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**Review**

# Relationship between earthquake and volcanic eruption inferred from historical records*

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**Abstract**

A large number of seismic records are discovered for the first time in the historical materials about Wudalianchi volcanic group eruption in 1720~1721, which provides us with abundant volcanic earthquake information. Based on the written records, the relationship between earthquake and volcanic eruption is discussed in the paper. Furthermore it is pointed that earthquake swarm is an important indication of volcanic eruption. Therefore, monitoring volcanic earthquakes is of great significance for forecasting volcanic eruption.

**Key words: historical record; volcanic earthquake; volcanic eruption; Wudalianchi volcanic group**
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## Introduction

From the records of Wudalianchi volcanic group eruption in 1720~1721 obtained from the Man ethnic group files of Heilongjiang General Yamen in Qing Dynasty (WU, 1998; CHEN, WU, 2003), we have discovered the eruption time, state, material and scale of Laoheishan and Huoshaoshan volcanoes, as well as numerous seismic records. These historical materials are discovered for the first time although the study on Wudalianchi volcanic group has a long history. These earthquakes could not be recorded by apparatus due to historical limitation. Therefore, it is even more important to study the features of volcanic earthquakes using the preserved historical records.

We should pay more attention to the seismic information included in the valuable historical materials, although the eruption events happened more than 280 years ago, because it could provide us with important bases for studying the relationship between earthquake and volcanic eruption, and eruption forecast. Considering from the earthquake records of Wudalianchi volcanic

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eruption in 1720~1721 and integrating with the achievements in volcanic research in the world (Gorelchik, *et al*, 1990; McNutt, 1996), we suggest that earthquake swarm in the volcanic area is an important indication of eruption. Therefore, monitoring volcanic earthquakes is of great significance for forecasting volcanic earthquake.

# 1 Historical seismic records of Wudalianchi volcanic group

In order to show the relationship between earthquake and volcanic activities of Wudalianchi volcanic group in 1720~1721 eruption, the records related to the eruption are listed as follows (in chronological sequence).

Sept. 11, Oct. 11, Nov. 21 of lunar calendar in the 58th year of Emperor Kangxi (Oct. 23, Nov. 22, Dec. 31, 1719. The Gregorian calendar is used hereafter). Earthquakes occurred in Namurhetuomoqintun (Tuanjie village in Wudalianchi City).

Jan. 14, 1720. In Wuyunherdongjishan area, rocks erupted from underground with sounds like thundering ··· (the eruption of Laoheishan volcano and seismic activities were recorded in this paragraph).

Feb. 17, 1720. Rocks and fire erupted from the same place. It sounded like thundering and rocks were flying. Rocks and fire were everywhere in the valley and kept spreading.

Mar. 27, 1720. The newly formed mountain was larger than before. The loudness was weakening.

Apr. 4, 1720. The velocity of rock spreading became slower. There were still sound, rocks and fire inside the mountain.

Jun. 16, 1720. Rocks and fire were erupting from the same volcano. The mountain became larger and higher. Sound could be heard.

Jul. 24, 1720. There were still rocks and fire erupting and sound in the same volcano in the original eruption area.

Sept. 18, 1720. There were still fire and flying rocks. It sounded like before in the mountain. The mountain became larger and thicker.

Oct. 27, 1720. Sounds could be heard. Rocks and fire were erupting.

Feb. 12, 1721. Sound could be heard inside the mountain with rocks and fire erupting and spreading.

Mar. 18, 1721. Rocks and fire stopped spreading. Rocks broke out and the inside part was burning. There was no sound inside the mountain. No rocks and fire. Up to the moment, Laoheishan eruption was ended.

Apr. 7, 1721. Rocks were not spreading. There was no sound any longer inside the volcano and no fire and rocks erupting.

Apr. 12, 1721. We (the leaders) could hear the sound underground when we went on a tour of inspection there.

