Estimation of seismic hazard around the Ordos Block of China based on spatial and temporal variations of b-values

Shoubiao Zhu

Ministry of Emergency Management of the People’s Republic of China, National Institute of Natural Hazards, Beijing, China; Key Laboratory of Computational Geodynamics, Chinese Academy of Sciences, Beijing, China

ABSTRACT
Ruinous earthquakes have frequently occurred on the border of the Ordos Block, historically. Thus, where is a future disastrous earthquake around the Ordos? This problem is becoming more and more urgent both in the scientific community and the public, particularly after the 2008 Wenchuan earthquake (Ms = 8.0). To this end, we at first compute b-values in and around the Ordos Block based on the updated catalogue with earthquakes (M ≥ 0.0) from 1 January 2010 to 31 December 2020, and presented the spatial distribution of b-values. By examining the distribution feature of b-values, we chose 14 locations on the border of the Ordos Block where the b-value is relatively low and neo-tectonic faults are active. After that, we calculate the temporal variations of b-values in these 14 places, respectively. Comparing the 14 curves of b-variations with seismic precursors on b-values, we found that four of fourteen b-variations have characteristics of earthquake precursors. Therefore, these four places, located in the western end of the Weihe Graben, both the eastern and western ends of Hetao Graben, and the northeastern front of the Tibet, are considered to be seismically dangerous in the future. Naturally, the seismic damage in these areas is more serious than other places. Hence, the study is helpful in earthquake prediction and also can provide important clues for earthquake hazard assessment around the Ordos Block.

ARTICLE HISTORY
Received 22 February 2021
Accepted 24 June 2021

KEYWORDS
Seismicity; b-values; seismic precursor; earthquake hazard; Ordos Block

Highlights
Spatial distribution of b-values is presented in and around the Ordos Block;
Temporal b-variations are calculated in fourteen locations around the Ordos Block;
Four most earthquake-prone areas are ascertained around the Ordos Block.

CONTACT Shoubiao Zhu zhusb@pku.edu.cn; zhushoubiao@gmail.com

© 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
1. Introduction

Since the 2008 Wenchuan earthquake (Ms = 8.0), a serious question has been arisen: Where is the next devastating earthquake in China? Naturally, we would focus on the border of Ordos Block, because, at least six M ≥ 8.0 earthquakes have occurred on the verge of the Ordos Block in the recent history (China Earthquake Administration (CEA) 1995, 1999; Wang et al. 2014) (shown in Figure 1), leading to a huge numbers of people died. For example, the 1556 M8.25 Huaxian earthquake in the Shanxi Province, China, killed more than 830,000 residents, and the 1920 M8.0 Haiyuan earthquake in the Ningxia Hui Autonomous Region, China, destroyed over 200,000 people (Qu et al. 2017).

Geographically, the Ordos Block and its surrounding regions are situated in the inner part of China. It borders the North China Plain in the east, the Tibetan Plateau in the southwest, the Alashan Block in the northwest, the Qinling Orogen in the

![Figure 1. Tectonic setting and historical earthquake distribution in and surrounding the Ordos Block in recent 1000 years (from 1000 to 2010) with magnitude M ≥ 6.0. The 849 Baotou earthquake (M = 8.0) is also shown in blue, while the red solid circles stand for major earthquakes with magnitude equal to or greater than 8.0. Fault name abbreviations are as follows: ONF, Ordos North Edge Fault; HGF, Horinger Fault; DNF, Daihai North Edge Fault; LSF, Lishi Fault; DBF, Dengkou-Benjing Fault; XJF, Xiangshan-Tianjiangshan Fault; LSPF, Langshan Piedmont Fault; YPF, Yinchuan-Pingluo Fault; HHF, Huanghe Fault; XGF, Xiaoguanshan Fault; QMF, Qishan-Mazhao Fault; WBF, Weihe Basin Fault; QLF, Qinling Fault; WQF, Western Qinliang Fault; JHF, Jinhuo Fault; HFP, Huoshan Piedmont Fault. Red star stands for large city.](image-url)
south, and the Yinshan-Yanshan Orogen in the north (shown in Figure 1). The Ordos Block is approximately 600 km in length from north to south and ~400 km long from west to east. It is surrounded all around by faulted grabens such as Hetao Graben in the northwest, Yinchuan Graben in the west, Weihe Graben in the southeast and Shanxi Graben in the east, except for the southwest boundary.

Geologically, the interior of the Ordos Block is stable and rigid without active tectonic structures, in which few earthquakes occurred and the magnitudes have not exceeded M6.0. However, on the peripheral zones of the Ordos Block, being full of active neo-tectonics and abundant faults, giant destructive earthquakes frequently occurred (Deng et al. 1984, 1999; Zhang et al. 2003, 2006; Shi et al. 2020). Particularly, at least six $M \geq 8.0$ earthquakes occurred in the margin of the Ordos Block in the recent 1000 years (China Earthquake Administration (CEA) 1995, 1999; Wang et al. 2014) (shown in Figure 1), giving rise to enormous loss of human life and property to the local people. Moreover, many metropolitan areas such as Shanxi urban group, Hohhot-Baotou urban group, Guanzhong urban group, and Ningxia Plain urban group are nowadays distributed surrounding the border of the Ordos Block. In fact, these areas are densely populated and industrially developed. In addition, there has not been a major earthquake with magnitude 7 or greater for nearly 100 years around the Ordos Block. Therefore, peripheral zones of the Ordos Block are in the great risk of major earthquakes. Thus, where is a future catastrophic earthquake around the Ordos? This problem is becoming more and more urgent both in the scientific community and society, especially after the 2008 Wenchuan earthquake (Ms = 8.0) which occurred on the junction area between the Tibetan Plateau and Sichuan basin.

As a matter of fact, the above question is involved in earthquake prediction, which is an international scientific and technological problem. Despite over 100 years of hard work to explore earthquake prediction (Tiampo and Shcherbakov 2012), it turned out to be impossible to make a successful forecasting (Zhu 2013). For example, to any degree, no earthquake prediction was made for the 2008 Chinese Wenchuan earthquake (Ms = 8.0) and for the 2011 Japanese Tohoku-Oki earthquake (Mw = 9.0). Even no seismic anomalies or precursors associated with the earthquakes were captured before the earthquakes in spite of the deployment of a large number of modern seismic and geodetic observation stations in and around the focal regions (Zhu 2020, Chen and Zhu 2020).

