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Characteristics of strong earthquake preparation in main-seismic type and multi-seismic type earthquake segments in the North China tectonic region

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The North China Tectonic Zone (NCTZ) is the most seismically active area in eastern China, where a large number of strong earthquakes, especially M8 or so, had occurred. In order to study the risk of future strong earthquakes in the NCTZ, we study tectonic features of strong earthquakes and the time series features of Ms $\geq$ 5 earthquakes since the year 1484 (MT). The results show that the 14 seismic segments of faults are classified into Main-seismic types and multi-seismic types. The characteristics of the main seismic segment include: NNE dextral strike-slip faults, only one prominent around M8 main shock has occurred since the year 1484, most of the deep and large faults cutting the Moho surface below the main earthquakes with high angles, the flower structures of tectonics. The characteristics of multi-seismic type include: NWW left-lateral strike-slip faults, NEE oriented tensional faults, convergence areas of several sets of faults since the year 1484, and the magnitude of most of them was not greater than M7.0. Finally, we analyze the strong-earthquake-generating characteristics of the similar seismic segments and discuss their strong-earthquake-generating patterns based on the relationship between the rupture zone and the main compressive stress field.

KEYWORDS

North China tectonic region, seismic segment, main-seismic type, multi-seismic type, strong earthquake preparation characteristics

1 Introduction

Studying the spatial and temporal distribution patterns of strong earthquakes of magnitude (M) six or above (especially M8 or so) in North China and their relationships with the rupture tectonics have great practical significance. The North China tectonic region has five seismic belts from west to east, including the Yinchuan, Fenwei, Hebei Plain, Tanlu, and downstream of the Yangtze River to Yellow Sea seismic belts. Of these, the first four are oriented in the NNE direction. The south and north sides of this tectonic zone are also bounded by the Qingling-Dabie, Hetao, and Zhangjiakou-Bohai belts, which are oriented in the NWW direction. More than 100 strong earthquakes of M6 or higher have been documented in the North China tectonic region in recorded history; of these, seven large earthquakes of M7.8 or greater (which we refer to as "around M8" in this study) have occurred along the NNE-oriented seismic belts or segments. These include the Pingluo M8.0 event in 1739 at the Yinchuan segment; Hongtong M8.0 event in 1303, Huaxian M8.3 event in 1556, and Linfen M7.8 event in 1695 at the Fenwei belt; Sanhe-Pinggu M8.0 event in 1679 and Tangshan M7.8 event in 1978 at the Hebei Plain belt; and Tancheng M8.5 event in 1668 at the Tanlu belt (Song et al., 2011). Hence, the NNE dextral strike–slip belts play important roles in the preparation processes of strong earthquakes in North China.

The North China tectonic region is an active earthquake region in North China. The area considered in this paper is bounded by the Chifeng-Kaiyuan faults in the north, Yunwu Mountain/East Luoshan Mountain/Niushoushan Mountain/Lang Mountain front faults in the west, Xiangfan-Guangji faults in the southwest, Changhua-Putuo faults in the southeast, and E125° in the east (Deng et al., 2002; Huan et al., 2002; Zhang et al., 2003a; Zhang et al., 2003b; Song et al., 2009; Zhu et al., 2010). This region has six major seismic belts, including the Yinchuan-Hetao, Fenwei, Hebei Plain, East Qinling-Dabie, Tanlu, and downstream of the Yangtze River to Yellow Sea seismic belts.

2 Research background and methodology

2.1 Study background

The seismic activity in China is driven by the combined forces of the Indian and Pacific plates. Here, the surface crust is characterized by active ruptures of landmasses of various scales and their boundaries, which are controlled by the collisions and thrusts of the Indian plate. The deep crust is affected by the westward subduction of the Pacific plate, which provides the energy source for shallow movements (Ma et al., 1998). The North China tectonic zone is under the joint action of the Indian and Pacific plates that has resulted in a large number of strong earthquakes, especially M8 and above, making it the most seismically active region in eastern China. A study of the characteristics of strong earthquakes in the North China tectonic zone entails study of the seismicity and rupture tectonic characteristics of the seismic zone as well as their relationships with the tectonic stress field and deep tectonics.

As most of the seismic zones in the North China tectonic region extend over thousands of kilometers, the tectonic features and seismic activity characteristics are not identical, and the pattern of occurrence of strong earthquakes is not consistent. In this paper, the seismic belts in the North China tectonic region were segmented mainly on the basis of tectonic features (directions and properties of the faults, changes in the morphologies of the fault belts and their relationship with the neighboring tectonic belts) and seismicity variabilities in the temporal and spatial characteristics. The results of these segmentations are as follows (Figure 1).

The Yinchuan-Hetao seismic belt is divided into the Yinchuan and Hetao segments.

The Fenwei seismic belt is divided into the Yanqing-Daixian, Yuanping-Xiangfen, and Houma-Weihe segments.

The Hebei Plain seismic belt is divided into the Sanhe-Laishui, Tangshan-Xingtai, and Anyang-Chengwu segments.

The Tanlu seismic belt is divided into the Kaiyuan-Liaodong Bay, Bohai Sea, Weifang-Jiashan, and Jiashan-Guangji segments.

In addition, considering that the strong earthquakes in the East Qinling-Dabie seismic belt occurred mainly in the Jiashan-Guangji segment (which partially overlaps with the East Qinling-Dabie seismic belt), relative lack of information on some of the faults in the sea area downstream of the Yangtze River to Yellow Sea seismic belt, and serious lack of records on historical earthquakes, no further segmentation was carried out. We also do not segment the NWW-oriented Zhangjiakou-Bohai seismic belt in this study, mainly because of the consideration that the segmentation of this belt is often related to the intersection of the Fenwei, Hebei Plain, and Tanlu seismic belts and reflects their tectonic features and strong seismic activity characteristics.

Therefore, the seismic segments in this study mainly include a collection of the seismic tectonic assemblages in seismic zones with similar deep and shallow tectonic features as well as patterns of strong earthquakes.

Since the Late Tertiary period, the North China tectonic region has been mainly under the action of a NNE-oriented near-horizontal main compressive stress field (Li, 1980; Xu et al., 1983; Xu et al., 1989; Wang and Xu, 1985; Xie et al., 2004; Cui et al., 2005; Xu et al., 2008), and the horizontal motions of the faults in the Neotectonic stage are much larger than the vertical motions (Ding and Lu, 1983). Since the middle of the Late Pleistocene period, these have mainly manifested as strike–slip fault movements under regional shear strain conditions (Xu et al., 2019; Zhang et al., 2019). Moreover, the general characteristics of the tectonic stress field in China since the Late Tertiary period have been consistent, and the mechanical properties of the major tectonic belts in each region have been mostly stable (Deng et al., 1979). Under the action of the tectonic stress field, strong earthquakes are developed mainly in the conjugate faults consisting of the NNE-oriented dextral strike–slip faults and NWW-oriented left-lateral strike–slip faults; of these, the NNE-oriented dextral strike–slip faults are important in the preparation processes of strong earthquakes in North China (Huan et al., 1994).

