RETRACTED ARTICLE: Fluid-induced high seismicity in Songliao Basin of China

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ABSTRACT

In recent years, moderate earthquakes with a magnitude of about 5.0 have occurred along the Fuyu/Songyuan-Zhaodong fault frequently. This fault is the most seismic active fault in the Songliao Basin, even in the Northeast Seismic Region of China. Based on previous studies, this fault has obvious segmentation from its activity. Some scholars considered the ground stress changes, which caused by the high pressure water injection method of oil exploration in Chaganhua area, maybe the reasonable interpretation of this phenomenon. This paper tries to synthetically assess and review the activity and segmentation of this fault, combining with previous data and the latest research findings. We also tried to reveal the relationship between the high seismicity and high pressure water injection of oil exploration. This effort will help us to understand the fault active characteristics and preparation tectonic conditions of the moderate earthquake in the weak seismic activity region such as the Songliao Basin or the Northeast Seismic Region of China.

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Introduction

In recent years, moderate earthquake events have frequently occurred in Songliao Basin. In 2006, an earthquake of magnitude 5.0 occurred in Chaganhua area. In 2013, the region has an earthquake swarm of major magnitude 5.8. The earthquake swarm caused about 200000 people affected and direct economic losses about 2 billion RMB. The two earthquakes occurred at the intersection of the fault junction of the Fuyu/Songyuan-Zhaodong fault (FSZF) and the Chaganpao-Daozijing fault (CDF). FSZF is an important seismogenic fault in Songliao Basin, it is north from Zhaodong, extends southward to the Chaganhua area, and through the Songyuan City. In history, the largest earthquake in Jilin Province occurred at the intersection of FSZF and the Second Songhua River fault (SSRF) in Songyuan area, an earthquake with a magnitude of 6.5/4 in 1119 (Tang, 1990; Wu, 1991). In 15 August 2017, a magnitude 4.5 earthquake occurred in Ningjiang district of Songyuan City, it is the latest moderate seismic activity of the FSZF. The epicenter of the earthquake was N 45.30°, E 124.81°, and the focal depth was 12 km. In summary, the FSZF has the most seismic active frequency and intensity in the Songliao Basin, even in the Northeast Seismic Region of China, which is an area with relatively weak seismic activity in China.

No matter what, the FSZF is obviously the most seismic active fault in Songliao Basin, even in the Northeast Seismic Region of China. However, the systematic activity assessment and segmentation of the FSZF is scarce or ex parte. This paper tries to synthetically assess and review the activity and segmentation of this fault, combining with previous data and the latest research findings. We also tried to reveal the relationship between the high seismicity and high pressure water injection of oil exploration. This effort will help us to understand the fault active characteristics and preparation tectonic conditions of moderate earthquake in the weak seismic activity region such as the Songliao Basin or the Northeast Seismic Region of China.

Geological structure background

The FSZF is buried by thick Quaternary soil strata. Furthermore, the ground surface trace has been mostly destroyed by human activities. Based on previous studies (Shi, Ren, Zhang, Fu, & Tang, 2012; Sun, Chen, Sun, Fu, & Hu, 2013), it is found that the FSZF has obvious segmentation from its geometric structure (Figure 1). The northern part of the fault (Fuyu-Zhaodong subsection in Figure 1) is the lowest seismic active segment with no moderate seismic record. The middle section of fault (Fuyubei subsection in Figure 1) intersects with the SSRF (Li, Liu, Zhang, & Ceng, 2012; Yang, Wang, Liu, Wu, & Chen, 2010), and it is also a region with frequent small earthquakes occurrence (Shao et al., 2015; Yu, Shen, Yu, & Wu, 2016). In the past, oil exploration data were implemented to assess this section (Shu, Mu, & Wang, 2003; Wang et al., 2016). Shallow artificial seismic exploration was carried out to understand the distribution characteristics and activity of the new fault (Shao et al., 2015; Yu et al., 2016). Now, it is considered that the
FSZF underwent structure inversion at the last phase of the Nenjiang Formation (Liu, Jiang, & Yang, 1998; Yu, Min, Wei, Zhao, & Ma, 2015). This section was formed characteristics of lower right and upper reverse. The structure inversion of the FSZF middle segment caused the Quaternary strata deformation. The fault activity has penetrated into the Quaternary strata. It may be the reason of earthquakes occurring frequently in the middle part of the fault. The current studies show the middle segment is the most active part of the FSZF (Shu et al., 2003; Wang et al., 2016). The southern part of the fault (Gudian and Chaganhua subsection in Figure 1) intersects with a group of NW-trending faults. The seismicity is the most frequent in recent years. Figure 2 is deep geophysical exploration data, whose survey line is located in Chaganhua area with the east-west arrangement. The deep data shows that the fault is a normal fault, resulting in the deformation of the reflection layer of $T_1$ (the