Nevertheless, previous workers have found spatial and temporal variations of b-values before major earthquakes such as 1974 Yongshan earthquake (M = 7.1), the 1975 Haicheng earthquake (M = 7.3), the 1976 Longling earthquake (M = 7.6), the 1976 Tangshan earthquake (M = 7.8), the 2003 Tokachi-Oki, Japan, earthquake (M = 8.0), and the 2004 devastating Sumatra shock (Mw = 9.0) (Wu et al. 1976; Li et al. 1978; Nuannin et al. 2005; Nakaya 2006; Chen and Zhu 2020). In particular, Chen and Zhu have found that the earthquake precursor of b-value before the 2008 Wenchuan earthquake (Ms = 8.0), and the b-variations could be used to predict future large earthquake to some extent. Indeed, quite a few authors have pointed out that b-value is an important seismic precursor in earthquake prediction (Li et al. 1978; Ma
1978; Ding 1980; Smith 1981, 1986; Main et al. 1989; Imoto 1991; Nuannin et al. 2005; Nanjo et al. 2012).

Therefore, in order to estimate seismic hazard around the Ordos Block or to predict where is the most likely place for the next strong earthquake to occur, we utilize the approach (Chen and Zhu 2020) to predict future large earthquake in the study. At first, we calculate the spatial distribution of b-value. Then, we map the temporal changes of b-values in some places on the border of the Ordos Block. And finally, based on b-variations we try to present the most likely places for the future strong earthquake and estimate seismic hazard.

2. Tectonic setting

The Ordos Block has a special geographical position, bordering the North China Plain, Yinshan-Yanshan Orogen, Alashan Block, South China Block and the Tibetan Plateau. The eastern side of Ordos Block starts with the Lüliang Mountains, and the western side reaches Table Mountains and Yunwu Mountains, with the distance of ~400 km. It is ~600 km in the NS direction, from the Weibei Mountains in the south to the shore of the Yellow River in the north (shown in Figure 1). Topographically, the Ordos Block is a famous Loess Plateau with the average altitude of 1000–1700 m. In contrast, the Ordos Block is surrounded by numerous down-faulted basins, being 400–1000 m above the sea level, through which pass the Yellow River and two tributaries of Fen and Wei Rivers. Beyond outsides of the basins, stand the high mountains, with the Qinling Mountains in the south, Helan Mountains in the west, Yin Mountains in the north, and Lüliang and Taihang Mountains in the east. Between the basins, mountains and plateaus, and surrounding the Block is distributed the active faults which form a ‘Rectangular ring’, called active fault system around the Ordos Block (The research group on “Active fault system around Ordos massif” State Seimological Bereau 1988).

The whole Ordos Block has uplifted since Cenozoic, and formed a series of active fault system and concomitant faulted basins. The Ordos Block is surrounded by almost all of faulted basins except for the southwestern boundary, where a compressional tectonic belt trending NW, along which sinistral strike-slip fault zones with thrust components, such as the Haiyuan-Liupanshan fault, Xiangshan-Tianjingshan fault, Niushoushan fault and Xiaoguanshan fault are developed due to the northeastward movement of the Tibetan Plateau. The Yinchun faulted basin on the western boundary of the Ordos Block, as well as the Shanxi faulted basin on the eastern boundary, is NNE-trending dextral shear-extension zones. In contrast, the Hetao faulted basin on the northern boundary of the Block, together with the Weihe faulted basin to the south of the Ordos is nearly EW-trending sinistral shear-extension zones. The main active faults around the Ordos Block are displayed in Figure 1.

Depth of the Moho discontinuity beneath the Ordos Block is 40–42 km with a little variance, but for the faulted basin around the Block, the depth of Moho discontinuity has relatively uplifted 5–10 km (Chen et al. 2009; Wang et al. 2014). Geodetic observation suggests that the Ordos Block and its southwestern boundary are now still uplifting, with uplift rates of 1.0–2.8 mm/yr and 4.4 mm/yr, respectively. But the
surrounded faulted basins are relatively subsiding, with a rate of 4 to 5 mm/yr (Deng et al. 1999).

Particularly, no earthquakes (M ≥ 6.0) occurred in the interior of the Ordos Block, and all strong earthquakes are located in the peripheral region of the Ordos, including some giant events with magnitude equal to or greater than 8.0 such as the 1739 Pingluo earthquake (M = 8.0) and the 1920 Haiyuan earthquake (M = 8.0), shown in Figure 1.

3. Historical and modern seismicity

China has a civilization history of ~5,000 years, with the cradle being in the Yellow River valley, which encircles the Ordos Block (shown in Figure 1). Thus, in ancient times, the peripheral zones of the Ordos Block were very developed and densely populated. Most of the moderate and strong earthquakes (M ≥ 6.0) were almost completely recorded by historical documents in and around the Ordos, particularly in the recent 1000 years (China Earthquake Administration (CEA) 1995, 1999). Figure 1 displays the spatial distribution of earthquakes (M ≥ 6.0) in and around the Ordos Block from 1000 to 2010. On the west of the Ordos Block, apart from the 1920 Haiyuan event (M = 8.0), the figure shows that the 1739 M8.0 Pingluo earthquake occurred in

![Spatial distribution of recent earthquakes in and around the Ordos Block with M ≥ 0.0 from 1 January 2010 to 31 December 2020. Red stars stand for large cities such as Xian and Taiyuan.](image)
the Yingchuan Graben on the east Helanshan fault, which was the largest event ever recorded in the graben (Lei et al. 2015), leading to over 50,000 deaths. After that no earthquakes with magnitude greater than 7.0 occurred in the Yinchuan Graben. Correspondingly, on the east of the Ordos Block, the figure exhibits that the 1303 Hongdong earthquake ($M = 8.0$) and 1695 Linfen event ($M = 8.0$) occurred in the Shanxi Graben (Qin and Yan 1992; Qi et al. 2017). In fact, the two major events are only 40 km apart in space and 392 years apart in time.