With the implementation of the Urban Active Fault Detection Program, numerous deep seismic reflection profiles have been completed for the large earthquake area in the North China tectonic region since 2000, revealing a complex tectonic image of a NNE-trending strike–slip deep major fault; here, shovel-type normal faults and low-angle slip tectonics in the upper part of the Earth's crust coexist with a high-angle deep fault that cuts through the lower crust to the Moho surface beneath the source of the earthquake (Wang et al., 2017). Seven earthquakes of M8 or so in North China were mostly associated with the NNE-oriented high-angle deep major faults that cut across the Moho surface.

2.2 Research methodology

This paper is an attempt at investigating the time-series characteristics of M5 and greater earthquakes since the third active period (years 1484–1730) (Ma and Jiang, 1987) in each seismic segment based on the study of six major seismic belts in the North China tectonic region (Zhu et al., 2010). Based on similarities between the deep and shallow tectonic characteristics of these

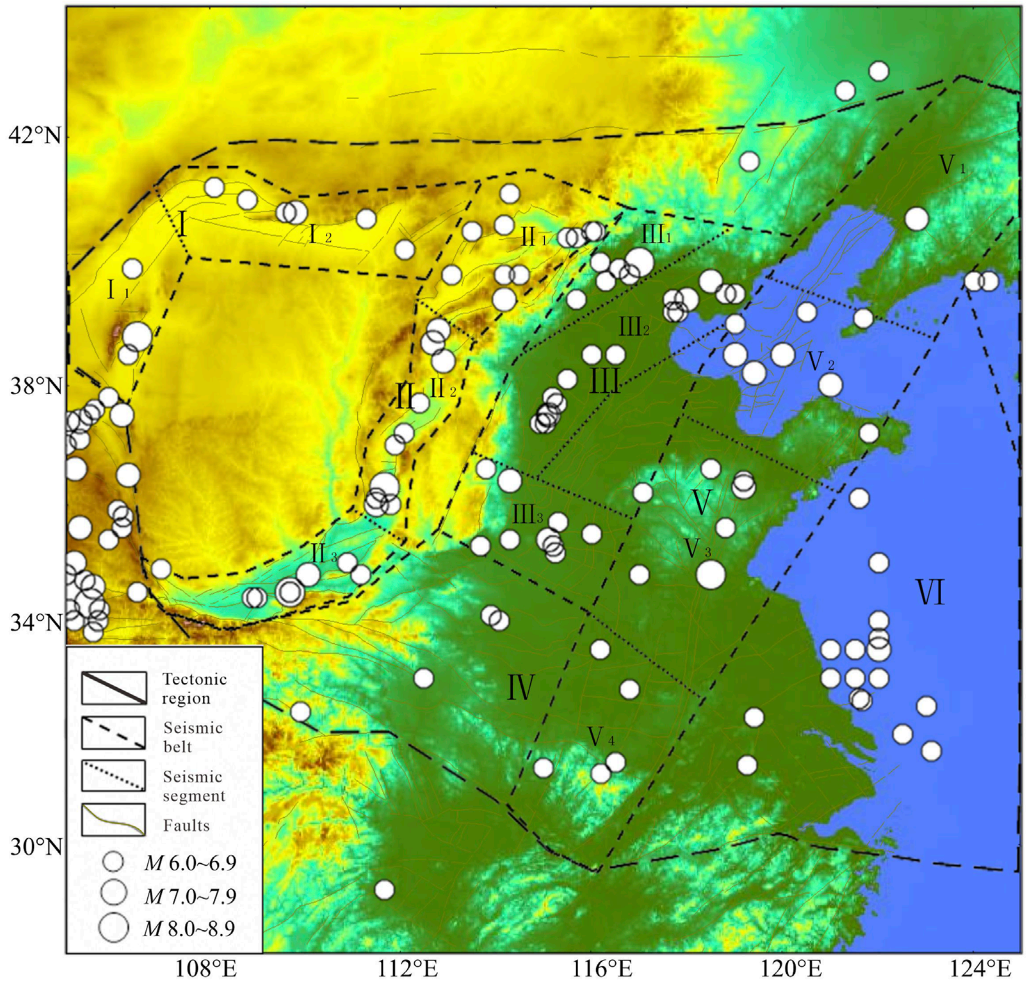

FIGURE 1
Map of the seismic belt division and main seismic belt segmentation in the North China tectonic region (modified from Zhu et al. (2010)). I. Yinchuan-Hetao seismic belt; I_1. Yinchuan segment; I_2. Hetao segment; II. Fengwei seismic belt; II_1. Yanqing-Daixian segment; II_2. Yuanping-Xiangfen segment; II_3. Houma-Weihe segment; III. Hebei Plain seismic belt; III_1. Sanhe-Laishui segment; III_2. Tangshan-Xingtai segment; III_3. Anyang-Chenwu segment; IV. East Qingling-Dabie seismic belt; V. Tanlu seismic belt; V_1. Kaiyuan-Liaodong Bay segment; V_2. Bohai segment; V_3. Weifang-Jiashan segment; V_4. Jiashan-Guangji segment; VI. Downstream of the Yangtze river to Yellow Sea seismic belt.

seismic segments and the occurrence patterns of strong earthquakes, 14 seismic segments were analyzed and categorized. By combining the relationships between the rupture zone and main compressive stress field with the deep and shallow tectonic features of the rupture zone, we analyze the strong-earthquake-generating characteristics of similar seismic segments and discuss their patterns.

The earthquake records used in this paper include catalogs of the historical strong earthquakes (Department of Earthquake Defense of the State Seismological Bureau, 1995) and modern earthquakes (Department of Earthquake Hazard Defense, China Earthquake Administration, 1999) in China as well as the catalogs of national quick reports of earthquakes compiled and edited by the China Earthquake Network Center (http://10.5.160.18) until December 2023. Huang et al. (1994) concluded that the records of earthquakes ≥ M4.7 in North China (except for the Yellow Sea and remote areas) since 1484 are basically complete and can be used to study the spatial and temporal distribution of earthquakes ≥ M5 in this region.

