Study on the relationship between radon characteristics of underground water and seismicity in the Longxian - Baoji fault zone, NW China

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Abstract. Destructive earthquakes are mostly located in the active fault zones. The underground gas anomalies result to basically be consistent with the inferred distribution of active fault systems. Among them, radon is the earliest used as the effective prediction index of fault zone earthquake prediction. In this paper, radon concentrations in groundwater from the Longxian – Baoji fault zone in the Northwestern China are analyzed. Results show that the NW sector has a lower radon concentration (~12 Bq/L) than that of the SE sector (40 ~ 50 Bq/L). It indicated that the connectivity between the shallow and deep crust is relatively poor in the NW sector, which is not conducive to the upward diffusion and migration of deep fluids. Given that there is a seismic gap with no rupture of M ≥ 6 ½ strong earthquake in the NW sector, it can be infered that the NW sector of the Longxian – Baoji fault zone has a higher risk of strong earthquakes than that in the SE sector.

1. Introduction
Earthquakes are one of the most serious natural disasters to the sustainable development of human life, property and economy. The Tangshan M 7.8 earthquake on the 28th of July, 1976 and the Wenchuan Mw 7.9 earthquake on the 12th of May, 2008 caused hundreds of thousands of casualties and billions of direct economic losses [1]. Seismic data showed that the epicenters of the strongest earthquakes are located in active fault zones. Active faults refer to those systems that have been active since the late Quaternary, which are still active or they were in modern geological periods and may be reactivated in the future. The new faults that caused destructive earthquakes are consistent or completely coinciding with those of the existing active faults. Moreover, the extension directions of most strong earthquakes' seismoseismal areas and isoseismal lines are consistent with those of the local active faults. The identification of specific fault activity and its correlation with earthquakes play a key role of the geoengineering work. This is particularly true when critical infrastructures (hydropower station, building, oil and gas pipeline, highway, etc.) are directly crossed by fault systems. Detailed studies are thus to be performed in order to take specific actions. That is, an approach that can be simplified in: "there is an active fault or not, it is active or not, it is deep or not, it occurs or not, it moves or not and good countermeasure" [2]. Detecting fault activity usually includes geological and geomorphic investigations, geophysical and geochemical studied. The geochemical parameters that commonly investigated and monitored in seismic areas include radon (Rn), hydrogen (H₂), mercury (Hg), carbon dioxide (CO₂), hydrocarbons and S-bearing gases. Gas anomalies are basically consistent with the inferred distribution of active faults [3]. Among them, Rn concentration is a good prediction parameter of earthquake prediction in faulting zones, and is one of the most effective observation means.
Variations in Rn concentration are widely used to predict seismic events at short-to-long [3, 4-12]. The Longxian - Baoji fault zone is situated in the NS seismic belt of China. It is located in the western end of the Weihe Fault Basin and the SW margin of Ordos block. It is prone to strong and high frequent earthquakes and several times M ≥ 5 earthquakes hit this area [13, 14]. Since the 1970s, in the Longxian - Baoji fault zone moderate or strong earthquake events have not been recorded, which makes many researchers think that it is a weak seismic area. Nevertheless, the weak earthquake activities of several active faults in the area are relatively concentrated and frequent [15, 16]. In addition, recent studies showed that there is a seismic gap with no rupture of M ≥ 6 1/2 strong earthquake occurred in the Longxian - Baoji fault zone in the last 1400 years. The GPS data in the seismic gap showed that there is significant strain accumulation. Seismically, there are sparse or vacant parts of small earthquakes. Its “b” value is low, indicating a high stress accumulation. Therefore, the fault zone is a dangerous area where strong earthquakes may be occurring in the future [17]. In this paper, we present and discuss the concentration of Rn from the groundwater system in the Longxian - Baoji fault zone and the features of the fault segmentation activity. This study is meant to provide a geochemical basis to better understand the characteristics of active faults and evaluate the potential seismic risk.