On the south of the Ordos Block, the 1556 Huaxian earthquake ($M = 8.25$) occurred on the Weinan-Huaxian faults, the southeast verge of the Weihe Graben (Ma et al. 2016; Feng et al. 2020). The earthquake with normal faulting is regarded as the deadliest event in human history with a death toll of ~830,000. Moreover, on the southwest of the Ordos Block, occurred a 1654 Tianshui earthquake ($M = 8.0$) along the Lixian-Luojiabu fault which characterized by left-lateral strike-slip sense with

Figure 3. Magnitude–Time (M–T) plots for historical and modern earthquakes in and around the Ordos Block. (a) M-t plot for historical earthquakes with $M \geq 6.0$ from 1000 to 2010; (b) M-t plot for modern earthquakes with $M \geq 0.0$ from 1 January 2010 to 31 December 2020.
normal components (Yuan et al. 2017). In contrast, on the north border of the Ordos Block, there have been no earthquakes with magnitude equal to or greater than 8.0 in recent 1000 years. However, the 849 Baotou earthquake ($M = 8.0$) occurred on the piedmont fault of Daqingshan, Hetao Graben (Jiang et al. 2000), shown in Figure 1.

In order to know more about the seismicity in and around the Ordos Block at present, we compiled the earthquake catalog with $M \geq 0.0$ from 1 January 2010 to 31 December 2020 from China Earthquake Networks Centre. The epicenter distribution is shown in Figure 2. Indeed, we could see from the figure that few earthquakes, even in very small magnitude (e.g., $M < 3.0$), occurred in the interior of the Ordos, demonstrating that the Ordos Block is really a rigid stable block.

The corresponding Magnitude-Time ($M$-$T$) plot for historical earthquakes and recent events is displayed in Figure 3. Figure 3(a) shows that earthquake magnitude changed with time from 1000 to 2010 with magnitude equal to or greater than 6.0. We noticed that the number of earthquakes becomes more and more over time, suggesting that some of earthquakes were missing in ancient China around the Ordos Block. Using the maximum curvature method by means of ZMAP Software (Wiemer and Wyss 2000; Wiemer 2001; Zhu and Miao 2015; Chen and Zhu 2020), we found that the $M_c$ is 6.0 only after 20 December 1920, implying that earthquakes with magnitude $M \geq 6.0$ were completely recorded in the study region only after the 1920 Haiyuan M8.0 earthquake.

Figure 3(b) displays the Magnitude-Time ($M$-$T$) plot in the period of 1 January 2010–31 December 2020 with earthquake magnitude $M \geq 0.0$. We can observe that some even smaller events ($M < 1.0$) were recorded since June, 2012 due to the improvement of Earthquake Network systems in China. We can also see from Figures 2–3 that the earthquakes are not equally distributed in space and time. As to the earthquakes with $M < 6.0$, the number of earthquakes to the east of the Ordos Block is more than that to the west.

4. Results

4.1. Spatial and temporal $b$-values

Using the earthquake catalog in the period from 1 January 2010 to 31 December 2020 with $M \geq 0.0$ in and around the Ordos Block, we calculate the spatial- and temporal-variations of $b$-values by means of the ZMAP Software (Wiemer and Wyss 2000; Wiemer 2001). For computing details, please refer to Chen and Zhu (2020).

Before calculating the $b$-value, it is necessary for us to consider the completeness of the earthquake catalogue. To explore the minimum magnitude of catalog completeness ($M_c$), the maximum curvature method proposed by Wiemer and Wyss (2000) is used in the study. $M_c$ is usually estimated based on the Gutenberg-Richter power law distribution of magnitudes which is expressed as the following equation.

$$\log_{10} N(M \geq m) = a - bM$$

where $N(m)$ is the number of earthquakes exceeding magnitude $M$ (Gutenberg and Richter 1944). The method is used to calculate the goodness of fit between a power
law fit to the data and the observed Gutenberg-Richter distribution as a function of a lower cutoff of the magnitude data. $M_c$ is defined as the magnitude at which 90% of the data can be modeled by a power law fit (Wiemer 2001; Zhu and Miao 2015). Figure 4 illustrates the relation between the cumulative number of earthquakes and magnitudes performed by ZMAP Software (Wiemer 2001). In the figure are shown the $M_c = 1.8$ and $b = 0.87$ in the entire study area for 10 years.

Since the Ordos Block is located in the western part of China, there are wide disparities in social development between different regions. Thus, seismic stations are much unevenly deployed in space around the Ordos. It could be inferred that different $M_c$ is distributed in different places if we study in more detail. Figure 5 presents the contour distribution of $M_c$ in space in and around the Ordos Block. Obviously, the $M_c$ is smaller to the eastern part of Ordos than that in the western part, generally.

Figure 6 shows the spatial distribution of $b$-values in and around the Ordos Block. The figure clearly displays significant spatial variations in $b$-value from about 0.3 to 1.5 around the Ordos Block. On the whole, the figure tells us that the low $b$-values are mainly located in the Weihe Graben, Shanxi Graben, in the west of the Hetao Graben, and in the south of the Yinchuan Graben. Specifically, the $b$-value is less
than 1.0 in the west of the Weihe Graben, west of the Hetao Graben and Yinchuan Graben. But, in some other places, e.g., around the Liupanshan fault on the southwest verge of the Ordos, east of the Hetao Graben, the b-value is greater than 1.0. At the same time, there is a gap region of b-values in the inner part of the Block due to lack of earthquakes. The heterogeneously distributed b-values in space demonstrated that the tectonics and stresses around the Ordos are much complex. However, in general, low b-value represents high differential stresses (Mogi 1967; Scholz 1968; Schorlemmer et al. 2005; Narteau et al. 2009; Spada et al. 2013; El-Isa and Eaton 2014; Wang 2016), corresponding to high risk area for future strong earthquakes. Moreover, the spatial distribution of standard deviations of b-values is shown in Figure 7. Also, we can see that the magnitude of standard deviation is less than 0.15 in most part of the study area except for the small region located in the southwest of the Ordos Block.

