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Temporo-spatial Characteristics of Swarm Distribution before Two M_S6.0 Earthquakes in the Tianshan Area, China and Their Application to Earthquake Prediction[1]

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The Nilka-Gongliu earthquake with M_S6.0 and Xinyuan-Hejing earthquake with M_S6.6 successively occurred in Xinjiang on November 1, 2011 and June 30, 2012. Massive swarm activity was observed in a large area around the main shock epicenters before the two strong earthquakes. Main features are as follows: ① The swarm activities not only increased significantly in number of earthquakes, but also presented a distinct swarm gap in spatial distribution, and the epicenters of the following strong earthquakes were all located in the swarm gap. ② The duration of the swarm gap lasted longer, for 2 – 3 years. ③ The time-history characteristics of the swarm's cumulative frequency indicates that swarm activity was quieter a few months before the main shocks. Finally, we discuss the results as well as the issues of their application in earthquake prediction.

Key words: Earthquake   Temporal-spatial swarm activity   Earthquake prediction

INTRODUCTION

In recent years, earthquake prediction research in China has focused more and more on the relationship between earthquake swarms and strong earthquakes. A lot of studies have shown that an earthquake swarm that contains seismic precursor information has gradually become a relatively important medium- and short-term precursory observation method in earthquake prediction (Qin

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Baoyan, Jiang Xiu'e, 2000; Huang Yun et al., 2011; Huang Yun, Sun Yejun, Ye Biwen et al., 2011).

Earthquake swarm research was started by Mei Shirong as early as in 1993. She carried out corresponding analysis of some indicators and spatial-temporal dynamic changes before earthquakes through two different approaches, e. g. the earthquake swarm itself and its overall characteristics, and eventually sought out the anomaly patterns of an earthquake swarm before large earthquakes (Mei Shirong et al., 1993). This article presents a research approach aimed at the general characteristics of an earthquake swarm. Some scholars in China have studied the images of migratory and periodic anomalous seismic swarm activities (Song Zhiping et al., 2001; Ji Dongpu et al., 2011). Many scholars abroad also gradually started research and application of earthquake swarm activity. Holt Kamp S. G. et al. (2011) and Shishay Bisrat et al. (2012) respectively studied spatial-temporal distribution characteristics of earthquake swarms in different regions using different earthquake catalogues and seismic wave data, and got relationships between earthquake swarm activity and other earthquakes and fault zone changes.

Xinjiang is a seismically active area in China, where the occurrence of moderate-strong earthquakes would cause certain casualties and property losses, and numerous earthquakes also provide good conditions for the study of earthquake prediction. In recent years, the research of the relationship between earthquake swarms and strong earthquakes in Xinjiang has gradually deepened. Ao Xueming et al. (2010) successively studied more systematically the spatial-temporal distribution characteristics of earthquake swarm activity before earthquakes with magnitude of approximately 7.0 in the Tianshan area of Xinjiang in recent years. Meanwhile, they systematically analyzed the Wenchuan $M_S8.0$ earthquake on May 12, 2008, the Tangshan $M_S7.8$ earthquake on July 28, 1976 and a number of major earthquakes in the Sichuan-Yunnan region, trying to seek new effective means for earthquake prediction. In this article, starting with the overall spatial-temporal distribution characteristics of many earthquake swarms in a large area, we analyze the evolutionary characteristics of spatial-temporal distribution of earthquake swarms before the two $M_S6.0$ earthquakes, the Nilka and Xinyuan earthquake, to further explore the relationship between the spatial-temporal distribution characteristics of earthquake swarms and strong earthquake prediction. The results once again find new and useful seismic precursor information before strong earthquakes, which verifies the actual forecast application of existing research results.

1 DEFINITION OF EARTHQUAKE SWARM AND DATA SELECTION

1.1 Definition of Earthquake Swarm

When studying the relationship between earthquake swarms and moderate-strong earthquakes, it is important and necessary to first determine the criteria for earthquake swarm screening, and conduct corresponding screening according to the uniform standard. Using the correlation methods of the Programming Guide for Seismology Monitoring and Forecasting as a reference, the standard of earthquake swarm screening in this article is mainly based on the results of previous studies (Zhu Chuanzhen et al., 1981; Song Jungao et al., 1989; Department of Earthquake Monitoring and Prediction, State Seismological Bureau, 1990). The ones that satisfy the corresponding conditions are chosen as the earthquake swarm:

(1) The epicenter distribution of the earthquake sequence is required to be in a rectangular area within a certain range, generally less than $2500km^2$, and earthquakes within this range should be relatively concentrated, which shows significant difference with the distribution of

peripheral earthquakes, and the maximum daily frequency and total frequency are required to be respectively more than 3 and 6 times.