3 Results

Based on the division of the 14 seismic segments in the above six major seismic belts, segments with similar characteristics were categorized into the main- and multi-seismic types depending on the similarities in the deep and shallow tectonic features and strong earthquake occurrence patterns in these seismic segments (Zhu et al., 2015). In this study, the temporal characteristics of each seismic segment are investigated through the time-series curves of earthquakes ≥ M5 during the third active period (Ma and Jiang, 1987). The main-seismic-type category has experienced only one prominent event of M8 or so since 1484, while the multi-seismic-type category has experienced more than two earthquakes that do not differ much and are less than M7 in this active period. The specific features of the classification are as follows:

1. Main seismic type: This category includes the Yinchuan segment of the Yinchuan-Hetao belt, Yuanping-Xiangfen and

Houma-Weihe segments of the Fenwei belt, Sanhe-Laishui and Tangshan-Xingtai segments of the Hebei Plain belt, and Kaiyuan-Liaodong bay and Weifang-Jiashan segments of the Tanlu belt (Figure 1). The main feature of this category is that the strong earthquakes are mainly controlled by the NNE-oriented deep faults, and only one prominent main shock of around M8 has occurred since the third active period while most of the deep and large high-angle faults cutting across the Moho surface exist below most of the main shocks. There are also shallow and deep tectonic inconsistencies, such as flower structures, and the magnitudes of the earthquakes appear to increase before the main shock and decline thereafter, with the significant seismic quiescence of moderate-to-strong earthquakes. The recurrence period for earthquakes of around M8 in the North China tectonic region is approximately 2000–4000 years (Research group, 1988). Considering that an active period in North China lasts for approximately 300 years (Ma and Jiang, 1987), it is believed that at least earthquakes of around M8 since the third active period can be used as the main shocks of the entire seismic segment; hence, such events constitute the main seismic type.

2. Multi-seismic type: This category includes the Hetao segment of the Yinchuan-Hetao belt, Yanqing-Daixian segment of the Fenwei belt, Anyang-Chengwu segment of the Hebei Plain belt, Bohai and Jiashan-Guangji segments of the Tanlu belt, downstream of the Yangtze River to Yellow Sea seismic belt, and East Qinling-Dabie seismic belt (Figure 1). The main features of this category are that the strong earthquakes are controlled by the faults in other directions in addition to the NNE-oriented fault (i.e., intersection of several sets of faults) and that more than two main earthquakes with small differences in magnitude tend to occur in each active period since the third active period, where most are shallow cutting faults with a lack of high-angle deep faults. Considering that more than two main earthquakes with small differences in magnitude tend to occur in each active period in this category, this seismic segment is called the multi-seismic type.

It is worth noting that there are still some limitations to the division of the main- and multi-seismic types mentioned above. In terms of seismicity, although the history of earthquakes in North China is almost completely available since the year 1484 (Huang et al., 1994), there are uncertainties in the magnitudes and epicenter locations of historical earthquakes (e.g., the Huaxian Earthquake of 1556); furthermore, records of historical earthquakes in remote areas are missing (e.g., the Hetao segment). In terms of tectonic features, there are fewer deep seismic reflection sections in North China that can portray the deep fractures in greater detail; these are also mainly concentrated in the historical large-earthquake areas, which makes it difficult to construct a complete picture of the fracture zones, especially given the lack of mutual validation with other precise technical means. Therefore, the delineation between the main- and multi-seismic types is more of a qualitative analysis and cannot be analyzed quantitatively.

4 Discussion

4.1 Tectonic and seismic activity characteristics of the main seismic type

The main seismic type is mainly controlled by the NNE-oriented dextral strike–slip faults, and the strong earthquakes are mainly distributed in the NNE-oriented band. For example, the strong earthquakes at the Yinchuan, Yuanping-Xiangfen, Sanhe-Laishui, Tangshan-Xingtai, and Weifang-Jiashan segments were distributed along the NNE-oriented faults and were mainly controlled by these faults. Statistics on the previous earthquakes show that about 58.3% of those ≧ M6 and 100% of those ≧ M7.8 in North China occurred along the NNE-oriented dextral strike–slip faults (Huan et al., 2002).

In the main seismic type, the main shocks are M8 or so; below the main shock, there are mostly deep and large high-angle fractures cutting across the Moho surface. The deep and shallow tectonics are often flower-like structures, meaning that there are tensile shovel-like tectonics (flower branches) in the shallow part and near-erect strike–slip faults (flower trunks) in the deep part. These deep and shallow tectonic features are mainly based on the Pingluo seismic area of the Yinchuan segment (Fang et al., 2009; Zhao et al., 2009; Feng et al., 2011), Linfen seismic area of the Yuanping-Xiangfen segment (Li et al., 2014; Chen et al., 1995), Sanhe-Pinggu seismic area of the Sanhe-Laishui segment (Zhang et al., 2002; Liu et al., 2009, 2011a; Zhao et al., 2013), Tangshan seismic area of the Tangshan-Xingtai segment (Liu et al., 2011b; Xu et al., 2012), Tancheng seismic area of the Weifang-Jiashan segment (Liu et al., 2015; Zhang and Tang, 1988), and other large-earthquake areas with deep seismic reflection profiles.

The NNE-oriented faults of the main seismic type mostly intersect with the NEE–SWW principal compressive stress field at a large angle, which is an important seismogenic condition for the near-M8 earthquakes in North China. The larger the angle, the larger is the positive stress on the fault surface and the greater is the tendency toward strong fault locking, which leads to continuous accumulation of energy and preparation of near-M8 earthquakes (Figure 2A). Xu et al. (2002) also concluded that a small angle between the fracture strike and principal compressive stress along the maximum axis leads to easy sliding, while a larger angle leads to difficult sliding and easy accumulation of elastic strain energy.

The main seismic type is not strongly affected by the neighboring tectonic belt to deflect the orientation of the fault. For example, the Yuanping-Xiangfen and Weifang-Jiashan segments are mostly oriented NNE and are not connected with the northern Yinshan-Yanshan and southern Qinling-Dabie tectonic belts; hence, they are not affected by them to deflect the fault orientation and intersect with the principal compressive stress field at a large angle. The Yinchuan, Sanhe-Laishui, and Tangshan-Xingtai segments are connected with the Yinshan-Yanshan tectonic belt in the north, but the fractures still have a mainly NNE direction. The fracture orientations have not deflected significantly and still intersect with the principal compressive stress field at large angles.