Since the spatial distribution of b-values represents an average value of the long term with the time scale of 10 years, possible seismic anomaly or precursors may be smoothed or concealed (Chen and Zhu 2020). In order to unveil some precursors prior to strong earthquakes around the Ordos Block, we will map the temporal

---

Figure 5. Contour distribution of Mc in space with gird size of 10 km × 10 km around the Ordos Block. Red stars stand for large cities such as Xian and Taiyuan.
changes of b-values in the places of low b-values in space, shown in Figure 6, or in the key areas such as the intersection region of large active faults. Hence, based on Figure 6, we choose fourteen sub-regions in which b-value is relatively low, and the centers of these places are denoted by black triangles marked with English capital letter from A1 to A14, respectively. The longitude and latitude of centers of these fourteen locations are as follows: A1(107.3°E, 34.7°N), A2(108.7°E, 34.7°N), A3(110.8°E, 34.9°N), A4(112.0°E, 36.7°N), A5(112.5°E, 38.7°N), A6(112.3°E, 40.0°N), A7(111.0°E, 40.5°N), A8(109.3°E, 40.8°N), A9(107.6°E, 40.9°N), A10(107.0°E, 40.2°N), A11(106.7°E, 39.0°N), A12(106.2°E, 37.7°N), A13(106.5°E, 36.6°N), and A14(105.0°E, 36.7°N). Taking each of these fourteen locations as a center of the circle with a radius of 100 km, we choose earthquakes with magnitude $M \geq 0.0$ from 1 January 2010 to 31 December 2020 in each sub-region. Next, using these earthquakes, we compute the temporal variations of b-value in all fourteen regions, represented by a capital letter from A1 to A14, shown in Figure 6. We calculate the b-value by means of sliding windows including 100 events with sliding step of 25 events. Thus, the time length of

Figure 6. Spatial distribution of b-values in and around the Ordos Block. Red stars stand for large cities such as Xian and Taiyuan. Black solid triangles, marked by capital letters A1–A14, represent the centers in which temporal b-variations will be computed with radius of 100 km with earthquakes ($M \geq 0.0$) from 1 January 2010 to 31 December 2020, which will be shown in Figure 8(a)–8(n).
each window may change, but each data window remains unchanged with 100 earthquakes (Chen and Zhu 2020).

The fourteen b-variations in corresponded fourteen sub-regions from 1 January 2010 to 31 December 2020 are exhibited in Figure 8, in which b-value, represented by red solid line, varies against time in each region, and the dashed lines denote the corresponded standard deviation of b-values. Evidently, the figure shows that the pattern of the temporal variations of b-value in each sub-region is different from each other, suggesting different evolutions of stress states in different places.

Figure 8(a) shows temporal variations of b-value in the region of A1 with the center located at longitude and latitude of 107.3°E, 34.7°N, respectively. As displayed in the figure, at the beginning b-value is \( \sim 1.6 \), and then it increased to 2.3 in June 2010. After that, b-value began to decrease. From June 2010 to June 2011, it dropped quickly, afterwards went down slowly. Again, from October 2107 to March 2018, b-value decreased rapidly for about half a year. Later, b-value changed little by little until December 2020. In general, b-values kept a decreased trend within over 10 years, possibly suggesting the increase of stresses in the region A1.
Figure 8. $b$-value varies as a function of time from 1 January 2010 to 31 December 2020 in each fourteen sub-regions shown in Figure 6 with black solid triangles lettered by A1–A14. (a) Temporal $b$-variations in A1 sub-region; (b) $b$-variations in A2; (c) $b$-variations in A3; (d) $b$-variations in A4; (e) $b$-variations in A5; (f) $b$-variations in A6; (g) $b$-variations in A7; (h) $b$-variations in A8; (i) $b$-variations in A9; (j) $b$-variations in A10; (k) $b$-variations in A11; (l) $b$-variations in A12; (m) $b$-variations in A13; (n) $b$-variations in A14. In the figure, red solid lines represent $b$-values, and gray dashed lines stand for corresponded standard errors.
The temporal b-variations in the region A2 is shown in Figure 8(b). The figure depicts b-value kept rise and fall with tiny fluctuations, implying the unchanged stresses there. Figure 8(c)–8(d) show that b-value varied with time up and down violently, but kept the average value almost the same. In Figure 8(e) is shown that b-value oscillated over time with a little increased trend.

Figure 8(f) displays temporal changes of b-value in A6 area, located in the northeastern corner of the Ordos Block, with the center situated at longitude and latitude of 112.3°E, 40.0°N, respectively. At the first stage, from January 2012 to March 2013, b-value decreased rapidly from 0.85 to 0.5. Then, it increased a little and got to maximum value of 0.6 in 2016. Since that time, it declined slowly until the end of 2020.

Figure 8(g)–8(h) show that b-value changed with large fluctuations for the period with average value almost invariant. These variation patterns are unlike the seismic precursors before major earthquakes. In contrast, the temporal variations of b-value shown in Figure 8(i), represented the region of A9, kept almost unchanged from 2010 to 2017, and dropped slowly until to the end of 2020. It is obvious that the variation pattern of b-values is something like the seismic precursor. Therefore, it is possible that major earthquakes may happen in future in the region of A9. The temporal variation of b-value in A10 is displayed in Figure 8(j). The figure show that the b-value declined to 0.6 from 0.82 in 2011 to May 2015, after that it increased abruptly to 0.9 in short period of time, and then kept almost the same for about 3 months, and dropped to 0.8, then remained almost unchanged for over 3 years, and finally increased until the end of 2020. The variation curve shown in Figure 8(j) is something like a seismic anomaly. Figure 8(k) illustrates that the b-value decreased from 2011 to 2015, then increased and dropped largely, and finally increased slowly. The b-value in Figure 8(l) changed rapidly at the first stage (2010–2013), then increased gradually from 2013 to 2018, and later decreased until 2020. The general trends of the variations of b-values shown in Figure 8(m) and 8(n) are almost the same. They decrease at the first stage, and then increased gradually from 2015 to until December 2020.

4.2. Seismic hazard around the Ordos Block

In general, there are spatiotemporal variations of b-values before a major earthquake due to stress and medium evolutions in the process of earthquake preparation. However, without a unified pattern, the types of b-variations before major earthquake are much complex. El-Isa and Eaton (2014) summarized at least three types of temporal variations in the b-value preceding large earthquakes, which are called seismic precursor in b-value (SPb) in the paper. (1) A rise in the b-value prior to a major earthquake, at timescales of a few years or more; (2) A decline in the b-value previous to a strong earthquake, at timescales of a few years or more; (3) An rise in the b-value long before a large event, with a precursory drop for a short period before the mainshock.