![Figure 1. Segmentations of the FSZF.](image)

- a. Fuyubei subsection fault (FYBF), b. Fuyu-Zhaodong subsection fault (FZSF), c. Chaganhua subsection fault (CGHSF), d. Gudiansubsection fault (GDF).
bottom of Nenjiang formation), controlling the buried depth of Quaternary basement. It is presumably an early Middle Pleistocene fault. Petroleum data can help us clearly understand the distribution of faults in the deep part, but there are also shortcomings of insufficient or missing data in the upper formation. In the “Activity identification of the southern section of Fuyu/Songyuan-Zhaodong fault” project (2015–2017), which organized and implemented by the Earthquake Administration of Jilin province, researchers arranged shallow artificial seismic survey lines on the NE and NW-trending faults, the upper part structural features of the fault was studied in detail. The Chaganhua subsection (Figure 1) was considered an early Middle Pleistocene fault, whose ability to trigger an earthquake of more than 5.0 magnitude is not available. While, as a matter of fact some earthquakes with magnitude above 5.0 have occurred on the intersection area of the FSZF and the CDF. Some scholars considered the ground stress changes, which caused by the high pressure water injection method of oil exploration in Chaganhua area, maybe the reasonable interpretation of this phenomenon (Lei, Yu, Ma, Wen, & Wang, 2008; Pan et al., 2007; Terakawa, Miller, & Deichmann, 2012; Wen, Wen, & Zhang, 2007).

**Activity of the Chaganhua subsection**

The Chaganhua subsection fault is located in the southern tip of the FSZF (Figure 1), which has the most frequent and intense seismicity in the fault zone. There are two different viewpoints about the distribution of the Chaganhua subsection fault. The first one is based on previous data and the deep fault distribution information from the oil department. The second one is according to the research achievements of “Fault activity identification and seismic risk assessment in Songyuan City” project. Shallow geophysical comprehensive survey and controlling borehole detection help located the strike line of this fault (Figure 1). The fault length is about 38 km, trending NE, the main tendency towards NW. Seismic reflection profiles show that the Chaganhua subsection fault is a reverse fault, and it breaks T03 reflective layer (Figure 3). The T03 reflection layer is interpreted as the top surface of Cretaceous Nenjiang formation, so the fault does not extend to the Quaternary strata. The fault is strongly active during rifting, the deep fault is combined into structures like an inverted flower, and structure inversion may have occurred in some areas.

**Discussion and conclusion**

The seismic waveform recorded in 2013 Qianguo earthquake of magnitude 5.8 is different from that of the general tectonic earthquake, which contains abundant surface wave components (Figure 4). Several shallow artificial seismic survey lines are set-up at the intersection of Chaganhua subsection fault and CDF. The interpretation result of the reflection profile indicates that the two faults do not disturbed the Quaternary strata. Base on the tectonic analogy method, both of Chaganhua subsection fault and CDF do not have the ability of preparation moderate earthquake of about magnitude 6.0. The Chaganhua area is a high pressure water injection mining zone, so the earthquake swarm of magnitude 5.8 may be triggered by induced ground stress changes. Due to the faults exist in this area before water injection, the pore water pressure increases with high pressure injection of water, and the stress equilibrium state of stratum has changed. In addition, the FSZF is now coming under
NW-trending compression stress from plates. High pressure water injection will lead to lubrication between faults, and the friction coefficient will decrease, so the shear strength of the stratum will decrease, and the strata will be prone to shear sliding along the fault plane. House (1987) studied the focal mechanism of the earthquakes induced by high pressure water injection. It is found that some large scale-induced earthquakes are not caused by tensional rupture, but are characterized by shear slip. This may be similar to the mechanism of some scale tectonic earthquakes in Qianguo area where the focal mechanism is shear slip.

The FSZF can be roughly divided into four subsections, each of them has obvious differences in geometry, seismic activity and latest activity age. The Fuyu-Zhaodong is an early Middle Pleistocene fault with relative weak seismic activity. The Fuyubei subsection fault has high seismic activity, and it is the most frequent earthquake activities fault except Chaganhua subsection fault. It is also the most affected fault during the structure inversion, the geometry of the fault has been changed. The structure inversion led to the change of its activity. Another late Pleistocene fault in the region is Gudian subsection fault. Although there is no record of the moderate earthquake, some studies suggest that it has the strongest earthquake generating ability (Shao et al., 2015; Shi et al., 2012; Wang et al., 2016). It is considered that the structure inversion affects the activity of the faults. The Chaganhua subsection fault is also Middle Pleistocene fault, but it has the most intense seismic activity. Although the exact cause of such intense seismic activity is still unknown, fluid-induced high seismicity maybe the reasonable interpretation of this phenomenon.

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