2. Seismogeological background

The Longxin - Baoji fault zone is a key conjunction of the middle and northern sector of the famous NS-oriented seismic belt in central China. It is located in the NE margin of Qinghai Tibet block and the southernmost end of the arc fault bundle in the SW margin of Ordos. It is also the conjunction of the giant EW and NS tectonic belts (the Altun - Qilian - Qinling - Dabie tectonic belt and the North - South tectonic belt) in China mainland, with very complex geological structures (Figure 1). It is mainly composed by the Longxian - Qishan – Mazhao (F1), Qianyang – Biaojiao (F2), Guguan – Baoji (F3), and Taoyuan – Guichuansi (F4) fault systems. It is generally NW-trending, narrow to the north, and gradually spread to SE. It reaches the west of Weihe basin, and ends near the northern foot of Qinling Mountains, forming a structural pattern of "one uplift and two depressions". Wang S D (2018) [18] has made a systematic study on the activity of each fault in this fault zone. And the results show that: 1). the Longxian – Qishan - Mazhao fault is the most active fault in the fault zone since the late Quaternary, which has been mainly left lateral strike slip and normal fault since the late Pleistocene; 2). the Guguan - Baoji fault has an active fault in the Middle Pleistocene, which has not been active since the late Pleistocene. And it is left lateral strike in the early Quaternary; 3). the Taoyuan - Guichuansi fault has a weak fault activity since the early and Middle Pleistocene, and it is right lateral strike slip fault; 4) the Qianyang – Biaojiao fault’s activity has been weak since the Pliocene. And it mainly acts as normal fault.

Previous studies on the historical earthquakes in this area indicated that there were two M ≥6 earthquakes, three M 5 - 6 earthquakes [14]. Based on the analysis of historical records and the data of Seismograph Monitoring Networks of China Seismological Bureau, in the past 200 years, the seismic activity level in this area was not high, mainly M 1 ~ 2 earthquakes. Significant earthquake damages were mostly due to the earthquakes that hit the neighboring areas. In addition, the increase of seismicity in the NS-aligned seismic belt complicates the seismic geological background of this area. In this paper, Rn concentrations in underground waters of three wells in the Longxian - Baoji fault zone (LX, SW and BJ) and one well (MX) in the Northern Margin of Qinling Mountains fault zone are analyzed (Figure 1).
3. Analytical methods
The Rn concentration data presented in this paper are from the geophysical monitoring network of Shaanxi Earthquake Agency. The water samples were from springs, which mean that the four wells are artesian wells. A 2 ~ 3 m well with a drive pipe was built so as to collect fresh water every day. A 2 L bottle was used to collect the water sample, and an FD-125 radon detector was used to analyze the radon concentration. Firstly, the water sample was bubbled and degassed, and the bubbling mode, time, speed and temperature were strictly controlled. Then, the instrument was pre-heated for 15 minutes and then, the Rn measurement in the sample could start. Finally, reading of the Rn concentration was obtained. This process was performed at 10 a.m. everyday thus to get a new Rn value. The instrument was regularly calibrated. This paper mainly discusses the data of 2019 and 2020. First, the average value of each month was analyzed. Secondly, the second average value was obtained by eliminating the monthly data where interferences from the external environment, i.e. rainy and the dry seasons, were recognized. Finally, on the basis of the monthly average values of Rn concentrations in 2019 and 2020, the difference in terms of Rn values between 2019 and 2020 was calculated. Thus, the contour map is made by using software Surfer 8. The seismic catalogue data since 1970 are from the seismic monitoring network of China Seismological Bureau.

4. Results and discussion

4.1. Rn concentration characteristics in well water
(1) Characteristics of average Rn in well water
The monthly Rn average values of four wells in 2019 and 2020 are shown in Table 1. After removing environmental interference in recent two years, it shows that Standard Deviation of the monthly Rn average value in April is the lowest all over the year. Considering the meteorological conditions (rainfall, temperature, atmosphere, etc.) and industrial activities (hot spring pumping), its value is the most reliable in April. The measured Rn average values in April of 2019 of MX, BJ, SW
and LX are 46.13, 46.57, 41.84 and 12.93 Bq/L, respectively. The measured Rn average values in April of 2020 are 47.00, 49.00, 40.60 and 12.23 Bq/L, respectively. The overall trend is higher in the South and lower in the north (Figure 2).