(2) Earthquake magnitude of the earthquake sequence is required to be $3.0 \leqslant \mathrm{Max}(M_L) \leqslant 5.2$, and the difference between two relatively large magnitudes should be $\Delta M_L \leqslant 1.1$.

(3) No $M_L1.0$ earthquake occurred for half a month before and after the earthquake sequence, and the dates on which the first and the last earthquake occurred are respectively used as the starting date and end date of the earthquake swarm sequence.

1.2 Data Selection

Seismic data used in this article are taken from the earthquake catalogue from the Xinjiang Regional Digital Seismic Network, with three relevant elements of strong earthquakes taken from the Shared Earthquake Catalogue of the China Earthquake Networks Center, China Earthquake Administration. Considering the locations and tectonic settings of the two $M_S6.0$ earthquakes studied in this article, the study area for the selection of the earthquake swarm covers the west section of the north Tianshan Mountains, the east section of the south Tianshan Mountains and their adjacent region in Xinjiang, where the epicenters of the two earthquakes are included. Because the Xinjiang Regional Digital Seismic Network instrument data has gradually changed from analog records to digital since 2000, and the density of the stations has been increased, the data obtained shows relatively good consistency. Therefore, in this article, we will select the time interval between the Wuqia $M_S6.8$ earthquake on October 5, 2008 and the $M_S6.6$ earthquake on June 30, 2012 as the study period, and analyze and discuss the spatial-temporal variation characteristics of the earthquake swarm during this time interval.

2 SPATIAL-TEMPORAL DISTRIBUTION CHARACTERISTICS OF THE EARTHQUAKE SWARM BEFORE THE TWO $M_S6.0$ EARTHQUAKES IN NORTH TIANSHAN

Moderate-strong earthquakes frequently occur in the north Tianshan area in Xinjiang. An $M_S6.0$ earthquake occurred in the junction of Nilka and Gongliu on November 1, 2011, in the west section of the north Tianshan area in Xinjiang, where earthquake monitoring capability is relatively strong. According to the China Earthquake Networks Center, the epicenter of this earthquake is located at 43.60° north latitude and 82.40° east longitude, and the main shock is of magnitude $M_S6.0$, showing a focal depth of 28km. The earthquake sequence is mainly of the mainshock-aftershock type, the earthquake shows a reverse faulting focal mechanism, and the seismogenic structure is the southern Awulale fault (Nie Xiaohong et al., 2012). It can be seen from Fig. 1 that before the main shock, its surrounding earthquake swarm is rather active and focused, which mainly distributes in the periphery of the epicenter of the main shock, and there are no swarm activities near the epicenter of the main shock, presenting a distinct swarm gap, the geometrical shape of which approximates an unenclosed ellipse (the semi-major is about 250km), by which the main shock is partially surrounded. The number of earthquake swarms is relatively lower in the western side of the epicenter of the main shock because most of the western side is beyond the border, where monitoring capability is limited, while the earthquake swarm distribution is rather focused in the middle and east segment of the Tianshan Mountains, where monitoring capability is rather strong.

An $M_S6.6$ earthquake occurred in the junction of Xinyuan and Hejing, where earthquake monitoring ability is relatively strong. According to scientific field investigation, it is preliminarily determined that the earthquake occurred in the junction of the Kashi river, Nalat fault and southern Awulale fault, where seismic tectonic environment is complex. The earthquake sequence shows a mainshock-aftershock type, and the focal mechanism shows a strike-slip type, which is mainly subjected to the nearly SN principal compressive stress (Wei Yunyun et al., 2012). As shown in Fig. 1, from the Wuqia $M_S6.8$ earthquake on October 5, 2008 to the $M_S6.6$ earthquake occurring in the junction of Xinyuan and Hejing on June 30, 2012, the earthquake swarm was mainly distributed in the periphery of the epicenter of the subsequent main shock, presenting a distinct swarm gap, which approximates an unenclosed ellipse (the semi-major axis is about 192km, semi-minor axis about 114km), and the earthquake swarm distribution is rather focused in the middle and east segment of the Tianshan Mountains, where monitoring capability is rather strong.

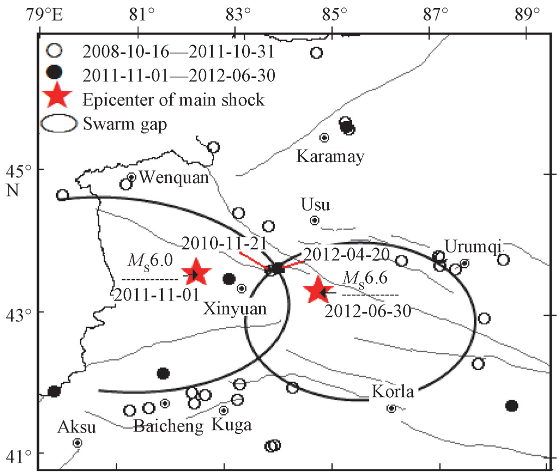

Fig. 1
Spatial distribution of earthquake swarm after the Wuqia $M_S6.8$ earthquake on October 5, 2008 (2008-10 – 2012-06)

