Study on Seismic Precursory Anomaly Signals Based on Critical Slowing Phenomena

Xiaoyun Su1,2*, Lijun Chen1,2, Wencai Wang1,2, Hongmei Liu1,2 and Weidong Zhou1,2
1 Gansu Earthquake Agency, Lanzhou, China
2 Lanzhou National Geophysical Observation and Research Station, Lanzhou, China
*Corresponding author e-mail: suxy@gsdzj.gov.cn

Abstract. This paper applied the principle of critical slowing down to the processing of radon concentration observation data, calculated the autocorrelation coefficient and variance which can characterize critical slowing down by taking Wenchuan Ms8.0 earthquake on May 12, 2008, Lushan Ms7.0 earthquake on April 20, 2013, Minxian-Zhangxian Ms6.6 earthquake on July 22, 2013, Jiuzhaigou Ms7.0 earthquake on August 8, 2017 as examples. The result indicated that the water radon concentration at several stations has obvious critical slowing phenomenon before server earthquakes. The formation mechanism of radon concentration anomalies in seismic underground fluids was discussed in the context of the focal mechanism solution of several earthquakes. It is considered that the phenomenon of critical slowing down before server earthquakes is related to the earthquakes occurred combined with the hydrodynamic mechanism of radon anomaly and the structure of the abnormal points.

1. Introduction
The relevant researches on earthquake precursor anomalies are in the ascendancy and have achieved a lot of achievements. These studies were mainly focus on the retrospective studies of the possible short-term, medium-term and long-term seismic activity anomalies and their various mechanisms after the occurrence of earthquakes [1-3]. However, it is still one of the scientific problems to be discussed whether the abnormal early signals indicating the imminent occurrence of earthquake can be observed before the earthquake.

In China, seismic fluid observations based on hydrogeology and hydrogeochemistry have been conducted since the magnitude 7.2 earthquake in Xingtai in 1966 [4], and radon, as a seismogenic sensitive component of underground fluids, is one of the underground fluid measurements observed for the longest time and most widely studied in seismic science research. Some scholars have attempted to extract anomalies using underground fluid observation approaches. For example, Yan Rui used the critical slowing down method to study the critical slowing down phenomenon of water radon before the magnitude 8.0 Wenchuan earthquake, and concluded that the water radon of several stations in the epicenter and nearby areas before the earthquake was anomalous [5]. Yang et al. used the 13-point moving average and membership function method to analyze the changes of water radon observation data in Southeastern Gansu before the Wenchuan earthquake and the Minxian-Zhangxian earthquake and found that there were synchronous or quasi-synchronous changes in the observation data. They considered that the simultaneous changes of multiple data at different measuring points in a certain area are precursor anomalies of earthquakes [6]. Tang et al. used the slope k and correlation...
coefficient r values to extract the single short-term anomalies of water radon and water mercury in Sichuan and Yunnan regions, and used the population non-uniformity calculation method to calculate the selected multi-point observation data, and the results showed that the changes in rising or dropping of water radon before a moderate to strong earthquake have some predictive significance [7]; Wang et al. analyzed some of the anomalies using the membership function method based on a review of the anomalies proposed by previous authors [8]; all of these have practical implications for earthquake prediction.

The paper applied the principle of critical slowing down to the processing of radon concentrations observation data, and analyzed the variance and autocorrelation coefficient indexes that can reflect the critical slowing down characteristics, taking the magnitude 8.0 Wenchuan earthquake on May 12, 2008, the magnitude 7.0 Lushan earthquake on April 20, 2013, the magnitude 6.6 Minxian–Zhangxian earthquake on July 22, 2013 and the magnitude 7.0 Jiuzhaigou earthquake on August 8, 2017 as examples, it is considered that the phenomenon of critical slowing down before server earthquakes is related to the occurrence of earthquakes combined with the hydrodynamic mechanism of radon anomaly and the structure of the abnormal points.

2. Detection Method

When a control parameter approaches the threshold (bifurcation point) of a system with random action, critical slowing often leads to the phenomenon of autocorrelation and increase of fluctuation variance [9-10]. In general, in the process of the system approaching the critical point, the recovery rate of small disturbance will be slower and slower [11-12]. When the system approaching the critical point, the recovery rate will approach zero, the autocorrelation term will approach 1, and the variance will approach infinity. Therefore, the increase of variance and autocorrelation coefficient can be used as the precursor signal of the system approaching the critical point to detect the critical slowing down phenomenon.

3. Critical slowing down of water radon

In this study, the theory of critical slowing down was applied to the processing of radon concentration observations data, and the autocorrelation coefficients and variance characterizing the critical slowing down phenomenon are calculated to obtain information on earthquake precursor anomalies. The calculation results show that the water radon concentration observation data of several stations have shown obvious critical slowing down phenomenon before several earthquakes. Here, the water radon data from Wulipu, Wushan No. 22 well and Fujianchang are used as examples to illustrate the critical slowing down phenomenon before several earthquakes.

Figure 1 shows the calculation results of Wulipu water radon observation data. From (c) and (d), we can see that the high-frequency information of Wulipu water radon after removing the trend shows an obvious phenomenon of increased perturbation amplitude and gradually lengthened period since around August 2007 and October 2012, while the autocorrelation coefficient and variance show an obvious phenomenon of increase until the earthquake occurs. Hence, the Wulipu water radon demonstrated obvious critical slowing down approximately 3 years before the Wenchuan earthquake, 1 year before the Lushan earthquake, 10 months before the Minxian earthquake, and 1 year before the Jiuzhaigou earthquake.
Figure 1. Critical slowing down of water radon in Wulipu
(a) the original water radon observation data, (b) the high-frequency perturbation information with period and trend removed, (c) the variance of high-frequency information, (d) the autocorrelation coefficient of high-frequency information.