Table 1. The monthly Rn average values of four wells in 2019 and 2020.

|       | 2019  |       | 2020  |       |
|-------|-------|-------|-------|-------|
|       | Rn (Bq/L) STD | Rn (Bq/L) STD | Rn (Bq/L) STD | Rn (Bq/L) STD |
| Jan.  | 11.94 ±0.33 | 39.86 ±0.35 | 40.39 ±0.94 | 45.10 ±2.09 |
| Feb.  | 12.27 ±0.34 | 39.85 ±0.62 | 41.74 ±0.72 | 43.75 ±1.32 |
| Mar.  | 12.41 ±0.36 | 40.32 ±0.54 | 43.53 ±0.75 | 41.19 ±1.74 |
| Apr.  | 12.93 ±0.34 | 41.84 ±0.35 | 46.57 ±0.46 | 46.13 ±1.16 |
| May.  | 14.19 ±0.35 | 42.16 ±0.43 | 47.49 ±1.31 | 47.54 ±2.26 |
| Jun.  | 15.03 ±0.38 | 42.33 ±0.52 | 47.13 ±0.68 | 46.01 ±3.47 |
| Jul.  | 14.82 ±0.79 | 42.85 ±0.58 | 47.99 ±0.45 | 47.61 ±1.90 |
| Aug.  | 13.36 ±0.36 | 43.82 ±0.47 | 48.03 ±0.68 | 46.62 ±2.22 |
| Sept. | 13.12 ±0.30 | 42.87 ±0.45 | 46.73 ±1.60 | 49.97 ±2.97 |
| Oct.  | 14.05 ±0.30 | 42.08 ±0.59 | 49.76 ±1.00 | 43.03 ±3.71 |
| Nov.  | 13.76 ±0.34 | 41.48 ±0.42 | 48.22 ±1.82 | 38.67 ±4.37 |
| Dec.  | 13.43 ±0.30 | 41.14 ±0.89 | 44.41 ±0.59 | 27.29 ±3.50 |

*represents that the data reliability has been affected by environmental interference
/represents “no data available”. The analysis of Rn concentration had stopped because of the 2019-nCoV.

Figure 2. The contour map of average well water Rn values in April of 2020 in the Longxian - Baoji fault zone.
(2) Analysis of Rn difference in well water from 2019 to 2020

The difference of Rn values of MX, BJ, SW and LX stations between 2020 and 2019 are 0.87, 2.43, -1.24 and -0.70 Bq/L, respectively. As shown in Figure 3, the contour map of Rn concentration trend in this area shows that there is a differential gradient zone between SW and BJ site. It indicates that Rn measurement value in the BJ - MX sector is on the rise, and that in the LX - BJ sector is on the decline. This is corresponding to the fact that the BJ - MX sector is a magnitude 7 fracture area and the LX - BJ sector is a seismic gap proposed by Du F et al. (2018)[17].