Comparing the temporal variations in b-value in each subregion shown in Figure 8(a)–8(n) one by one with the typical SPb before major earthquakes, we cannot find any curves in b-variations are in full agreement with SPb. Therefore, there are not
any rigorous seismic precursory or earthquake anomalies around the Ordos Block. Thus, it is difficult for us to predict future major earthquakes in and around the Ordos Block by means of b-variations in space and in time.

But luckily, by means of closer examination, we found that some parts of the b-variation curves shown in Figure 8 present seismic precursors. For example, in Figure 8(a) is displayed that b-value declined for about five years from January 2016 to December 2020. So, it is a typical seismic precursor of b-variations, suggesting that A1 region is the likely places for future major earthquakes. In fact, in Figure 6 is shown that A1 is located on the southwest corner of the Ordos Block and on the west end of the Weihe Graben. From the figure, we also see that A1 is situated on an intersection region between the Liupanshan fault, the West Qinling fault, Qishan-Mazhao fault and Weihe fault (Wang 1984; Rao et al. 2015; Li et al. 2019). In particular, these faults are active at present. Hence, A1 is supposed to be one of the likely regions for the future strong earthquakes around the Ordos Block.

Next, we notice that b-value slowly declined in the period for October 2016–December 2020 illustrated in Figure 8(f) denoted A6 region in Figure 6. As is shown in Figure 6, A6 is located at the eastern end of Hetao Graben, northeast corner of the Ordos Block. Also, A6 is the intersection region between Ordos North Edge fault, Daihai fault, and Horinger fault. In addition, there has been no strong earthquakes for a long time in this region (Ran et al. 2003). Thus, taken together, A6 is assumed to be the other likely location for future major earthquakes.

In addition, b-values shown in Figure 8(i) also declined gradually from January 2015, and dropped quickly from February 2017 until the end of 2020, with the value dropped from 0.7 to 0.5. Figure 8(i) represents the b-variations as a function of time in A9 region, where the Dengkou-Benjing fault, the Langshan piedmont fault and the Ordos north fault intersect (Dong et al. 2018). Also, there has not been a major earthquake for a long time in A9 region, located on the western end of the Hetao Graben, northwestern corner of the Ordos Block (Ran et al. 2003). Hence, A9 is assumed to be another region for possible strong earthquake in future.

Finally, in the Figure 8(m) we could observe that b-value changed up and down as a function of time with an increased trend from ~0.5 in January 2015 to 0.82 in December 2020. It is clear that the b-variation is also a typical seismic precursor, implying that a major earthquake may occur in the region of A13, where the Liupanshan fault and Xiaoguanshan fault meet. Moreover, A13 is located on the northeastern front of the Tibet Plateau, the main collision zone of the Eastern Tibet with the Ordos Block.

In sum, based on the spatiotemporal b-variations, the four most likely areas for future major earthquakes around the Ordos Block are provided. They are located in the western end of the Weihe Graben, south of the Ordos; both the eastern and western ends of Hetao Graben, north of the Ordos; and the northeastern front of the Tibet, southwest of the Ordos Block. Nonetheless, the occurrence time for future earthquakes cannot be decided by the b-variations shown in Figures 8 due to not a turn in the course of the long trend of b-variations, according to the previous precursors on b-variations before major earthquakes (Chen and Zhu 2020). Accordingly, the seismic hazard in these four places may be more serious than other places around the
Ordos Block. Additionally, we should note that the estimation of future strong earthquakes in the study is still an empirical method, rather than a numerical prediction (Zhu 2013). It is necessary for us to make an in depth study.

5. Discussions

5.1. b-Values and GPS strain rates

In some senses, b-value is considered as a strain meter or stress indicator (Mogi 1967; Scholz 1968; Schorlemmer et al. 2005; Narteau et al. 2009; Spada et al. 2013). On the other hand, strain rates based on GPS observation are associated with strain accumulation or stress loading. In principle, b-value may be associated with strain rates. Then, in the study, we will present spatial distribution of strain rates around the Ordos Block in order to see whether or not they have some connections between them.

The GPS data used in the study were from multiple sources (Wang and Shen 2020), which are the Crustal Movement Observation Network of China (CMONOC) Project, regional campaign GPS networks, and regional continuous GPS sites, respectively. As to how to process these GPS observational data, refer to Wang and Shen.
It should be noted that the coseismic and postseismic effects of strong earthquakes (e.g., the 2001 Kokoxili M 8.1 earthquake, the 2008 Wenchuan M 8.0, 2010 Yushu M 7.1, 2011 Japan M 9.0 earthquakes; the 2001 Kokoxili and 2008 Wenchuan earthquakes, the 2004 Sumatra and 2011 Tohoku-Oki earthquakes, the 2015 Gorkha earthquake) on the surface displacements in the GPS survey have been removed from the GPS velocities (Wang and Shen 2020). Then, GPS measurements are representative of the recent interseismic secular movements in and surrounding areas of the Ordos block. Figure 9 displays the GPS velocities with 70% confidence error ellipses with respect to the stable Eurasia plate in the period from 1991 to 2016.

Strain rate is independent of the reference frame and can disclose regional strain accumulation rates and their possible connections to tectonic stresses or earthquake damage (Zhu and Shi 2011; Riguzzi et al. 2012; Kreemer et al. 2014; Li et al. 2018; Rui and Stamps 2019). In the work, we compute the strain rates by means of the method proposed by Zhu et al. (2005, 2006). In the approach, at first kriging technique is applied (Deutsch and Journel 1997) to interpolate the spatially irregularly scattered GPS velocity data on uniform grids, and then strain rate is calculated in each grid region (Zhu and Shi 2011).
Figure 10 shows the spatial distribution of maximum shear strain rates in and around the Ordos Block. The figure tells us that the high values of the maximum shear strain rates are found on the margin of the Ordos Block, and the small strain rates are located in the interior of the Block, which is in good agreement with our common understanding of deformation on the Ordos Block in geoscience. In fact, if we take a look at the figure in detail we could notice that the highest value of maximum shear strain rates are mainly concentrated in a few areas such as the Yinchuan Graben, south of the Hohhot and west of the Xian and along the Haiyuan fault zone, respectively, with the value of $3\times10^{-8}$/yr.