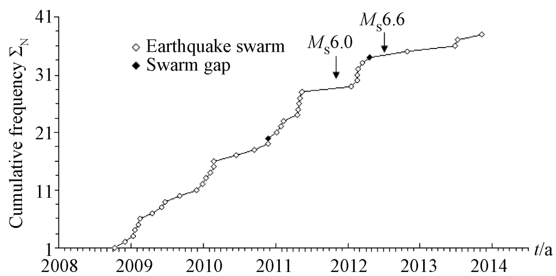

Fig. 2
The time course of cumulative frequency of the earthquake swarm along the west segment of the north Tianshan Mountains and east segment of the south Tianshan Mountains

2.1 *Spatial Distribution Characteristics of Earthquake Swarm*

Fig.1 simultaneously provides the spatial distribution of earthquake swarm before the two $M_S6.0$ earthquakes (for the sake of clarity, the $M_S6.0$ earthquake on November 1, 2011 and the $M_S6.6$ earthquake on June 30, 2012 are abbreviated as the $M_S6.0$ earthquake and $M_S6.6$ earthquake). It can be seen from Fig.1 that the earthquake swarm activities increased significantly in the study area after the Wuqia $M_S6.8$ earthquake in 2008, but the spatial distribution of the earthquake swarm is very uneven. There are two most concentrated areas. One is Kuqa, Luntai and Baicheng, the other one is nearby Urumqi. There are also some scattered earthquake swarm activities.

It is found by the above analysis that in addition to a certain non-uniformity, the spatial distribution of the earthquake swarm also presents some more prominent features as follows: The geometrical shape of the earthquake swarm presents the characteristics of an approximate circular or elliptical distribution, that is, swarm activities are mainly centered in the periphery of the ellipse, and there is no swarm activity in the interior of the ellipse. Mei Shirong (1993) described the distribution characteristics as an earthquake swarm gap.

As shown in Fig. 1, the $M_S6.0$ and $M_S6.6$ main shocks respectively lie in the swarm gap formed before the occurrence of the two earthquakes. A nearly NS approximate semi-elliptical earthquake swarm gap is formed before the $M_S6.0$ earthquake, while the epicenter of the $M_S6.6$ earthquake lies in an approximate elliptical swarm gap stretching in a nearly EW direction. The geometric position of the earthquake swarm may be associated with the underground medium stress, which affects the direction of interaction of pulling and tensile force that the underground medium structure suffers from strong earthquakes. Although earthquake swarm activity hasn't happened in the swarm gap for a long time, swarm activities can often be observed at the medium-short term or short term anomalous stage before the main shock. As shown in Fig. 1, about 1 year before the $M_S6.0$ earthquake, on November 21, 2010, a gap-filling earthquake swarm was observed in Nilka, about 110km from the epicenter of the future main shock, and about 2 months before the $M_S6.6$ earthquake on April 20, 2012, a gap-filling earthquake swarm was observed 80km from the epicenter of the main shock.

2.2 *Time Course of Earthquake Swarm*

Fig. 2 provides the time course of the cumulative frequency of the earthquake swarm before the two $M_S6.0$ earthquakes in the study period, from which we can see that the formation of the earthquake swarm before both strong earthquakes began on October 5, 2008, while only the earthquake occurrence time varies. Swarm activities lasted for about 3 years before the $M_S6.0$ earthquake, including 28 earthquake swarms; and swarm activities last for about 3 and a half years before the $M_S6.6$ earthquake, including 34 earthquake swarms. It is found by analysis that from April 23, 2011 to May 11, 2011, 5 earthquake swarms were observed in less than a month, the rate of which is significantly accelerated, and immediately followed by a period of apparent quiescence for as long as 8 months. The $M_S6.0$ earthquake occurred after a quiet period of 5.7 months, while the $M_S6.6$ earthquake occurred 5 months after the re-active period following the quiet period of 8 months. Therefore, earthquake swarm activity before the two $M_S6.0$ earthquakes respectively presents a short-term or medium- and short-term anomaly of active – quiet – earthquake occurrence and quiet – active – earthquake occurrence. Earthquake swarm activity decreased after the two $M_S6.0$ earthquakes, and the number of earthquake swarms was less than that in the active phase. Altogether 4 earthquake swarm activities were observed within 2 years after the earthquakes (Fig. 2). After comparing the magnitude and duration time of earthquake swarm activity of the Nilka $M_S6.0$ earthquake and the Xinyuan $M_S6.6$ earthquake, we found that for different earthquakes at the same area (or adjacent area), the greater the magnitude of the strong earthquake, the longer the duration of the earthquake swarm before the main shocks.