4.2. Relationship between Rn characteristics of well waters, fault movement and seismicity

According to the spatial distribution, fault activity characteristics, historical and current seismicity, Wenchuan earthquake’s impact and geological structure researches of the Longxian - Baoji fault zone, it infers that F1 is the most active fault in this fault zone [16,18](Zhang X K et al., 2017; Wang S D, 2018). Correspondingly, the Rn values in the area where F1 was distributed (Figure1). Additionally, the Rn value has increased in 2020 compared with that of 2019 (Figure 2). In detail, the results of this study show that there is a differential gradient zone between SW and BJ site, indicating that the Rn value of well water in the BJ - MX sector (SE sector) is on the rise, while that in the LX - BJ sector (NW sector) is on the decline. This is corresponding to the fact that the SE sector is characterized by a magnitude 7 fracture area and the LX - BJ sector is located in a seismic gap proposed by Du F et al. (2018)[17].When the fault zone is in the active period, the original equilibrium between water and rock in the crustal medium is broken, and the gas components (Rn, CO₂, He, etc.) in the underground water will change abnormally. 1). Spatially, the content of gas escaping from the fault fracture zone is generally higher than other places. And the amount of gas escaping from the underground in the epicenter area is significantly higher than that from the peripheral area. F1 is the most active fault in this fault zone, resulting in that the Rn values around F1 is higher than other places. The Rn values of the NW sector is lower than that in the SE sector, which indicates that the NW sector has a poor gas diffusion channel and a high locking degree. 2). Temporally, the duration of the escaping gas anomaly may also be related to the magnitude of the impending earthquake. Therefore, the concentration value of the escaping gas and its variation characteristics can reflect the strong and weak state of fault activity. The Rn values of the NW sector have decreased while the Rn values of the SE sector have increased in 2020 than in 2019. It can be inferred that energy accumulation in the NW sector is higher than that of the SE sector. 3). The distribution characteristics of underground gas in different fault types are different. For example, a). there are many high value areas in the hanging wall of the reverse fault; b). the high value of the normal fault is widely distributed; c). the high value of the strike slip fault is concentrated in the core. F2, F3, F4 and F5 meet with each other in BJ site, which is why the Rn values of BJ site has a highest increase among the four sites (Figure 3). 4). The escaping form of underground gas varies with the fracture degree of fault. For example, if the main fault has a weak rupture and the development of its secondary fracture is poor, the underground gas is not easy to escape; otherwise, it will escape from the crust with a higher concentration. The high Rn values of the SE sector is consistent with the characteristics of a magnitude 7 fracture area [17].

At the same time, this paper analyzes three typical historical earthquakes in this area and the earthquake catalogue of seismic monitoring network of China Seismological Bureau since 1970. As shown in Figure 4, a) represents the distribution of earthquakes with M ≥ 2 in the Longxian - Baoji fault zone; b) represents the distribution of earthquakes with M ≥ 0 in this fault zone. It can be seen that there is a sparse section of minor earthquake in the gray shadow area, which is consistent with the research results of Du F et al. (2018)[17]. According to the variation characteristics of Rn concentration in well water, it can be roughly divided into two ends: 1). The LX - BJ sector (NW sector), medium to strong earthquakes are relatively developed in history. There is a seismic gap with no rupture of M ≥ 6 1/2 strong earthquake occurred in the Longxian - Baoji fault zone for at least 1400 years. And there is a small earthquake gap in the recent 200 years. At the same time, the Rn value of well water in this sector is low and shows a downward trend in recent two years. It indicates that the
underground gas escape channel is not developed; the connectivity with the underground is poor. And the stress of the fault has a trend of gradual accumulation [19]. 2). In the BJ - MX sector (SE), there is an M 7 earthquake rupture zone. In recent years, small earthquakes are relatively developed, and Rn in well water is high and rising in recent two years. It shows that the underground gas channels are relatively developed; better connected with the underground. And the fault has a less stress accumulation.

Figure 3. The contour map of 2019 - 2020 well water Rn values’ difference in the Longxian - Baoji fault zone.

Figure 4. Seismic activity since 1970 and three strong historical earthquakes in the Longxian – Baoji fault zone.
Notes: 1) different circles represent earthquakes of different magnitudes; 2) the biggest red circles represent three M 5 ~ 6 earthquakes in history; 3) the circle in shadow represent weak active area of small earthquakes.

In conclusion, the Rn concentration of well water in the NW sector (~12 Bq/L) of the Longxian - Baoji fault zone is lower than that in the SE sector (40 ~ 50 Bq/L). And Rn measurement value in the NW sector has been on the decline, and that in the SE sector has been on the rise since 2019 to 2020. Combining with the seismic activity, the fault locking degree is higher, and the geological structure and fault distribution form of the NW sector are more complex than those of the SE sector. In detail,
the connectivity between the NW sector and the deep crust is relatively poor, which is not conducive to the upward diffusion and migration of deep fluids. At least in the last 1400 years, there is a seismic gap with no rupture of M ≥ 6 1/2 strong earthquakes occurred in this sector. And there has been a small earthquake sparse zone in the past 200 years. All these evidences show that medium to strong earthquake is more likely to occur in the NW sector of the Longxian – Baoji fault zone in the future.

