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Lithospheric rheology and Moho upheaval control the generation mechanism of the intraplate earthquakes in the North China Basin

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ABSTRACT

Many devastating intraplate earthquakes, such as the 1966 Xingtai earthquake (Ms 7.2) and the 1976 Tangshan earthquake (Ms 7.8), occurred in the North China Basin (NCB). This study aims to investigate the generation mechanism of the large intraplate earthquakes in the NCB and the spatial distribution of earthquake activity through numerical experiments. In order to simulate the interseismic stress accumulation process in the NCB, we set up several 3D finite element models based on different lithospheric rheological structure and apply boundary conditions of horizontal compression. We find that stress concentration with high rate in the regions where Moho upheaves is responsible for the large earthquakes in the NCB. During the interseismic period large stress rate is located nearly around the bottom of the brittle upper crust, where stress accumulates fast to reach fault strength and active the main shocks. Aftershocks in the seismogenic layers could be triggered by the main shocks. Two factors are critical to the crustal stress accumulation process. (1) The first is Moho upheaval in the seismic zones. (2) The second is viscosity contrast among the crustal layers. Our results support the lithospheric rheological structure in the NCB as following: the brittle upper crust, brittle–ductile transition in the middle crust, the ductile lower crust, and the ductile lithospheric upper mantle.

1. Introduction

The North China Basin is a very seismically active region where devastating intraplate earthquakes frequently occurred, although it is far away from the collision zone between the western Pacific plate and the eastern Asian continent. Gu (1983) suggested that more than 100 earthquakes with M > 5.0 have been recorded in this region during the last 1000 years, in which 35 events are larger than M 6.0 and 7 events are larger than M 7.0. In 1679, an earthquake of M 8.0 occurred in the Sanhe county of Beijing (Fig. 1), which is the largest one among the known historical earthquakes in this region. During a single decade from 1966 to 1976, a series of destructive earthquakes (Fig. 1) occurred in the NCB, such as the 1966 Xingtai earthquake (Ms 7.2), the 1967 Hejian earthquake (Ms 6.3), the 1969 Bohai earthquake (Ms 7.4), and the 1976 Tangshan earthquake (Ms 7.8) which totally destroyed the Tangshan city (then population 1 million) and claimed about 240,000 people.

Seismological investigations reveal that occurrence of the large earthquakes in the NCB is related to Moho undulation. The large earthquakes usually occurred in the regions where Moho upheaves, such as the 1966 Xingtai earthquake (Ms 7.2), the 1967 Hejian earthquake (Ms 6.3), and the 1976 Tangshan earthquake (Ms 7.8) (Fig. 2) (Zeng et al., 1985; Shao et al., 1986, 1993; Lin et al., 1990; Liu et al., 2007; Wang et al., 2008). It is also noted that the main shocks usually occurred nearly around the bottom of the upper crust (depth ranging from 9 to 15 km) (Ye and Zhang, 1980; Zeng et al., 1985, 1991; Zang and Yang, 1984; Shedlock et al., 1987; Nabelek and Chen, 1987; Mao et al., 1996), and aftershocks distributed in the upper crust and the upper part of the middle crust (depth ranging from 5 to 25 km) (Ye and Zhang, 1980; Zeng et al., 1985; Zang and Yang, 1984; Nabelek and Chen, 1987; Shedlock et al., 1987; Mao et al., 1996; Li et al., 2007; Zhang et al., 2011; Lei et al., 2011; Yu et al., 2010; Cai et al., 2014).

In the NCB there are several large cities such as Beijing, Tianjin, Tangshan, and Shijiazhuang, in addition to numerous towns and villages (Fig. 1). The Chinese capital, Beijing, is located in this very seismically active region. A detailed investigation of the causes of the large intraplate earthquakes in this region is quite important

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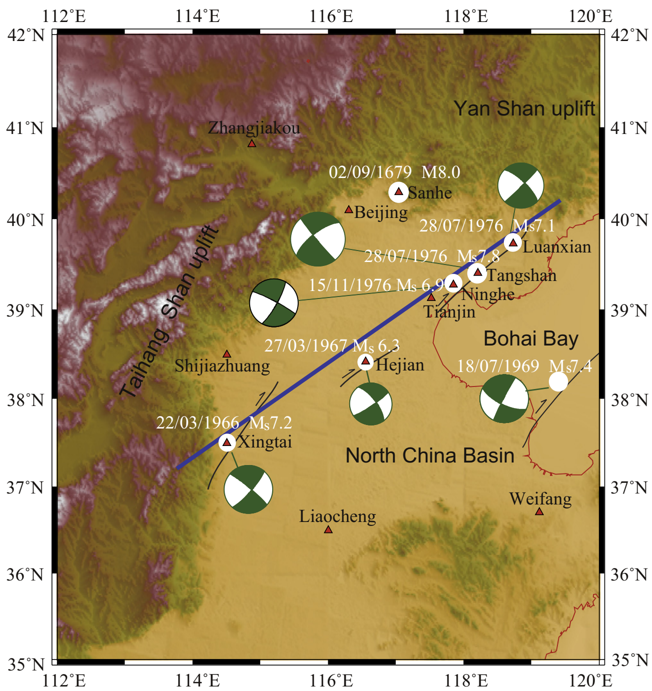