Comparing the spatial distribution of strain rates with that of b-values, we found that the basic features are comparative although they cannot be in good agreement in detail. The possible reason may be that they reflect different physics. The strain rates based on GPS measurements represent Earth’s surface deformation rates in the period 1991–2016, but the b-value is a statistical physical quantity indicating stress level of the studied geologic volume expressed by earthquake activities. Anyway, with the accumulation of data and improvement of computation method, independent b-value and strain rates will be found some relationships between them.

5.2. Factors influencing b-variations

The b-value in the G-R relation is a statistical variable, which describes the relative distribution of large and small earthquakes within a specific region and a particular time period. Thus, the larger the b-value, the greater numbers of small earthquakes is, and vice versa. The b-value depends on a number of contributory factors. For example, an increase (or decrease) stress on geologic volume will lead to a corresponding decrease (or increase) in the b-value (e.g., Gerstenberger et al. 2001; Zuniga and Wyss 2001; Wiemer and Wyss 2002; Wyss et al. 2004; Schorlemmer et al. 2005; Wyss and Matsumura 2006; Wang 2016). Moreover, this relationship is confirmed by a few laboratory experiments (e.g., Mogi 1967; Scholz 1968; Kurz et al. 2006). Besides, b-value is linked to crustal deformation such as faulting, cracking, folding, fracturing, and to liquid migration and magmatic intrusions. From the appearance of phenomena, the b-value is associated with tectonic characteristics and focal mechanisms. Different fault regime is corresponded with different b-value. Usually, b-value is approximately 1.0 in strike-slip faulting, and it is greater than 1.0 in thrust faulting and less than 1.0 in normal faulting regime (Amelung and King 1997; Beauval and Scotti 2004; Schorlemmer et al. 2004, 2005; Petruccelli et al. 2019). Also, the b-value varies with depth. It is reported that the b-value of the upper crust is significantly larger than that of the lower crust (e.g., Mori and Abercrombie 1997; Gerstenberger et al. 2001; Spada et al. 2013). Furthermore, b-value will vary with petrological, geophysical and rheological characteristics of rocks (e.g., Scholz 1968; Hauksson et al. 2002; Lin et al. 2007; Wang 2016). In addition, some studies suggest that temporal and spatial b-variations may be artifacts of incomplete catalogs or method of computation (e.g., Frohlich and Davis 1993; Jackson and Kagan 1999; Del Pezzo et al. 2003; Amorese et al. 2010).
Therefore, the b-value with statistical characteristics contains numerous contributory factors, which may influence the b-variations. But, we cannot differentiate these factors at present. Hence, we are unclear that the temporal b-variations shown in Figure 8 are associated with future major earthquakes. Therefore, the four possible places around the Ordos Block for future earthquakes are only used as a reference in seismic hazard assessments and project construction. Thus, we need more geological investigation and geophysical monitoring to get more seismic precursors in order to better assessment of seismic hazard around the Ordos Block.

6. Conclusion

In the study, we mapped the b-variations in space and in time. Some seismic precursors on b-values were found at the four locations on the verge of the Ordos Block where the b-value is relatively small and deformation is large. The four places are located in the western end of the Weihe Graben, south of the Ordos; both the eastern and western ends of Hetao Graben, north of the Ordos; and the northeastern front of the Tibet, southwest of the Ordos Block. These areas are assumed to be high risk regions for future major earthquakes, there will be more serious seismic hazard than other places around the Ordos Block. Nonetheless, the occurrence time for future strong earthquakes cannot be decided yet. It is necessary for us to carry out further in-depth research on geological investigations and geophysical monitoring around the Ordos Block to reduce the seismic damage. Therefore, the findings of this study will contribute to a better understanding, modelling and prediction of earthquakes, and can also provide important clues for seismic hazard evaluation around the Ordos Block.

Acknowledgments

The author thanks two reviewers and the Editor (Prof. Ramesh Singh) for the critical and constructive comments to improve the manuscript. This work was jointly supported by National key research and development program of China (2017YFC1500104), National Natural Science Foundation of China (41874060, 41574041) and by the research grant from Institute of Crustal Dynamics, China Earthquake Administration (ZDJ2020-15).

Disclosure statement

The author declares no conflict of interests.

Data availability statement

All the GPS data used in the current study are available from the cited references (Wang and Shen 2020), and all earthquake data are from National Earthquake Data Center of China (downloaded from: https://data.earthquake.cn/gcywfl/index.html). All output data of the models presented in the paper is available from the corresponding author upon request.
References