As shown in Fig. 2, since the Luntai earthquake on January 3, 2011, after a quiet period of 3 months, earthquake swarm activities again turned out to be focused and accelerated, that is, swarm activities transferred from a normal background to being enhanced, which also marks a gradual shift from medium-term to short-term. The earthquake occurred after the swarm activity turned from active to quiet, and the location of the epicenter was close to an approximate ellipse end of the swarm gap. After the occurrence of the main shock, the scale of the unilateral semi-enclosed ellipse narrowed, but there was still the presence of the earthquake swarm gap. The 5 new earthquake swarms were mainly located in the east and south side of the original focal area, while there were no new earthquake swarms on the west side. In combination with Fig.1, we can also see that earthquake swarms observed before the $M_S6.0$ and $M_S6.6$ earthquakes, forming two earthquake swarm gaps, are mostly the same ones, which occurred before the $M_S6.0$ earthquake, and after the $M_S6.0$ earthquake, and only 5 new earthquake swarms are added, followed by the $M_S6.6$ earthquake, which may be related to underground tectonic settings in the study area. The two earthquakes may have been developed during the same period, but they took place successively.

3 MAIN CONCLUSIONS AND THEIR PRACTICAL APPLICATIONS IN EARTHQUAKE PREDICTION

(1) The above analysis results indicate that clear earthquake swarm gaps are observed before the two $M_S6.0$ earthquakes. On this basis, we delineate the annual seismic risk area for earthquakes with magnitude around 6.0 respectively at the earthquake situation seminar and the annual earthquake tendency conference, and three elements of earthquakes that really occurred are basically in accordance with the forecast. Therefore, there is a certain efficiency to applying the anomalous characteristics of the earthquake swarm gap to actual earthquake monitoring and prediction to determine the possibility of strong or great earthquakes or using it for earthquake location forecast.

(2) After comparing the number of earthquake swarms before the $M_S6.0$ and $M_S6.6$ earthquakes and their duration time, we can see that the $M_S6.6$ earthquake has greater magnitude, which is in line with the results obtained by Ao Xueming et al. (2010) about the relationship between the number of earthquake swarms and strong earthquake magnitude, that is, the magnitude of strong earthquake increases with the number of earthquake swarms (Ao Xueming et al., 2010). Meanwhile, the earthquake swarm activity before the $M_S6.6$ earthquake lasted relatively longer. Accordingly, this further verifies that the magnitude of earthquakes in the same area may be related to the number of earthquake swarms observed before the main shocks and their duration time.

(3) The time course of earthquake swarms we observed a few months before the two $M_S6.0$ earthquakes reflects to varied degrees, the characteristics of active-quiet or quiet – active – earthquake occurrence. Therefore, in the process of earthquake tracking and monitoring, in the premise of seismic trend background, if the observed earthquake swarm activity presents a quiet period for a long time (for example, a few months), it indicates that the earthquake generating process may have entered the medium- and short-term stage with the possibility of a strong earthquake within 1 year. In the meantime, in combination with the spatial distribution of gap-filling earthquake swarm observed, these anomalous characteristics can be used as reference indicators for short-term or medium- and short-term prediction.

4 POSSIBLE PHYSICAL INTERPRETATION

(1) Many studies have focused on earthquake preparation process and qualitative changes of earthquake precursors. In recent years, based on research of deep structure, rock experiments, mechanical analysis and spatial-temporal variation characteristics of precursory fields observed using existing methods before moderate-strong earthquakes for the strong earthquake preparation

process, in combination with corresponding analysis of all kinds of seismogenic models, many scholars have put forward the concept of a strong body seismogenic model (Mei Shirong, Ding Wenyu et al., 1997; Mei Shirong, Xue Yan et al., 2009; Mei Shirong, 1995). According to the definition of this concept, the seismic source body should have greater rupture or slipping strength than that in surrounding areas. Therefore, under the effect of far-field tectonic stress, the area beyond the seismic source body will rupture or slide first, thus moderate and small earthquake activity will increase correspondingly and form an earthquake swarm, but the seismic source body remains stable. This is also why an earthquake swarm gap always precedes a great earthquake and is centered around the epicenter of future strong earthquakes (Ao Xueming et al., 2010).

(2) By reference to the discussions in literature (Mei Shirong, 1995), the strong body seismogenic model can be interpreted as a seismic source body embedded in the earth's crust, which, as a high stress concentration area, still remains stable and unbreakable. However, when stress accumulation exceeds a certain degree, that is, in the late period of earthquake preparation, a series of changes and ruptures will occur in the tectonic layers around the source body, which will decrease with the rupture of the source body, therefore, earthquake swarm activity can occur in and around the source body region. This is also a possible reason for the presence of a gap-filling earthquake swarm. The above results are preliminary, and comments and criticism are greatly appreciated.

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