5. Conclusions
Based on the analysis of the underground water Rn values of four wells in the Longxian - Baoji fault zone and its peripheral faults, this paper comparatively analyses the movement mode of the active faults, historical earthquakes and the distribution characteristics of earthquakes since 1970. The results show that there are the following corresponding relations between them: 1) the Rn values in well waters of the NW sector in the Longxian - Baoji fault zone are low, and they show a downward trend in recent two years; 2) there is a poor connectivity between escaping gas and deep crust; 3) the poor permeability is not conducive to the upward diffusion and migration of deep fluid; 4) there are strong earthquake gap and small earthquake sparse area, with high degree of locking. On the contrary, the SE sector has opposite characteristics. Thus, the possibility of medium to strong earthquake occurs in the NW sector in the future is larger than that in the SE sector.

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References
[1] Yu C H 2010 Research on the faults activity and seismic hazard in Shenzhen Zhejiang University
[2] Deng Q D 2002 Exploration and seismic hazard assessment of active faults in urban areas Seismology and Geology 4
[3] Deng Q D, Xu X W, Zhang X K, et al. 2003 Methods and techniques for surveying and prospecting active faults in urban areas Earth Science Frontiers 01
[4] Igarashi G, Wakita H 1990 Groundwater radon anomalies associated with earthquakes Tectonophysics 180 2-4.
[5] Igarashi G, Saeki S, Takahata N, et al. 1995 Ground-Water Radon Anomaly Before the Kobe Earthquake in Japan Science 269 5220
[6] Singh M, Kumar M, Jain R K, et al 1999 Radon in ground water related to seismic events Radiation Measurements 30 4
[7] Ghosh D, Deb A, Sengupta R, et al 2009 Anomalous radon emission as precursor of earthquake Journal of Applied Geophysics 69 2
[8] Lee, H.A, Woo, N C 2012 Influence of the M9.0 Tohoku Earthquake on groundwater in Korea. Geosci. J 16
[9] Lee S H, Ha K, Hamm S Y, et al 2013 Groundwater responses to the 2011 Tohoku Earthquake on Jeju Island, Korea Hydrological Processes 27 8
[10] Chanyotha S, Kranrod C, Burnett W C, et al 2014 Prospecting for groundwater discharge in the canals of Bangkok via natural radon and thoron Journal of Hydrology 519
[11] Hwa Oh Y, Kim G 2015 A radon-thoron isotope pair as a reliable earthquake precursor. Scientific Reports 5 1
[12] Sun X L, Wang J, Xiang Y, et al. 2016 Statistical characteristics of subsurface fluid precursors based on Earthquake cases in China Earthquake 036 004
[13] Shi W 2011 The analysis of the developmental characteristics and activity about fault zone of Longxian – Baoji. Chang’an University
[14] Wan H L, Liu D Y, Song H L 2016 Study on the spatial – temporal distribution characteristics
of earthquake disasters in the history of Baoji Journal of Baoji University of Arts and Sciences (National Science) 36

[15] Shi Y Q 1996 On the movement forms of Longxian – Qishan – Zhouzhi fault and the seismicity characters along the fault Northwestern Seismological Journal 018 002

[16] Zhang X K, Shao H C, Feng L L 2017 Analysis on seismicity in the Longxian – Baoji fault zone Plateau Earthquake Research 01

[17] Du F, Wen X Z, Feng J G, et al 2018 Seismo-tectonics and seismic potential of the Liupanshan fault zone (LPSFZ) China. Chinese Journal of Geophysics 061 002

[18] Wang S D, 2018, Tectonic deformation in Late Cenozoic of Liupanshan – Baoji fault zone in the NE Margin of Tibet Plateau. Northwest University

[19] Ye M S, Meng G J, Su X N 2018 Locking Characteristics and Slip Deficits of the Main Faults in the Northeast Margin of Tibetan Plateau. Earthquake 038 003