Apr. 26, 1721. In the marginal area with spreading rocks, 6 *li* to the northeast of new volcano (Laoheishan), ground broke with sound. Flames, smokes and rocks could be seen (This is the recordation of Huoshaoshan eruption). The sound, fire and smoke were weaker than those in the last eruption of Laoheishan. The erupted rocks fell down before spreading too far.

May 10, 1721. At the newly erupting volcano (Huoshaoshan), rocks were flying but there was no sound inside the volcano. Compared with the old fire-erupting volcano, the new one was smaller and about 6 or 7 *li* away.

May 28, 1721. There was no sound any more inside the new volcano and no erupting fire and rocks either. It indicated that Huoshaoshan eruption was finished. Slight smoke was rising from the cap. The sound, rocks and fire stopped erupting from the old one (Laoheishan). There was slight smoke inside rocks.

Jun. 25, 1721. The new volcano was 3~4 *sheng* high (1 *sheng* equals to 18 *zhang*, about 60 m). There was still smoke inside the volcano, but no flame. Rocks around stopped spreading. Smoke was everywhere. No sound.

Oct. 27, 1721. As days before, there were no smoke, fire and rock any more. Smoke filled the air. Rocks stopped spreading. Earthquakes happened sometimes.

Apr. 27, 1722. After inspection, the leader reported there was slight smoke inside the volcano. Sound could be heard sometimes. No smoke could be seen in other places.

The above historical materials are the descriptions about the earthquakes occurred before and after Wudalianchi eruption in 1720~1721. This is the first time in China to find so many earthquakes in volcanic activity. The narrative is simple, but the information on time, frequency and strength of earthquakes are clear and true. Thus the relationship between earthquake and volcanic eruption can be discussed on these records.

## 2 Types of volcanic earthquakes

Generally volcanic earthquake refers to the event happened in volcanic area and related to volcanic activities (McNutt, 1996). In the above records, the descriptions as "sound like thundering", "loudness" and "sound" are all manifestation of earthquakes. The earthquakes happened in Wudalianchi volcanic area are all related to volcanic activities and accompanied in the whole eruption process of Laoheishan and Huoshaoshan. Thus we determine them as volcanic earthquakes.

According to seismic phase, frequency brand, source depth and genesis, the volcanic earthquakes can be classified into 4 types: high frequency or type A earthquake, low frequency or type B earthquake, explosive earthquake and volcanic tremor (McNutt, 1996) (Table 1).

Table 1 Types of volcanic earthquakes

| Type of volcanic earthquake | Feature of seismic phase | Frequency band /Hz | Source depth | Genesis |
|---|---|---|---|---|
| High frequency or type A earthquake | P and S phases are clear | 5~15 | Deep | Shearing or sliding |
| Low frequency or type B earthquake | Lacks S wave | 1~5 | Shallow | Pressed by fluid |
| Explosive earthquake | Air seismic phase is dominant | | Extremely shallow | Explosive eruption |
| Volcanic tremor | Lasting several minutes, several days or more | 1~5 | Shallow | Hot water activity |

The characteristics of the four types volcanic earthquakes mentioned above are different from each other. The high frequency or type A earthquake is characterized by clear P and S waves and main frequency band of 5~15 Hz. The genesis is formation fracture and fault sliding. It is hardly to distinguish this kind of earthquake from structural earthquake just by waveform. However, they have different successions. Volcanic earthquake is of swarm type, while the structural earthquake has a main shock-aftershock succession. Low frequency seismic event usually has numerous P wave but lacks S wave. The main frequency band is 1~5 Hz and the source is shallow in depth. They are mainly caused by fluid pressure. Explosive earthquake is companied by explosive eruption and air phase is the main characteristic. Volcanic tremor is a kind of continuous signal lasting several minutes, several days or more. Its main frequency band is 1~5 Hz that is similar to low frequency seismic event (Figure 1).

The above classification has revealed the essential characteristics of volcanic earthquakes, however, it is mainly considered on waveform records. Detailed written records are helpful for dividing earthquake types. As mentioned above, during the eruption of Wudalianchi volcano in 1720~1721, many earthquakes occurred in succession. But it is difficult to determine the type of earthquakes occurred in 1720~1721 because there is no waveform records. However, according to written records we can determine at least two types of volcanic earthquakes. One is high frequency earthquake and the other is explosive earthquake.

