous studies, the general threshold of dynamic triggering stress is more than 0.005–0.010 Mpa (Kilb et al. 2000; Stein 1999). Thus, the question of whether such weak stress disturbance can trigger earthquakes is worth

discussing. Therefore, we have collected continuous waveforms from the $M_S9.0$ Tohoku earthquake on March 11, 2011, and observed the records of earthquakes at stations in the Datong volcanic area 5 h before and after the earthquake. We also checked the earthquakes 5 h before and after the Yaan earthquake in the same way. The results are as follows.

3.2.3.1 The $M_S9.0$ Tohoku earthquake The far-field dynamic transient stress caused by the $M_S9.0$ Tohoku earthquake in the Datong volcanic area is about 0.09 Mpa, greater than the threshold 5–10 kpa proposed by international and domestic scholars. Therefore, from a dynamic source point of view, it is possible that the Tohoku earthquake could trigger earthquakes in the Datong volcanic area. By removing instrument response and filtering the data, we found that the weak earthquakes occurred both before and after the $M_S9.0$ Tohoku earthquake. However, these weak earthquakes were never recorded in the catalog of the Shanxi seismic network. Taking the SHZ and SZZ station as an example, we observed 21 and 20 earthquakes before the $M_S9.0$ Tohoku earthquake, 61 and 54 earthquakes after the $M_S9.0$ Tohoku earthquake (Fig. 7). The energy of many earthquakes was big enough to be recorded by two stations.

3.2.3.2 The $M_S7.0$ Lushan earthquake Still using the SHZ and SZZ station as an example, we observed 30 and 5 weak earthquakes before the $M_S7.0$ Lushan earthquake, 21

Fig. 5 Every event recorded at the SHZ station (the *top panel* is high-pass filtering, the *bottom panel* is low-pass filtering, and the event number see in Fig. 4)

and 15 weak earthquakes after the $M_S 7.0$ Lushan earthquake, from the waveform data 5 h before and after the $M_S 7.0$ Lushan earthquake.

The occurrences of weak earthquakes in the Datong volcanic area before and after the two big earthquakes are shown in Table 3. Except the SHZ station, which recorded more events before the Lushan earthquake than those after the Lushan earthquake, the other stations showed that the

events before the Lushan earthquake are far fewer than the events after the Lushan earthquake, especially for the Tohoku earthquake with a closer epicenter distance to the Datong volcanic area and larger magnitude than the Lushan earthquake. In addition, the instant, far-field dynamic stress caused by the Tohoku earthquake was beyond the threshold, and the events after the Tohoku earthquake were far more numerous than ones after the Lushan earthquake.

Fig. 6 The earthquake recorded at the SZZ station (the *top panel* is high-pass filtering, the *bottom panel* is low-pass filtering)

4 Results and discussion

4.1 Triggering mechanism of dynamic stress

When studying the aftershock triggering mechanism, we find that the dynamic stress appears with the propagation of seismic waves. The changes in the dynamic stress are temporary, so the time for such stress acting on triggering fault planes is limited. How does the dynamic stress increment lead to the fault's instability and finally trigger

an earthquake in such a limited period of time? Although the dynamic stress triggering mechanism is still not entirely clear, the dynamic stress generated by large-amplitude surface waves and the action from underground fluids are considered to be important factors in dynamic triggering. By now, a number of related models have been developed. The first type of model attributes the generation of triggered earthquakes to the conductive properties of rock crevices and changes in interstitial fluid pressure (Hill et al. 2002; Brodsky et al. 2003). Followers of the second type of model believe that bubble oscillation, rising of fluid, and pressure changes, leading to the triggered earthquakes (Brodsky et al. 1998). The third type of model suggests that remote earthquakes cause injection of magma through the dynamic stress triggering (Linde et al. 1996; Hill et al. 2002). The fourth type of model concerns changes in fault friction, which can be caused by remote mainshock dynamic stress, resulting in the triggered earthquakes (Gomberg et al. 1998, 2001; Hough and Kanamori 2002; Voisin 2002).

Although earthquake triggering phenomenon has been found in certain geological areas, such as deep subduction zones and the Americas intraplate, trigger phenomena have mainly occurred in such known or similar geothermal activity areas. Several lines of evidence from regions of geothermal or volcanic activity have shown that trigger-earthquakes are caused mainly by changes in geothermal

Fig. 7 Every event recorded at the SHZ and SZZ station (the *top panel* is high-pass filtering, the *bottom panel* is low-pass filtering)

Table 3 The results of weak earthquakes in the Datong volcanic area before and after the two big earthquakes

Station code	Before earthquake		After earthquake	
	Lushan	Tohoku	Lushan	Tohoku
SHZ	30	21	21	61
YMG	2	17	1	26
YAY	Strong interference	13	Strong interference	25
HSH	Strong interference	8	Strong interference	5
SZZ	5	20	15	54
ZCH	13	14	15	32
YUY		3		23
LNQ	Strong interference	Strong interference	Strong interference	Strong interference
LCH	Strong interference	Strong interference	Strong interference	Strong interference

systems: (1) Large earthquakes can affect the water level, even from thousands of kilometers away (Roeloffs et al. 2003); (2) changes in Yellowstone National Park's thermal geyser activity have had a direct relationship with the adjacent shallow fountain-triggering earthquakes; (3) The dynamic frequency triggering threshold which was observed in the Long Valley caldera region coincides with trigger mechanism due to the void circulation (Brodsky and Prejean 2003).