Amelung F, King G. 1997. Earthquake scaling laws for creeping and non-creeping faults. Geophys Res Lett. 24(5):507–510.
Amorese D, Grasso J-R, Rydelek PA. 2010. On varying b-values with depth: results from computer-intensive tests for Southern California. Geophys J Int. 180(1):347–360.
Beauval C, Scotti O. 2004. Quantifying sensitivities of PSHA for France to earthquake catalog uncertainties, truncation of ground-motion variability, and magnitude limits. Bull Seismol Soc Am. 94(5):1579–1594.
Chen L, Cheng C, Wei Z. 2009. Seismic evidence for significant lateral variations in lithospheric thickness beneath the central and western North China Craton. Earth Planet Sci Lett. 286(1–2):171–183.
Chen J, Zhu S. 2020. Spatial and temporal b-value precursors preceding the 2008 Wenchuan, China, earthquake (Mw = 7.9): implications for earthquake prediction. Geomat Nat Hazards Risk. 11(1):1196–1211.
China Earthquake Administration (CEA). 1995. Historical Strong Earthquake Catalog of China (2300B.C.–1911A.D.). Beijing: Earthquake Publishing House. (in Chinese).
China Earthquake Administration (CEA). 1999. Recent earthquake catalog of China (1912–1990 A.D., MS ≥ 4.7). Beijing: Chinese Science and Technology Press. (in Chinese).
Del Pezzo E, Esposito A, Giudicepietro F, Marinaro M, Martini M, Scarpetta S. 2003. Discrimination of earthquakes and underwater explosions using neural networks. Bull Seismol Soc Am. 93(1):215–223.
Deng QD, Cheng SP, Min W. 1999. Discussion on Cenozoic tectonics and dynamics of Ordos block. J Geomech. 5(3):20–26.
Deng Q, Sung F, Zhu S, Li M, Wang T, Zhang W, Burchfiel BC, Molnar P, Zhang P. 1984. Active faulting and tectonics of the Ningxia-Hui Autonomous Region, China. J Geophys Res Solid Earth. 89(B6):4427–4445.
Deutsch CV, Journel AG. 1997. GSLIB: Geostatistical Software Library and User’s Guide. 2nd ed. New York: Oxford University Press.
Ding WJ. 1980. Physical basis of earthquake prediction by the b-Value. Acta Seismol Sin. 2(4):378–387.
Dong S, Zhang P, Zheng W, Yu Z, Lei Q, Yang H, Liu J, Gong H. 2018. Paleoseismic observations along the Langshan range-front fault, Hetao Basin, China: Tectonic and seismic implications. Tectonophysics. 730:63–80.
El-Isa ZH, Eaton DW. 2014. Spatiotemporal variations in the b-value of earthquake magnitude–frequency distributions: classification and causes. Tectonophysics. 615–616:1–11.
Feng X, Ma J, Zhou Y, England P, Parsons B, Rizza MA, Walker RT. 2020. Geomorphology and Paleoseismology of the Weinan fault, Shaanxi, central China, and the source of the 1556 Huaxian earthquake. J Geophys Res Solid Earth. 125(12):1–23.
Frohlich C, Davis SD. 1993. Teleseismic b values; or, much ado about 1.0. J Geophys Res. 98(B1):631–644.
Gerstenberger M, Wiemer S, Giardini D. 2001. A systematic test of the hypothesis that the b value varies with depth in California. Geophys Res Lett. 28(1):57–60.
Gutenberg B, Richter CF. 1944. Frequency of earthquakes in California. Bull Seismol Soc Am. 34(4):185–188.
Hauksson E, Jones LM, Hutton K. 2002. The 1999 Mw 7.1 Hector Mine, California, earthquake sequence: complex conjugate strike-slip faulting. Bull Seismol Soc Am. 92(4):1154–1170.
Imoto M. 1991. Changes in the magnitude-frequency b-value prior to large (M ≥ 6.0) earthquakes in Japan. Tectonophysics. 193(4):311–325.
Jackson DD, Kagan YY. 1999. Testable earthquake forecasts for 1999. Seismol Res Lett. 70(4):393–403.
Jiang WL, Xiao ZM, Xie XS. 2000. Segmentations of active normal dip-slip faults around Ordos block according to their surface ruptures in historical strong earthquakes. Acta Seimol Sin. 13(5):552–562.

Kreemer C, Blewitt G, Klein EC. 2014. A geodetic plate motion and global strain rate model. Geochem Geophys Geosyst. 15(10):3849–3889.

Kurz JH, Finck F, Grosse C, Reinhardt H-W. 2006. Stress drop and stress redistribution in concrete quantified over time by the b-value analysis. Struct Health Monit. 5(1):69–81.

Lei QY, Chai CZ, Du P, Yu JX, Wang Y, Xie XF. 2015. The seismogenic structure of the M8.0 Pingluo earthquake in 1739. Seismol Geol (in Chinese with an English Abstract). 37(2):413–429.

Li QL, Chen JB, Yu L, Hao BL. 1978. Time and space scanning of the b-value-A method for monitoring the development of catastrophic earthquakes. Chin J Geophys. 21(2):101–125.

Li X, Feng X, Li X, Li C, Zheng W, Zhang P, Pierce IKD, Li G, Li C, Liu Y, et al. 2019. Geological and geomorphological evidence for active faulting of the southern Liupanshan fault zone, NE Tibetan Plateau. Geomorphology. 345:106849.

Li S, Li C, Zhou Q. 2018. Kinematic analysis of the Ordos block and surrounding area based on GPS data: an initiative–passive vortex structure model. Arab J Geosci. 11(20):627–.

Lin J-Y, Sibuet J-C, Lee C-S, Hsu S-K, Klingelhoefer F. 2007. Special variations in the frequency-magnitude distribution of earthquakes in the southwestern Okinawa trough. Earth Planets Space. 59(4):221–225.

Ma HC. 1978. Variations of the b-values before several large earthquakes occurred in north China. Chin J Geophys. 21(2):126–141.

Ma J, Feng XJ, Li GY, Li X, Zhang Y. 2016. The coseismic vertical displacements of surface rupture zone of the 1556 Huaxian earthquake. Seismol Geol. 38(1):22–30.

Main IG, Meredith PG, Jones C. 1989. A reinterpretation of the precursory seismic b-value anomaly from fracture mechanics. Geophys J Int. 96(1):131–138.

Mogi K. 1967. Earthquakes and fractures. Tectonophysics. 5(1):35–55.

Mori J, Abercrombie RE. 1997. Depth dependence of earthquake frequency-magnitude distributions in California: Implications for rupture initiation. J Geophys Res. 102(B7):15081–15090.

Nakaya S. 2006. Spatiotemporal variation in b value within the subducting slab prior to the 2003 Tokachi-oki earthquake (M 8.0), Japan. J Geophys Res. 111(B3):1–13.

Nanjo KZ, Hirata N, Obara K, Kasahara K. 2012. Decade-scale decrease in b value prior to the M9-class 2011 Tohoku and 2004 Sumatra quakes. Geophys Res Lett. 39(20):3–6.

Narteau C, Byrdina S, Shebalin P, Schorlemmer D. 2009. Common dependence on stress for the two fundamental laws of statistical seismology. Nature. 462(7273):642–645.

Nuannin P, Kulhanek O, Persson L. 2005. Spatial and temporal b value anomalies preceding the devastating off coast of NW Sumatra earthquake of December 26, 2004. Geophys Res Lett. 32(11):1–4.

Petrucelli A, Schorlemmer D, Tormann T, Rinaldi AP, Wiemer S, Gasperini P, Vannucci G. 2019. The influence of faulting style on the size-distribution of global earthquakes. Earth Planet Sci Lett. 527:115791.

Qi Y, Lu G, Sun L, Fang S, Wang X, Feng X, Diao G. 2017. Seismogenic fault of the 1303 Hongdong M8 Earthquake in Shanxi Province. Earthquake (in Chinese with an English Abstract). 31(1):148–157.

Qin B, Yan W. 1992. Study on the cause of the 1695 M8 Linfen great earthquake. J Catastroph (in Chinese with an English Abstract). 7(3):14–18.