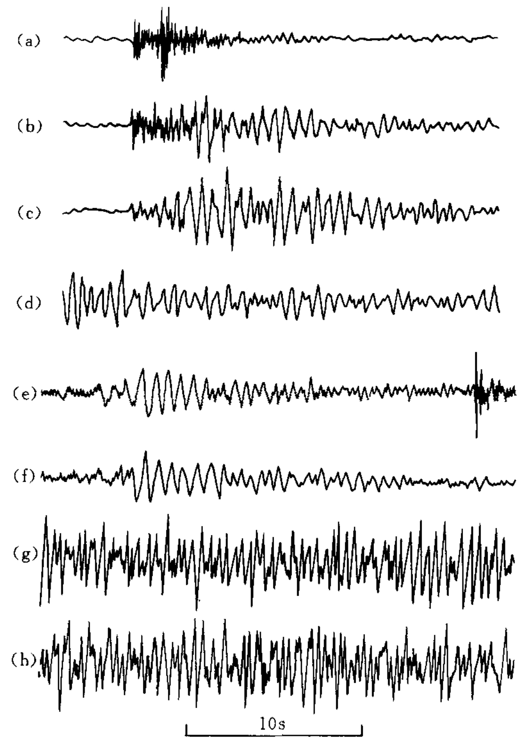


Figure 1 Typical waveform of volcanic earthquakes
(a) High frequency or type A volcano structural earthquake, Redoubt volcano, 6.8 km deep, RED recorded, 8 km away from crater; (b) Mixed frequency event, 0.6 km deep (0.61 m above sea level), Redoubt volcano, RED recorded; (c) Low frequency or long-periodic event, 4 km deep, RED recorded; (d) Volcanic tremor, Redoubt Volcano, RED recorded; (e) Explosive shock, Pavlof Volcano, PVV recorded, 8.5 km away from the volcano (note: arrival of abrupt air wave); (f) Low frequency or type B event, Pavlof volcano, PVV recorded; (g) Volcanic tremor before eruption, Spurr volcano, CRP recorded, 4.8 km away from the volcano; (h) Tremor in the eruption, Pavlof volcano, PVV recorded (after McNutt, 1996)

We have already found the characteristics of three earthquakes happened on Oct. 23, Nov. 22 and Dec. 31, 1719, respectively. First, the earthquakes happened in the eruption area; Second, considered from earthquake strength, there was no further description about the damage caused by these earthquakes, which demonstrated that the magnitude was not great, smaller than 5 generally; Third, their time interval was 30~40 days and difference in magnitude was not large, which indicated that they were not the main shock-aftershock type but the volcanic earthquake swarm of $M<5$. Therefore, we can confirm they are high frequency earthquakes. On Apr. 12, 14 days before the eruption of Huoshaoshan, "sound came continuously from underground", which might also be a swarm of earthquakes and belonged to high frequency earthquake.

Most of above-mentioned earthquakes happened in the process of volcanic eruption. Their performances were "sound" and "loudness". As this type of earthquakes were often companied by volcanic eruptions, they should be classified as explosive earthquake.

# 3 Relationship between earthquakes and volcanic eruptions

## 3.1 Earthquakes and volcanic eruptions from historical material records

As for the eruption of Wudalianchi volcano in 1720~1721, the interval from the beginning of swarm to the eruption of Laoheishan is 114 days (from Oct. 23, 1719 to Jan. 14, 1720). The interval from the end of swarm to the eruption is 14 days (from Dec. 31, 1719 to Jan. 14, 1720). It shows that Laoheishan eruption has precursory indication. From the interval (114 to 14 days), the swarm could be considered as mid-term predicting index for eruption forecast.

Huoshaoshan eruption started on Apr. 26, 1721. 14 days before the eruption, on Apr. 12, an earthquake swarm with low magnitude occurred. Taking the time into consideration, we can consider it as the mid-short-term warning sign of volcanic eruption.