Only one earthquake of around M8 of the main seismic type has occurred since the beginning of the historical record (mainly

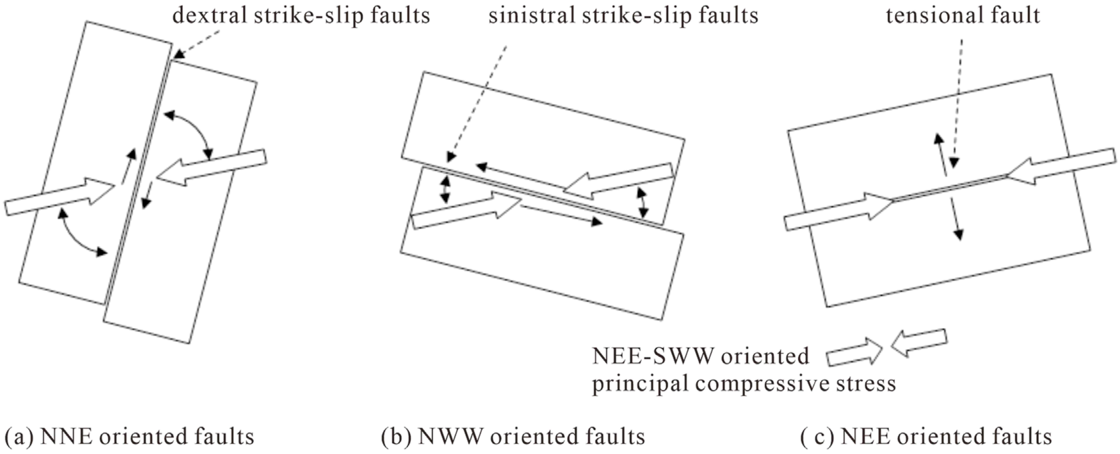

FIGURE 2
Movement mechanisms of the NNE-, NWW-, and NEE-oriented faults under the action of the main compressive stress field in the NEE–SWW direction in the North China tectonic region.

TABLE 1 Relevant seismic statistics since the beginning of the third active period for the main seismic type in the North China tectonic region.

Number	Earthquake segment name	M ≧ 6	M ≧ 7	Main shock	Second strongest earthquakes (excluding aftershocks)	Time interval	Difference in magnitude
1	Yinchuan	2 times	1 time	January 1739, Pingluo M8.0	September 1976, Alashan Left Banner M6.2	237.8 years	1.8
2	Yuanping-Xiangfen	4 times	2 times	May 1695, Linfen M7.8	November 1683, Yuanping M7.0	11.5 years	0.8
3	Houma-Weihe	7 times	2 times	February 1556, Huaxian M8.3	January 1501, Chaoyi M7.0	55.1 years	1.3
4	Sanhe-Laishui	5 times	1 time	September 1679, Shanhe M8.0	April 1665, Tongxian M6.5; September 1730, Summer Palace M6.5	14.4 years 49.0 years	1.5 1.5
5	Tangshan-Xingtai	16 times	3 times	July 1976, Tangshan M7.8	March 1966, Xingtai M7.2	10.4 years	0.6
6	Kaiyuan-Liaodong Bay	1 time	1 time	February 1975, Haicheng M7.3	August 1940, Liaodong Bay M5.8	34.5 years	1.5
7	Weifang-Jiasan	5 times	1 time	July 1668 Tancheng M8.5	November 1829, Qingzhou M6.3	161.4 years	2.2

the third active period) with a large difference in magnitude (≥ 0.6 and mostly 1.3–2.2) from the second strongest earthquake in the segment (Table 1; Figure 3A). With the exception of the Hongtong M8.0 earthquake in 1303 in the Yuanping-Xiangfen segment, the largest earthquakes in the other main seismic types since the third active period are also the largest earthquakes ever recorded in this segment since the beginning of the third active period.

The seismicity values of the main seismic type before and after the near-M8 earthquake generally have increasing and declining magnitudes, and the decades before and after the main earthquake may show significant seismic quiescence of moderate-to-strong earthquakes (Table 2; Figure 3A; relative quiescence refers to the occurrence of only individual M5.0–M5.1 earthquakes). For example, in the main seismic type of the Weifang-Jiashan and Yinchuan segments, there is more fault locking and more energy accumulation because the normal stress on the fault surface is much larger than the shear stress before the main seismic type; hence, it is difficult to have a pre-slip with the tendency for long-term seismic