Qu W, Lu Z, Zhang M, Zhang Q, Wang Q, Zhu W, Qu F. 2017. Crustal strain fields in the surrounding areas of the Ordos Block, central China, estimated by the least-squares collocation technique. J Geodyn. 106:1–11.

Ran Y, Chen L, Yang X, Han Z. 2003. Recurrence characteristics of late-quaternary strong earthquakes on the major active faults along the northern border of Ordos block. Sci China, D Earth Sci. 46(2):189–200.
Rao G, Lin A, Yan B. 2015. Paleoseismic study on active normal faults in the southeastern Weihe Graben, central China. J Asian Earth Sci. 114:212–225.

Riguzzi F, Crespi M, Devoti R, Doglioni C, Pietrantonio G, Pisani AR. 2012. Geodetic strain rate and earthquake size: New clues for seismic hazard studies. Phys Earth Planet Inter. 206:67–75.

Rui X, Stamps DS. 2019. A geodetic strain rate and tectonic velocity model for China. Geochem Geophys Geosyst. 20(3):1280–1297.

Scholz C. 1968. Microfracturing and the inelastic deformation of rock in compression. J Geophys Res. 73(4):1417–1432.

Schorlemmer D, Wiemer S, Wyss M. 2004. Earthquake statistics at Parkfield: 1. Stationarity of b values. J Geophys Res. 109(B12):1–17.

Schorlemmer D, Wiemer S, Wyss M. 2005. Variations in earthquake-size distribution across different stress regimes. Nature. 437(7058):539–542.

Shi W, Dong S, Hu J. 2020. Neotectonics around the Ordos Block, North China: a review and new insights. Earth Sci Rev. 200:102969.

Smith WD. 1981. The b value as an earthquake precursor. Nature. 289(5794):136–139.

Smith WD. 1986. Evidence for precursory changes in the frequency-magnitude b-value. Geophys J Int. 86(3):815–838.

Spada M, Tormann T, Wiemer S, Enescu B. 2013. Generic dependence of the frequency-size distribution of earthquakes on depth and its relation to the strength profile of the crust. Geophys Res Lett. 40(4):709–714.

The research group on “Active fault system around Ordos massif” State Seimological Bereau. 1988. Active fault system around Ordos Mssif. Beijing: Seimological Press.

Tiampo KF, Shcherbakov R. 2012. Seismicity-based earthquake forecasting techniques: Ten years of progress. Tectonophysics. 522:89–121.

Wang J. 1984. A study on the tectonics of the Weihe river graben. Geol Rev. 30(3):217–223.

Wang JH. 2016. A mechanism causing b-value anomalies prior to a mainshock. Bull Seismol Soc Am. 106(4):1663–1671.

Wang CY, Sandvol E, Zhu L, Lou H, Yao Z, Luo X. 2014. Lateral variation of crustal structure in the Ordos block and surrounding regions, North China, and its tectonic implications. Earth Planet Sci Lett. 387:198–211.

Wang M, Shen ZK. 2020. Present-day crustal deformation of continental China derived from GPS and its tectonic implications. J Geophys Res Solid Earth. 125(2):e2019JB018774.

Wiemer S. 2001. A software package to analyze seismicity: ZMAP. Seismol Res Lett. 72(3):373–383.

Wiemer S, Wyss M. 2000. Minimum magnitude of completeness in earthquake catalogs: Examples from Alaska, the western United States, and Japan. Bull Seismol Soc Am. 90(4):859–869.

Wiemer S, Wyss M. 2002. Mapping spatial variability of the frequency–magnitude distribution of earthquakes. Adv Geophys. 45:259–302.

Wu KT, Yue MS, Wu HY. 1976. Certain characteristics of Haicheng earthquake (M = 7.3) sequence. Chin J Sin. 63(8):265–267.

Wyss M, Matsumura S. 2006. Verification of our previous definition of preferred earthquake nucleation areas in Kanto–Tokai, Japan. Tectonophysics. 417(1–2):81–84.

Wyss M, Sammis C, Nadeau R, Wiemer S. 2004. Fractal dimension and b-value on creeping and locked patches of the San Andreas fault near Parkfield, California. Bull Seismol Soc Am. 94(2):410–421.

Yuan D, Lei Z, Wang A. 2017. Additional textual criticism of Southern Tianshui M8 earthquake in Gansu Province in 1654. China Earthq Eng J (in Chinese with an English Abstract). 39(3):0509–0520.

Zhang P, Deng Q, Zhang G, Ma J, Gan W, Min W, Mao F, Wang Q. 2003. Active tectonic blocks and strong earthquakes in the continent of China. Sci. China, D Earth Sci. 46(2):13–24.
Zhang YQ, Liao CZ, Shi W, Hu B. 2006. Neotectonic evolution of the peripheral zones of the Ordos Basin and geodynamic setting. Geol J China Univ. 12(3):285–297.

Zhu S. 2013. Numerical simulation of dynamic mechanisms of the 2008 Wenchuan Ms8. 0 earthquake: implications for earthquake prediction. Nat Hazards. 69(2):1261–1279.

Zhu S. 2020. Inter- and pre-seismic deformations in the 2011 Mw 9.0 Tohoku-Oki earthquake: implications for earthquake prediction. Chin J Geophys (in Chinese with an English Abstract). 63(2):427–439.

Zhu S, Cai Y, Shi Y. 2006. The contemporary tectonic strain rate field of continental China predicted from GPS measurements and its geodynamic implications. Pure Appl Geophys. 163(8):1477–1493.

Zhu SB, Cai YE, Shi YL. 2005. Computation of the present-day strain rate field of the Qinghai-Tibetan plateau and its geodynamic implications. Chin J Geophys. 48(5):1053–1061.

Zhu S, Miao M. 2015. How did the 2013 Lushan earthquake (Ms = 7.0) trigger its aftershocks? Insights from static Coulomb stress change calculations. Pure Appl Geophys. 172(10):2481–2494.

Zhu S, Shi Y. 2011. Estimation of GPS strain rate and its error analysis in the Chinese continent. J Asian Earth Sci. 40(1):351–362.

Zuniga F, Wyss M. 2001. Most-and least-likely locations of large to great earthquakes along the Pacific coast of Mexico estimated from local recurrence times based on b values. Bull Seismol Soc Am. 91(6):1717–1728.