Therefore, we can say that the historical records of Wudalianchi volcanic eruption have shown a definite precursory index, which is of great significance for forecasting volcanic eruption.

### 3.2 Examples of volcanic earthquakes and eruption abroad

It is very important to take research experiences abroad as a reference. Here are some achievements from external researches on volcanic earthquakes in volcanic areas.

#### 3.2.1 Volcanic earthquakes in Kamachatka

Kamachatka peninsular is a main region of active volcanoes in Russia and many eruptions occurred in the past decades, *e.g.*, Bezymianny volcano eruption in 1955~1956, Sheveluch volcano eruption in 1965, Klyuchevskoy volcano eruption in 1974~1987, great Tolbachik fissure eruption in 1975~1976. Through monitoring and researching these active volcanoes, Gorelchik, *et al* (1990) generalized the characteristics of volcanic earthquakes in this area: local earthquakes dominated by swarm, low magnitude earthquakes ($M$=5.5~6 at most), long periodic variation as compared with structural earthquake, and earthquake recurrence curve with a high slope. Earthquake swarms are divided into 4 types. Type I swarm happened before central eruption of andesite volcano, which was dominated by shallow earthquakes. The epicenter was 3~5 km away from the crater and the earthquake focus was inside the volcano with the depth of 10~15 km. Maximal earthquake energy $K_{max}=12\pm0.5$ ($K=4.6+1.5M_S$). And the swarm lasted 7~10 days to 3~5 weeks. In the active period of earthquake swarm, Total energy $E_N$, frequency $N$ and $K_{max}$ kept rising to the maximum at the eruption. Type II earthquake swarm happened before flank eruptions of basalt and andesite, which was dominated by shallow earthquakes. The epicenter was 3~10 km away from new crater and the depth of focus was 0~5 km. Swarm lasted 1~10 days. $K_{max}=11\pm0.5$. $E_N$ and $K_{max}$ went up sharply at the beginning and came down slowly after the maximum. $K\geq6.0$ earthquakes stopped several hours before the eruption. The characteristics of the above two types of earthquakes are so regular that they can be used for forecasting volcanic eruption. Type III contains explosive earthquakes companied by volcanic eruption. The focus depth was less than 500 m from the bottom of the crater and the epicenter lay in side crater. $E_N$, $N$ and $K_{max}$ varied with eruption strength and power. Type IV earthquake swarm happened at the beginning and end of eruption, sometime after the eruption. The depth of focus was 0~20 km and the epicenter was 10~20 km away from the crater or even further, reflecting the progressive release of accumulated stress in the periods of magma moving and erupting. $E_N$, $N$ and $K_{max}$ went down gradually from the maximum with time. Earthquake swarm lasted several hours to several some months (Gorelchik, *et al*, 1990). The development of earthquake swarm has laid a good foundation for successive forecasts of volcanic eruption.

#### 3.2.2 1980 eruption of Saint Helen volcano

Saint Helen volcano in Washington of USA erupted in May of 1980, which is an intensively explosive event containing lateral explosion. It happened 59 days after the intensified seismic activity. On Mar. 20, an earthquake with $M$=4 happened, which was followed by some small events.

On Mar. 25, $M \geq 4$ seismic activity came up 8 times per hour. Emanation started on May 27. The earthquakes in this succession amounted to more than 10 000 including high-frequency events, low-frequency events and volcanic tremor. Most events happened in the depth of 3~7 km on the north of volcano where eruptive vent located. There was not direct forerunning effect of earthquake several hours before the high-tension eruption. A $M$=5.1 earthquake took the coverage off and made a fan-shaped breakdown, and then eruption started. In a short period after the eruption, deep earthquakes with a source depth of 5~20 km happened, which lasted several days and then became small eruption. Before small eruption, there were usually swarms lasting several hours or several days (Malone, *et al*, 1981; Swanson, *et al*, 1983).