Figure 2 shows the results of critical slowing down in the water radon observation data from Wushan Well No. 22; the high-frequency information demonstrates a significant increase in autocorrelation coefficient and variance from 2003 and 2016, and the variance exhibits a significant increase since 2011 until the earthquake.
Figure 2. Critical slowing down of radon water in Wushan Well No. 22
(a) the original water radon observation data, (b) the high-frequency perturbation information with period and trend removed, (c) the variance of high-frequency information, (d) the autocorrelation coefficient of high-frequency information.

Figure 3 shows the results of the critical slowing down of water radon observations at Pingliang Fujianchang; the high-frequency information shows a significant increase in the autocorrelation coefficient and variance since around 2007 and 2015, and the autocorrelation coefficient shows a significant increase since around 2013 until the earthquake.
Figure 3. Critical slowing down of water radon in Fujianchang
(a) the original water radon observation data, (b) the high-frequency perturbation information with period and trend removed, (c) the variance of high-frequency information, (d) the autocorrelation coefficient of high-frequency information.

In addition, the short-term anomalies of water radon data before the Wenchuan earthquake are obvious and show trough-type changes. By performing moving filtering comparisons of water radon values at each measurement point, the effect of using 13-point smoothing was considered satisfactory. In this paper, the water radon data underwent moving filtering at 13 points to extract anomalies, and the curve of radon values after smoothing at some measurement points is shown in Figure 4. The variation of water radon data in 2008 in Tianshui Wulipu is characterized by annual cycle breaking low value anomaly. Around March, the water radon value fluctuates up and down anomalously with large amplitude, and after the reversal, the earthquake occurred during the high value fluctuation. The anomalous pattern of water radon in Tongwei is mainly low value with sudden jumps. From January 24 to February 20, 2008 the measured values were low, from February 21 to April 8, the measured values were slightly higher with fluctuations, among which two large sudden jumps occurred in March, with seismicity in the process of rising. Water radon in Qingshui Hot Spring is less affected by temperature and other factors, and the measured value is stable. Radon values begin to decline gradually in middle and late February and rose rapidly in late April, showing a positive correlation with rising seismicity. Well No. 22 and Spring No. 1 in Wushan are 100 m apart, and the changes of radon values at the two measurement points are basically synchronized. The radon values of the two
measurement points rise gradually from the beginning of January, start to drop in mid-April, and start to reverse and rise in the beginning of May, during which an earthquake occurred.

Figure 4. 13-point smoothed curve of daily water radon values before the Wenchuan earthquake in different observation stations (a) Wulipu; (b) Tongwei; (c) Qingshui; (d) Wushan Well No. 22; (e) Wushan Well No. 1; (f) Diangou.

4. Discussion
Since Ulomov discovered in 1966 that the water radon concentration in the precursor data of a magnitude 5.3 earthquake in the Tashkent region of the USSR had obvious abnormal changes before the earthquake, changes in groundwater radon concentrations before earthquakes have attracted
significant scholarly attention globally [13]. Regarding the formation mechanism of radon concentration anomalies in underground fluids, diffusion, convection, pumping caused by temperature change, transport of underground fluid, and stress-strain have been the most widely studied. Radon migration is highly complex and often controlled by many factors, functioning as a combination of many migration mechanisms.

The hydrodynamic mechanism of water radon anomaly shows that when the process of earthquake preparation affects the water-bearing rock, even a small magnitude of stress action may deform the rock, and the deformation may cause changes in void pressure and changes in hydrodynamic conditions in the seepage field, and lead to changes in the water flow state within the well aquifer system, resulting in anomalous changes in well water radon content [14-16]. In the Longmenshan active fault in the Wenchuan earthquake, the co-seismic deformation movement mode has obvious segmentation, with both thrust and right-lateral strike-slip component [17, 18]; the epicenter of the Lushan earthquake is located near the Qianshan rupture in the southern section of the Longmenshan fault zone, which is a pure trust seismic rupture [19]; the epicenter of the Minxian-Zhangxian earthquake is located between the northern edge of the West Qinling rupture and the Lintan-Tangchang rupture, near the Lintan-Dangchang rupture [20], the overall nature of the rupture is mainly southward trust, with a left-lateral strike-slip component; Jiuzhaigou earthquake structure is the Shuzheng rupture located between the Minjiang rupture and the Taizang rupture, which is left-lateral strike-slip [21], the uneven stress concentration of each rupture section in the process of neotectonic movement will affect the deformation of the water-bearing rock layer, underground fluids are widely present in the rock pore space and in constant movement, the migration of fluids drives the migration of radon dissolved in it [22]. Anomaly patterns and timing may be related to the tectonic location of measurement points and tectonic dynamic backgrounds of various seismic conditions.

5. Conclusion
The abrupt signal of radon concentration observation in water was studied based on the critical slowing down theory when combined with several moderate and strong earthquakes. The calculation results show that some water radon observation data appeared obvious critical slowing phenomenon before the magnitude 8.0 Wenchuan earthquake on May 12, 2008, the magnitude 7.0 Lushan earthquake on April 20, 2013, the magnitude 6.6 Minxian–Zhangxian earthquake on July 22, 2013 and the magnitude 7.0 Jiuzhaigou earthquake on August 8, 2017 and were relatively synchronous in time. It is considered that the phenomenon of critical slowing down before server earthquakes is related to the occurrence of earthquakes combined with the hydrodynamic mechanism of radon anomaly and the structure of the abnormal points. Although this paper is still a retrospective study of earthquake cases, the critical slowdown is a new method for judging whether the seismic observation data tends to the critical stage, which provides a new method for looking for early warning signals before the occurrence of disasters. It needs to be further studied by accumulating observation data and earthquake case data.

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