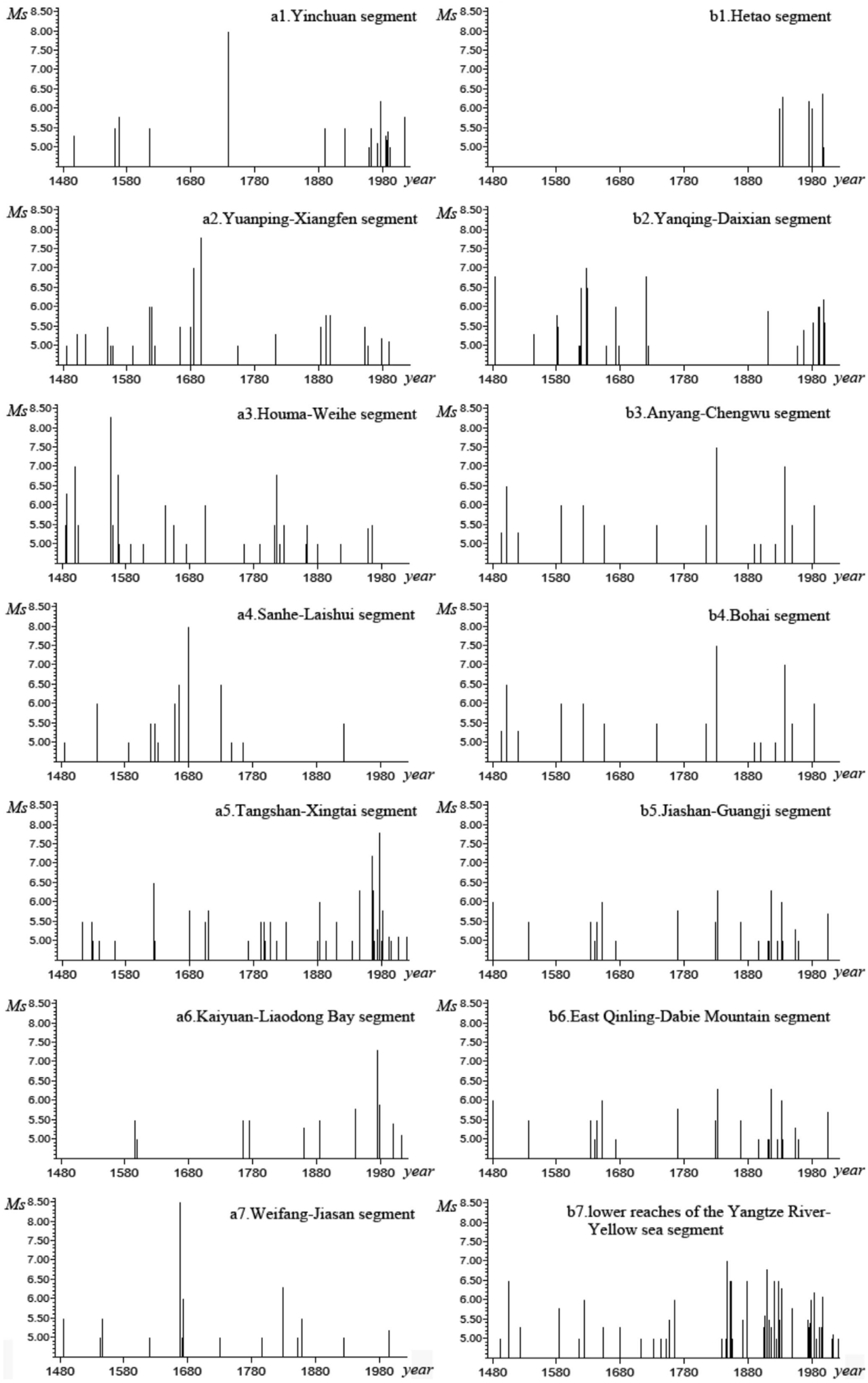

FIGURE 3
Seismic timing curves for events ≥ M5 since the third active period under the (a1–a7) main- and (b1–b7) multi-seismic types in the North China tectonic region.

quiescence. Complete energy release of the main shock may lead to long-term seismic quiescence thereafter. The increase and decrease of the magnitude before and after the main shock of the main seismic type as well as the significant seismic quiescence actually reflect the process of energy accumulation and release of the near-M8 earthquake in a deeply locked seismic segment.

TABLE 2 Seismic activities in the North China tectonic region before and after the main earthquake of the main seismic type.

Number	Earthquake segment name	M ≧ 5 seismicity before the main earthquake	Main shock	M ≧ 5 seismicity after the main shock
1	Yinchuan	The magnitude of the earthquake generally increased, and the region was calm for 124 years before the earthquake	1739, Pingluo M8.0	Overall decrease in magnitude and 149 years of calm after the earthquake
2	Yuanping-Xiangfen	The magnitude increased slowly, and there was no significant calm before the earthquake	1695, Linfen M7.8	Overall decrease in magnitude, with 59 years of calm after the earthquake and 118 years of relative calm after the earthquake
3	Houma-Weihe	The magnitude of the earthquake generally increased, and the region was quiet for 50 years before the earthquake	1556, Huaxian M8.3	Overall decrease in magnitude, with active aftershocks for 13 years after the earthquake and relative calm for the next 56 years
4	Sanhe-Laishui	General increase in magnitude without significant pre-earthquake calm	1679, Sanhe M8.0	Overall decrease in magnitude and 49 years of calm after the earthquake
5	Tangshan - Xingtai	General increase in magnitude without significant pre-earthquake calm	1976, Tangshan M7.8	Rapid decline in magnitude, with active aftershocks for 5.3 years after the earthquake and relative calm thereafter
6	Kaiyuan - Liaodong Bay	The magnitude of the earthquake generally increased, and the region was calm for 35 years before the earthquake	1975, Haicheng M7.3	Overall decrease in magnitude, with active aftershocks for 3 years after the earthquake and quiet for the next 21 years
7	Weifang-Jiasan	No significant increase in magnitude, with 26 years of calm before the earthquake and 122 years of relative calm before the earthquake	1668, Tancheng M8.5	Overall decrease in magnitude, with active aftershocks for 4 years after the earthquake and relative calm for the next 154 years

In summary, the features of the main seismic type are as follows. 1) Strong earthquakes are mainly controlled by the NNE-oriented dextral strike–slip faults and are distributed in a NNE-oriented belt pattern. 2) The seismogenic faults are NNE-oriented strike–slip faults that intersect with the NEE–SWW principal compressive stress field at large angles and are not strongly influenced by the adjacent tectonic belts to cause orientation deflections of the faults. 3) There are high-angle deep faults cutting across the Moho surface under most M8 earthquakes, where the upper crust exhibits tensional shovel-like faults or detachment structures while the middle and lower crust exhibit compressive shear faults with inconsistent deep and shallow tectonics of mostly flower-type structures. 4) There is always one earthquake of around M8 since the beginning of the third active period and a large difference in magnitude between the main shock and second strongest earthquake; furthermore, there is magnitude increase before and decrease after the main shock as well as a long seismic quiescence of moderate-to-strong earthquakes.

4.2 Tectonic and seismic activity characteristics of the multi-seismic type

The tectonic features of the multi-seismic type are complex, where the strong earthquakes are mainly controlled by NWW-oriented left-lateral strike–slip faults, NEE-oriented tensional faults, and part of the NE-oriented dextral strike–slip faults or fault crossing areas of multiple sets of faults. With the exception of some seismic segments where strong earthquakes are distributed in EW-oriented (e.g., the Hetao segment) or NWW-oriented (e.g., the Anyang-Chengwu segment) bands, the other seismic segments do not have clearly distributed bands because they are controlled by fault belts in multiple directions or scarce strong earthquakes (Xu et al., 1992; Research Group, 1988; Zhu et al., 2010; Xu et al., 2017). According to statistics from previous records, about 9.5% of the earthquakes ≧ M6 in North China occurred along the NWW-oriented strike–slip faults while about 23.8% occurred along the NEE-oriented normal faults (Huan et al., 1994).

In the multi-seismic type, the NEE-oriented tensional faults show shallow cuts, and there may be deep faults beneath some of the NWW-oriented and NE-oriented strike–slip faults. For example, there are deep large faults truncating the Moho surface below the NWW-oriented Yinshan-Yanshan tectonic belt on the north side and Qinling-Dabie tectonic belt on the south side of the North China block (Wang et al., 1997; Zhang et al., 2019; Feng et al., 2015; Yan et al., 2020; Feng et al., 2020); they are not nearly as upright as the NNE-oriented deep faults, and their origins may be related to block collisions and thrust nappe structures. Moreover, both the NWW and NE strike–slip faults intersect the NEE–SWW principal compressive stress field at small angles and are very different from the seismogenic characteristics of the NNE-oriented high-angle dextral strike–slip deep faults.

The fault strikes in the multi-seismic type are complex, but irrespective of the NWW-oriented left-lateral strike–slip faults, NEE-oriented tensile faults, or even part of the NE-oriented dextral strike–slip faults, the strike angles of these faults with the NEE–SWW principal compressive stress field tend to be smaller (Figure 2B) or even roughly similar (Figure 2C). The faults may slide easily and are not conducive to the accumulation of seismic energy; hence, no earthquakes of around M8 have occurred since the beginning of the historical record.