### 3.2.3 1991 eruption of Pinatubo volcano

Pinatubo volcano in Philippine is not a well-known one until Plinian explosive eruption — caldera eruption happened on Jun. 15, 1991, which was the largest in the past 79 years. Seismic activity intensified 2 months or more before the eruption. The exact beginning time is not clear since seismic apparatus was only fixed up after the vapor explosion on Apr. 2, 1991. In the period from the last ten days of May to the beginning of June, seismic activity intensified progressively and the source depth was usually shallow. Before Jun. 3, the epicenter lay about 5 km northwest to the summit. After that, seismic activity transformed to underground near the summit of volcano. Volcanic tremor started on Jun. 3 and a small dome emplacement appeared on Jun. 7. Two strong volcanic tremors happened several hours before the Plinian explosive eruption on Jun. 12, after which came a low frequency swarm event and a volcanic tremor. The high-intensity eruption appeared on Jun. 15 made the top down by 200 m. Effusive mass went as high as 35 000~40 000 m. After that, the volcano had small events lasting 3 weeks. The large deep earthquakes had the magnitude as high as $M$=5.7 and the source depth of 25 km. They happened somewhere no more than 20 km from the summit and from the moment of high-intensity eruption (Mori, *et al*, 1996).

According to the seismicity level, gas and land deformation, Pinatubo volcano eruption was forecasted successfully. So, population was dispersed group by group and damage was decreased because of the prediction.

## 4 Discussion and conclusions

We can see from the above-mentioned facts that earthquakes have close relation with eruption of volcanoes. Seismic activities intensified before almost every eruption; earthquake swarm appeared meanwhile. Therefore, seismic monitoring is an effective way for forecasting volcanic eruption. Epicenter distribution can be used to predict the location of eruption because most earthquakes occurred in the vicinity of active crater or eruptive vent. The time of eruption can also be predicted with the help of volcanic earthquake. Some successful forecasts were already given in the paper but mistaken forecast occurred sometimes. Generally speaking, high-frequency earthquakes last longer time, which is likely to predict with error; while low-frequency events and volcanic tremors last shorter time, which often lead to eruption (McNutt, 1996). Every volcano would experience the period of dormant, buildup and development corresponding to the features of seismic activities, which are caused by complicated volcanic structure, quality of magma and so on.

It has been indicated that earthquakes happened in Oct. 1719 to Apr. 1722 in Wudalianchi volcanic area are volcanic types. And the earthquakes occurred on Oct. 23, Nov. 22 and Dec. 31, 1719 are volcanic structural earthquake swarms, which are medium-term indication of Laoheishan volcano eruption forecast. It is of great significance for reducing natural disasters. There were 14 days from the end of earthquake swarm to the volcanic eruption, which was long enough for population dispersing.

The comparison between Wudalianchi and Kamachatka volcanic earthquakes shows the former swarm corresponds to type II of the latter. Both of them were caused by breakage and faulting due to basbltic magma. Seismic activity intensified before eruption but quieted down close to eruption. This regular phenomenon is of great significance for forecasting volcanic eruption.

The volcanic earthquake usually has a magnitude of $M<5$. It is related to the formation of earthquake focus that lies close to magma chamber or volcanic conduit. Thus the magnitude is restricted. However, the magnitude of a few volcanic earthquakes is higher than 5, which relates to the formation of caldera (*e.g.*, Pinatubo volcano) or fan-shaped breakdown (Saint Helen volcano) (McNutt, 1996).

Based on the achievements from volcanic observation and research, the geoscientific scholars have found that deep earthquakes (10~40 km) often happen after volcanic eruption. This is stress-changing response caused by deep-seated magma transformation. The earthquakes occurred after Wudalianchi volcanic eruption might also be caused by magma transformation. It inspires us to keep seismic monitoring for a longer time rather than stop it, because deep-seated magma may cause earthquake and some magma may cause new eruption.

Although apparatus are widely used in earthquake recording and data are transmitted in real time, for historical earthquakes, there is no substitute for written records. Therefore, it is very important to discover and study historical materials.

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