Surveying the regional geology of triggered event areas can help us to understand triggering mechanisms. So far, all of the volcanic or geothermal areas where tremor events have been observed, are in extensional or transtensional environments. The Anderson fault theory, which depends on stress field around the fault, suggests that the vast majority of cracks will develop along a vertical direction if the geothermal system has been changed by the seismic waves from distant earthquakes. The high-pressure liquid from the deep cracks will rise to the low-pressure zone along the shallow crust, which will consequently trigger the seismic activity. Related to the study put forward by Hough and Kanamori (2002), faults in extensional environments can be fragile, and low stress regimes can lead to unstable rupturing.

Our results show that triggered earthquakes in volcanic areas occurred after the arrival of the surface waves with a period greater than 10 s, and the earthquake is highly potentially to be triggered when the peaks of earthquake seismic wave train passed away. Seismic activity triggered during the period of main shock wave trains clearly demonstrates that changes in stress and low-frequency waves occur almost at the same time. Although it looks that there are some corresponding to the troughs, and some in the middle of peaks and troughs, including event 2, 4, and 9. However, event 2 actually occurred just after the arrival of one peak of surface wave which are not shown in the subplot. For event 4 and 5, things are a little different, event 5 may be one event triggered by the peak wave of a cycle of surface, but the uncertainty is quite high. Event 4

is a little too small, it could be a small event which is belong to the background earthquake. Event 9 is quite weird, it occurred just before the arrival of the surface wave peak. There are two possible reasons for this phenomenon: first, event 9 is triggered by previous peak of surface wave which is not shown in the subplot; second, it is not a triggered event. Anyway, our results show that there might be some small earthquakes triggered by the surface waves of the Lushan earthquake. The possible model for the triggering may be relate to two models: first, the high-pressure liquid from the deep cracks will rise to the low-pressure zone along the shallow crust, which will consequently trigger the seismic activity. Second, bubble oscillation, rising of fluid, and pressure changes lead to the triggered earthquakes.

4.2 Discussion and conclusions

The seismic waves of the Lushan earthquake traveled from the Longmenshan Fault zone to the Datong volcanic zones with a path distance of $\sim 1,400$ km from the epicenter. After the passage of the Rayleigh wave, 14 earthquakes occurred within 50 min of the main event, which might have been caused by dynamic triggering caused by the surface waves of the Lushan earthquake. At the seismic stations in the Datong volcanic zone, the first possible triggered event occurred 15 s after the arrival of the Rayleigh wave peak amplitude. During or after the passage of the Lushan $M_S 7.0$ earthquake surface wave, the characteristics of triggered quakes showed an intermittent, clustered distribution, and each waveform of each triggered event lasted between 3 and 30 s. But similar events would be ignored without high-pass filtering. Since previous catalogs do not use bandpass filter to pick out small earthquakes from the waveforms.

Calculations show that initial dynamic Coulomb stresses caused by the Lushan earthquake for most of the sub events were about 0.001 MPa in the Datong volcanic area, which

were lower than the usual threshold of the dynamic stress triggering. However, based on the filtering results, we still observed many events, which might indicate that stresses as low as those observed can trigger microseismic activity. Most of the characteristics of the triggered events have in common with those of the natural earthquakes, thus it demonstrates that these triggered events should be small earthquakes. Thus, we propose that rocks in the Datong volcanic area may be more sensitive to stress changes. These microseismic activity may have some relevance with the dynamic triggering stress accompanied with the surface waves from the main shock.

For comparison, the triggering phenomenon of the 2011 Tohoku $M_{\text{S}}9.0$ earthquakes also investigated. Our result shows that instantaneous initial dynamic Coulomb failure stress change caused by the Tohoku earthquake was approximately 0.09 MPa. This value is higher than the threshold of the dynamic stress triggering. Consequently, the number of trigger events is much higher than found in the aftermath of the Lushan earthquake. However, there were still some small events before the arrival of the Rayleigh wave of the main shock, which may have been caused by background seismicity or by local anthropogenic sources.

The high-pass filtering results of the $M_{\text{S}}7.0$ Lushan and the $M_{\text{S}}9.0$ Tohoku earthquakes have shown that the background microseismicity in the Datong volcanic region was high, therefore weaker dynamic stress changes may have triggered microseismic activities. The Lushan earthquake provides us some explanations about the cause to the remote triggering of seismic activities, and a possible physical model could be used to explain the remote triggering phenomenon of the Lushan earthquake seismic wave train, using geothermal systems located in these regions. Similar triggered earthquakes observed in some other volcanic zones, these additional seismic records provided an opportunity to understand the triggering mechanism and the usual sense of the physical processes causing an earthquake rupture. However, after the Lushan earthquake, there were many issues unresolved which deserve in-depth study, such as the physical process of remotely triggered earthquakes. In future, we plan to collect the continuous records to obtain a completeness catalog for the studies area.

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