The multi-seismic type segments are greatly affected by their neighboring tectonic belts, because of which some segments may even experience fault orientation deflections. Deflections have usually been known to occur on both ends of the Fenwei, Tanlu, and other S-shaped seismic belts, such as the Yanqing-Daixian segment; the northern end of the Fenwei seismic belt may have been affected by the Yinshan tectonic belt, so the original northern ends of the NNE-oriented faults may have deflected to the east into the NE–NEE-oriented faults to become the northern segment of the S-shaped Fenwei seismic belt. The southern end of the Tanlu seismic belt in the Jiashan-Guangji segment may have been affected by the East Qinling-Dabie tectonic belt, such that the original southern ends of the NNE-oriented faults may have deflected to the west into the NE-oriented faults to become the southern segment of the S-shaped Tanlu seismic belt. The S-shaped tectonics may also precede the Neotectonic stage. The dextral strike–slip and drag of the NWW-oriented faults on the northern and southern sides of the North China tectonic region may have led to fracture orientation deflections at the ends of the previously NNE-oriented faults in the tectonic zone.

For the multi-seismic type segments, more than two main earthquakes with small differences in magnitude (≤0.5 and mostly ≤0.2) have occurred since the beginning of recorded history in each active period, with most of the events being ≤ M7.0 with intervals of approximately 50–170 years between the main earthquakes (Table 3; Figure 3B). With the exception of the Hetao segment, where an M7.0 earthquake occurred northwest of Baotou in October 849, the largest earthquakes in the other multi-seismic types since the third active period are the largest events ever recorded throughout history in this segment; of these, only three earthquakes with main seismic magnitudes >7.0 were recorded in this segment, namely Bohai M7.5 in 1888 and Bohai M7.4 in 1969 in the Bohai segment as well as Cixian M7.5 in 1830 in the Anyang-Chengwu segment. The Bohai segment also has the seismogenic characteristics of the main seismic type category because it is difficult to produce M8 earthquakes in this segment owing to the intersection of multiple sets of faults. The time sequences of the strong earthquakes in the multi-seismic type actually reflect the process of energy release while accumulating around the M6 earthquakes in poorly locked seismic segments.

The multi-seismic type is characterized by an undulating or continuous decline in strong seismic activity during each active period (Table 3; Figure 3B) and can be further classified into three subtypes as follows. 1) The Yanqing-Daixian subtype is mainly characterized by the occurrence of one main shock with a magnitude difference of ≤0.2 in the early, middle, and late parts of each active period, including the Yanqing-Daixian, Jiasan-Guangji, and Hetao segments as well as the East Qinling-Dabie seismic belt. 2) The Bohai subtype is mainly characterized by the occurrence of two or more main earthquakes with magnitude differences of ≤0.1 in each active period, with relative quiet in the early and late stages and activity in the middle stage. 3) The Anyang-Chengwu subtype is mainly characterized by the occurrence of the largest earthquake in the early stage of each active period and gradual decreases in magnitude thereafter; the largest earthquake in each cluster decreases sequentially by about M0.5 at certain time intervals (approximately 60–140 years), and the downstream of the Yangtze River to Yellow Sea seismic belt has similar characteristics.

In summary, the main features of the multi-seismic type are as follows. 1) The strong earthquakes are mainly controlled by the NNW-oriented left-lateral strike–slip faults, NEE-oriented tensile faults, and part of the NE-oriented dextral strike–slip faults or the fault crossing area of multiple sets of faults, where the banded distribution of strong earthquakes is not significant or even non-existent. 2) The seismogenic faults include the NNW-oriented strike–slip faults, NNE-oriented tensile faults, and NE-oriented strike–slip faults influenced by the adjacent tectonic belts that cause fault orientation deflections; these faults intersect with the principal compression stress field at small angles. 3) Most of the faults are shallow such that there is a lack of high-angle deep faults. 4) More than two main earthquakes with small differences in magnitude tend to occur in each active period, and the strong seismic activity is characterized by undulations or a continuous decline from the early to middle to late stages.

4.3 Uncertainty analysis for division into the main- and multi-seismic types

With the exception of the Yuanping-Xiangfen segment of the main seismic type and Hetao segment of the multi-seismic type in North China, the largest earthquakes in each of the seismic segments since the third active period have also been the largest events in history, and the temporal sequence of the medium-to-strong earthquakes since 1484 reflects the activity patterns of strong earthquakes in North China to a certain extent.

However, there are still uncertainties in the division of the main- and multi-seismic types. For example, three earthquakes around M8 have been recorded in the Fenwei seismic belt (i.e., Hongtong M8 in 1303, Huaxian M8.3 in 1556, and Linfen M7.8 in 1695), among which the Houma-Weihe segment in which the Huaxian M8.3 occurred is the only main seismic type under the control of the NEE-oriented faults in North China. The Yuanping-Xiangfen segment is one of the main seismic types controlled by the NNE-oriented faults; although this is a main-seismic type segment dominated by the Linfen M7.8 earthquake in 1696 during the third active period, the Hongtong M8.0 earthquake was also recorded to have occurred in this segment in 1303. The above two segments both have atypicality and uncertainty. If the Huaxian M8.3 earthquake of 1556 occurred along the NNE-oriented dextral strike–slip faults along the Yellow River (Huan et al., 2003; Feng et al., 2012), the three M8 earthquakes noted above could actually form a seismic segment controlled by these faults, with the Huaxian M8.3 earthquake as the main shock. This segment has the characteristics of the main seismic type (significant rise and fall in the magnitude before and after the main shock) as well as the multi-seismic type (smaller magnitude

TABLE 3 Relevant seismic statistics since the beginning of the third active period for the multi-seismic type in the North China tectonic region.