Fig. 1. Geological map of the NCB. Red triangles indicate the locations of the cities with name marked. White dots indicate the epicenters of the main shocks. Blue line indicates the profile across several seismic zones. Gray lines indicate the active faults associated with the earthquakes. Red lines indicate the coast. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

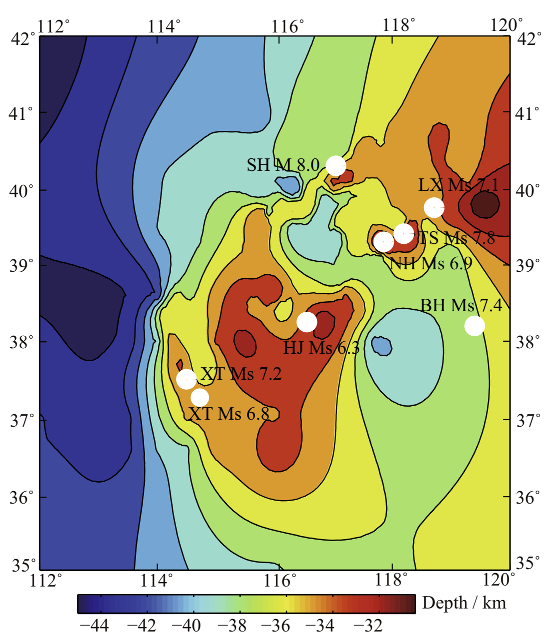

Fig. 2. Depth distribution of Moho discontinuity in the NCB. White dots indicate the epicenters of the main shocks. TS indicates Tangshan. XT indicates Xingtai. SH indicates Sanhei. HJ indicates Hejian. BH indicates Bohai.

for understanding of physics of intraplate earthquakes, and for the assessment and migration of earthquake hazards in the NCB (Liu et al., 2011).

In order to explore the causes of the large intraplate earthquakes in the NCB, seismological investigations, such as deep seismic sounding and seismic tomography, have been conducted to reveal the velocity structure in the crust and uppermost mantle beneath NCB (Huang and Zhao, 2004; Qi et al., 2006; Lei et al., 2011; Wang et al., 2013; Cheng et al., 2014). Results from these studies suggest that low velocity and high conductivity anomalies exist under the source zones of the large earthquakes, which generally occurred in high velocity areas in the upper to middle crust. These low velocity and high conductivity anomalies are considered to be associated with fluids causing the weakening of the seismogenic layer in the upper and middle crust and thus contribute to the initiation of the large earthquakes. Numerical modelling studies have investigated the local tectonic stress field in different seismic zones in the NCB (Song et al., 1982, 2004; Zhen et al., 1984; Wang and Xu, 1989; Mei and Liang, 1989; Zhang and Zeng, 1995; Feng et al., 1996; Chen et al., 1999; Xiao et al., 1999; Yin and Mei, 1999; Zhu et al., 2010). The previous wisdom is that the earthquakes in the NCB is the consequent result of the horizontal compression induced by the plate collisions surrounding the Chinese continent during different stages of tectonic evolution (Chen et al., 1999; Xu et al., 1999), such as the India and the Eurasia plate collision in the Cenozoic (Yin and Harrison, 2000; Royden et al., 2008) and the Pacific plate and the eastern Asian continent collision in the Mesozoic–Cenozoic (Huang and Zhao, 2006; Zhao, 2015). However, these previous numerical studies were based on either 2D crustal models (Zhen et al., 1984; Wang and Xu, 1989; Mei and Liang, 1989; Zhu et al., 2010) with flat Moho and elastic crustal rheological structure, or simplified 3D models (Song et al., 1982; Feng et al., 1996; Yin and Mei, 1999; Xiao et al., 1999; Chen et al., 1999) excluding the realistic crustal structure and crustal rheological layering in the NCB. Yin and Mei (1999), for example, investigated the relation between the stress accumulation process and the Moho upheaval beneath the Xingtai earthquake zone with 3D numerical experiments. Their results showed that under the compressional environment stress concentrates along the slop of the undulating Moho instead of over its hump. This proposal supports an early conclusion resulting from optic–elastic analogue experiment conducted by Sun et al. (1983). However, their crustal models were assumed to be elastic in the numerical experiment by Yin and Mei (1999) and the analogue experiment by Sun et al. (1983). This preliminary assumption of elasticity is not consistent with the nowadays understanding of crustal rheological layering in the NCB. Thus, their conclusion cannot reflect the tectonic stress accumulation distribution under the compressional environment in the NCB. So far, a good description and quantification of interseismic crustal stress accumulation distribution when subjected to compression in the NCB has yet been provided. The causes of the large intraplate earthquakes in the NCB remain uncertain.

This study aims to investigate the causes of the large intraplate earthquakes in the NCB through numerical experiments. For the first time, we simulate the interseismic crustal stress accumulation distribution in the NCB with 3D finite element models based on lithospheric structure constrained by previous seismological and geological studies. We investigate the spatial distribution of earthquake activity by analyzing the crustal stress accumulation distribution in the NCB. We also examine the influence of different lithospheric rheological structure on the stress accumulation process. Compared with previous studies, our results from numerical experiments shed new light on the causes of the intraplate earthquakes in the NCB.

2. Geological background

The NCB is a large epicontinental basin (Fig. 1), where the basement of the North China craton is underneath, and is characterized by alternate uplift and depression zones (Li, 1981; Ye et al., 1985,