Serial number	Earthquake segment name	M ≧ 6	M ≧ 7	Third active period			Fourth active period		
				Main shock	△t/a	△M	Main shock	△t/a	△M
1	Hetao	5	0	None	None	None	None (early) Wuyuan M6.3 in 1934 (middle) Baotou M6.4 in 1996 (late)	None 62	None 0.1
2	Yanqing-Daixian	7	1	Yanqing M6.8 in 1484 (early) Lingqiu M7.0 in 1626 (middle) Huailai M6.8 in 1720 (late)	142 94	0.2 0.2	None (early) Daixian M5.8 in 1898 (middle) Zhangbei M6.2 in 1998 (late)	None 100	None 0.4
3	Anyang-Chengwu	7	2	Pucheng M6.5 in 1502 (early) Yuncheng M6.0 in 1622 (middle) Fengqiu M5.5 in 1737 (late)	120 115	0.5 0.5	Cixian M7.5 in 1830 (early) Heze M7.0 in 1937 (middle) None(晚)	107 None	0.5 None
4	Bohai	8	4	Bohai M7.0 in 1548 (middle); Bohai M7.0 in 1597 (middle)	49	0.0	Bohai M7.5 in 1888 (middle); Bohai M7.4 in 1969 (middle)	81	0.1
5	Jiashan-Guangji	5	0	Guoyang M6.0 in 1481 (early) Huoshan M6.0 in 1652 (middle) None (late)	171 None	0.0 None	Fengtai M6.3 in 1831 (middle) Huoshan M6.3 in 1917 (middle) Jiujiang M5.7 in 2005 (late)	86 89	0.0 0.6
6	Lower reaches of the Yangtze River –Yellow sea	19	1	Yellow sea M6.5 in 1505 (early) Yangzhou M6.0 in 1624 (middle) Yellow sea M6.0 in 1764 (late)	20 140	0.5 0.0	Yellow sea M7.0 in 1846 (early) Yellow sea M6.8 in 1910 (middle) Yellow sea M6.2 in 1984 (late)	64 74	0.2 0.6
7	East Qinling-Dabie Mountain	7	0	Guoyang M6.0 in 1481 (early) Huoshan M6.0 in 1652 (middle); None (late)	171 None	0.0 None	Fengtai M6.3 in 1831 (early) Huoshan M6.3 in 1917 (middle); Jiujiang M5.7 in 2005 (late)	86 89	0.0 0.6

Note: Δt/a refers to the time interval (years) between the main-seismic-type events; ΔM is the magnitude difference between the main-seismic-type events.

of deviation). The other earthquakes in the Houma-Weihe segment may also belong to the multi-seismic type controlled by the NEE-oriented faults. Because the principal compressive stresses along the maximum axis in the Hejin and Weihe partition in the southeast of Ordos (Wang and Xu, 1985) or the southern segment of the Fenwei graben (Xu et al., 1989) are upright and mainly show tensional characteristics, it is reasonable to regard this region as a multi-seismic type segment.

Recently, He et al. (2024) found that there may be a deep, high-angle, and NNE-trending large fracture that cuts across the Moho surface along the Yellow River between the Weihe Basin and shallow depression at the southern margin of the Zhongtiao Mountains with a near-EW-trending deep seismic reflection profile. We believe that this deep major fault may be the origin of the M8.3 Huaxian earthquake. Considering that the other main seismic types with M8 or so often overlay the NNE-trending high-angle deep fractures, deeper seismic reflection profiles that can finely delineate the deep fractures would be the main technical means by which we can accurately classify the main- and multi-seismic types. Considering that the current mainstream opinion is that the Huaxian M8.3 earthquake occurred along the NEE-oriented Huashan Mountain front fault (Research Group, 1988), we do not intend to change the original segmentation scheme until more detailed data are available.

Although there are uncertainties in the categorization of the main- and multi-seismic types in the North China tectonic region, these two categories essentially reflect the different seismogenic abilities of tectonic belts with different orientations and structures. The main seismic type usually produces earthquakes of around M8 with long recurrence periods spanning different active periods, whereas the multi-seismic type can only produce earthquakes with short recurrence periods along with several possible earthquakes around M6 during an active period.

The main- and multi-seismic types are relative in terms of their time series. The main seismic type may also exhibit multi-seismic characteristics over a longer period of time, such as thousands of years before and after an earthquake of around M8, reflecting the process of energy accumulation and release of such earthquakes; conversely, the multi-seismic type may also exhibit main-seismic characteristics over a shorter period of time, such as decades before and after an earthquake of around M6, reflecting the process of energy accumulation and release of such earthquakes.

4.4 Seismogenic comparison of strong earthquakes of the main- and multi-seismic types

Considering the six seismic belts and 14 seismic segments in the North China tectonic region, it is noted that there are certain differences in the seismic tectonic features and strong seismic activity characteristics of different segments of the same seismic belt. For example, the Yinchuan segment of the Yinchuan-Hetao seismic belt is of main seismic type while the Hetao segment of this belt of multi-seismic type. The Yuanping-Xiangfen and Houma-Weihe segments of the Fenwei seismic belt are of main seismic types while the Yanqing-Daixian segment of this belt is of multi-seismic type. The Sanhe-Laishui and Tangshan-Xingtai segments of the Hebei Plain seismic belt are of main seismic types while the Anyang-Chengwu segment is of multi-seismic type. The Weifang-Jiashan and Kaiyuan-Liaodong Bay segments of the Tanlu seismic belt are of main seismic types while the Bohai and Jiashan-Guangji segments are of multi-seismic types. These examples show that the seismogenic tectonics and environments in different parts of the same seismic belt may differ along with the seismogenic patterns of strong earthquakes.

The seismogenic characteristics of the main seismic type are as follows. The NEE–SWW principal compressive stress field continues to act at large angles on the NNE-oriented high-angle deep faults, while the normal stresses on the planes of the NNE-oriented faults are much larger than the shear stresses. This is favorable to the strong locking and energy aggregation at the fault but unfavorable to fault sliding and energy release; based on the profile, there are many flower tectonic structures along the NNE-oriented faults. The areas where the upper crustal shovel-like structures, slip structures, and the middle and lower crustal high-angle deep faults converge but have not yet intersected are more prone to strong blocking and energy aggregation (Figure 4A). On the one hand, high-angle deep faults with flower structures are often developed beneath the NNE-oriented faults in the North China tectonic region, and most of these are sub-block boundary belts that provide seismogenic zones for strong earthquakes. On the other hand, the large angles of the intersects of the NNE-oriented faults with the NNE–SWW principal compressive stress field cause strong blocking near the obstacles in the NNE faults (such as areas where the shallow and deep tectonic faults converge but have not yet intersected). These lead to the occurrence of a large earthquake after a lengthy period. Because of the long recurrence period between main shocks, it is noted that the main seismic characteristics at least since the third active period (i.e., rise and fall of magnitude before and after the main shock) and larger magnitudes of the main shock result in stronger preseismic locking and more complete energy release during the earthquake; these can manifest as seismic quiescence of moderate-to-strong earthquakes decades or even centuries before and after the main shocks.

The seismogenic characteristics of the multi-seismic type are as follows. Under the continuous action of the NEE–SWW principal compressive stress field, the NWW-oriented left-lateral strike–slip faults may intersect with the principal compressive stress field at small angles on the plane, and some of the NE-oriented dextral strike–slip faults may be influenced by the adjacent tectonic belts and deflected to intersect at smaller angles with the principal compressive stress field. There may also be influences of the intersection of the NWW-oriented faults such that the shear stresses on the fault surfaces exceed the normal stresses or some of the NEE-oriented tensile faults may be aligned in the same direction as the principal compressive stress field, which are unfavorable to the strong locking of faults and preparation of larger earthquakes. With the exception of some of the large NWW-oriented left-lateral and NE-oriented dextral strike–slip faults under which there may be large deep faults, most of the other faults are shallow and lack high-angle large deep characteristics. It is difficult to aggregate sufficient energy to generate larger earthquakes (Figure 3) owing to the small angles of intersection with the principal compressive stress field or intersection of multiple sets of faults (Figure 4B). On the one hand, there are no high-angle deep faults beneath most of the faults, so there are insufficient sites for large earthquakes; on the other hand, the faults tend to intersect with the principal compressive stress field at small angles (or even in the same direction), which makes it easier for medium-to-strong earthquakes to occur compared with the main seismic type as it is difficult to generate strong earthquakes around M8. Owing to the short recurrence period of the main shock, many main shocks with small differences in magnitude

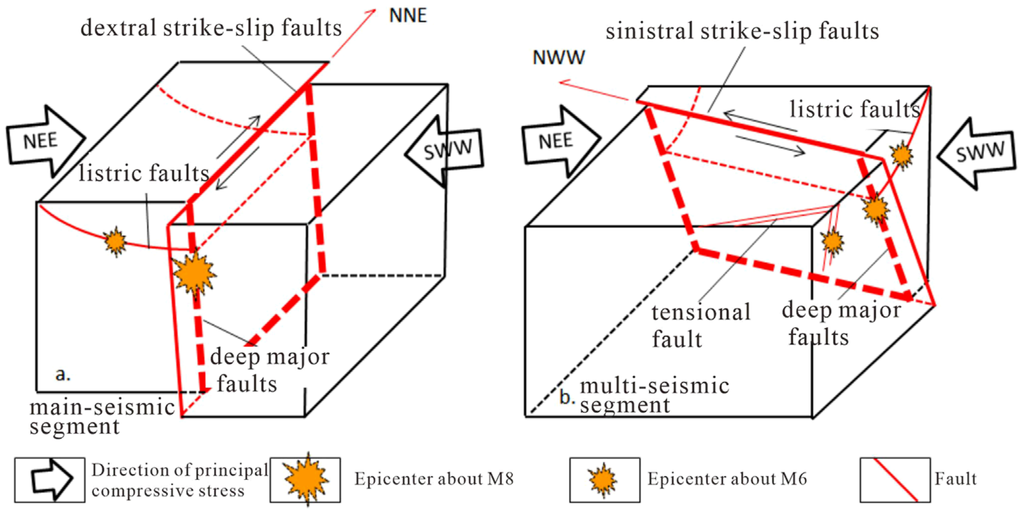

FIGURE 4
Characteristics of strong earthquake generation of the **(A)** main- and **(B)** multi-seismic types in the North China tectonic region.

often occur within a single active period, presenting multi-seismic characteristics.

Therefore, in the North China tectonic region, under the action of the NEE–SWW and near-horizontal principal compressive stress field with the NNE-oriented dextral deep faults supplemented by the NWW-oriented left-lateral and NEE-oriented tensile faults, the tectonic deformation mechanisms of fault belts with different strikes may differ; furthermore, the deformation mechanisms of the different segments of the same strike fault belt may vary owing to differences in the fault structures and properties, so strong earthquakes may also have different preparation patterns. The NNE-oriented high-angle deep faults that intersect the uniform principal compressive stress field at large angles and have tectonic inconsistencies in the deep and shallow parts (such as flower structures) are prone to strong locking that can generate large earthquakes (main-seismic characteristic), which make them the ideal preparation environment for earthquakes of around M8 in North China. The other faults that intersect at small angles may cause moderate-to-strong earthquakes, which makes it difficult to cause large earthquakes (multi-seismic characteristic).

5 Conclusion

Based on similarities in the tectonic features and seismic activity characteristics, we classified 14 seismic segments in six major seismic belts in the North China tectonic region into the main- and multi-seismic types. By analyzing the seismogenic characteristics of strong earthquakes under these two categories, we deduced the following main findings and conclusions.

(1) Most faults in the main seismic type are NNE-oriented dextral strike–slip faults that are not influenced much by adjacent tectonic belts, and these faults often intersect with the principal compressive stress field at large angles. Only one prominent main shock around M8 has occurred since the third active period, with rise and fall of the magnitude before and after the main shock or a lengthy period of seismic quiescence of moderate-to-strong earthquakes. Deep and large high-angle faults cutting across the Moho surface exist below most of the main shocks along with deep and shallow tectonic inconsistencies, such as flower structures.

(2) The faults in the multi-seismic type are mainly NWW-oriented left-lateral strike–slip faults, NEE-oriented tensile faults, and a part of the NE-oriented dextral strike–slip faults or the convergence areas of several sets of faults that are greatly influenced by the adjacent tectonic belts and tend to intersect with the principal compressive stress field at small angles. More than two main earthquakes with small differences in magnitude were found to have occurred in each active period since the beginning of recorded history, with most of the events being ≤ M7.0, and the strong seismic activities in each active period showed undulating or continuous declines from the early to middle to late stages. Most of these faults were shallow and lacked high-angle deep characteristics.

(3) In the North China tectonic region, the activities of the NEE–SWW and near-horizontal principal compressive stress field ensured that the NNE-oriented dextral deep faults supplemented by the NWW-oriented left-lateral and NEE-oriented tensile faults caused different tectonic deformations of the fault belts with different strikes; furthermore, the deformation mechanisms for different segments of the same strike fault belt differed owing to differences in the fault structures and properties. Thus, strong earthquakes also have different preparation laws. The NNE-oriented high-angle deep faults intersecting with the unified principal compressive stress field at large angles and having tectonic inconsistencies, such as flower structure, are prone to strong locking and capacity to generate large earthquakes, which are characteristics of the main seismic type. The other faults that

intersect at small angles are prone to causing moderate-to-strong earthquakes and cannot generate large earthquakes, which are the characteristics of the multi-seismic type.

(4) The NNE-oriented dextral high-angle deep faults having tectonic inconsistencies in the deep and shallow parts are the ideal environment for the development of earthquakes around M8 in North China.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding authors.

Author contributions

HZ: data curation, methodology, supervision, writing–original draft, and writing–review and editing. LH: writing–review and editing. YC: validation and writing–review and editing. HL: writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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