A method for analyzing the correlation between earthquakes and underground fluid: The case of hydrogen concentration at Eryuan, Yunnan, China

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ABSTRACT

Underground fluid monitoring is a common method for earthquake prediction. However, the correlations depending on statistic between the results of various underground fluids and earthquakes are usually not significant. In this study, based on a set of experimental instruments to monitor the hydrogen concentration escaping from the observation wells at Eryuan station, it was found that the hydrogen concentration changed dramatically before most earthquakes occurred in the surrounding area. Based on this finding, a detailed analysis of the changes in the hydrogen concentration in the wells is conducted to extract the changes that are related to earthquakes and to derive the related anomaly indicators. Then, the concept of the impact factor is proposed, and correlation analysis is performed with the impact factor and the integral value of hydrogen concentration at Eryuan. The results show that there is a significant correlation between the sudden changes of the hydrogen concentration at Eryuan and the neighboring earthquakes.

Keywords: Underground fluid, Correlation analysis, Hydrogen concentration,

Earthquake prediction,

1. INTRODUCTION

Underground fluid analysis is an important tool for earthquake prediction. Underground fluid parameters include the water level, water temperature, radon, mercury, methane, helium and carbon dioxide concentration within the fluid in earthquake-prone areas. Analyzing their changes helps to predict some earthquakes. Earthquakes are caused by fault zone activities and these activities are thought to affect underground fluids which are contained in crevices or fissures of rocks. Researchers have tried to predict earthquakes by analyzing underground fluids changes.

However, the correlation between underground fluid and earthquakes is mostly statistical. If the changes of underground fluid are large enough and the duration of them is long enough simultaneously, it is called an anomaly. Researchers record the earthquakes after each anomaly, and get the probability. Then, once another anomaly occurred again, this probability can be used to show earthquakes possibility. However, it requires numerous samples to make a reliable statistical analysis, while large earthquakes will generally not occur too many times in a limited area.

Hydrogen is one of the components of underground fluids. Since Hiroshi et al. (1980) found that hydrogen is related to fault activity, many scholars have researched fracture zone activity and the sources of hydrogen (Sugisaki et al., 1984, 1986; Ware et al., 1984; Ito et al., 1999). Two main kinds of hydrogen have been studied: hydrogen in fracture zones, mainly in soil, and hydrogen in groundwater, such as in wells and springs. They thought earth’s interior gas is escaping more rapidly into the atmosphere, and some chemical reactions may occur there. Consequently, monitoring in such places may obtain more obvious information. Usually, hydrogen diffuses from the Earth's interior to the atmosphere because its concentration in these places is generally higher than that in the atmosphere. The seismogenic activity may be accompanied by a change in the stress states of underground rocks. The change may affect the gas diffusion speed and adsorption state (Sugisaki et al., 1986; Ito et al., 1999; Kuo et al., 2006) and even generate hydrogen directly (Kameda et al., 2002, 2003). Hirose et al. (2011) proposed a quantitative formula of generated hydrogen and rock fractures. Seismogenic activity may also change the hydrogen concentration. These changes can be detected by instruments installed in wells, springs and fault zones. Earthquake predictions can be based on detected information.

Although scholars found that the hydrogen concentrations in some springs changed before earthquakes in the 1980s, they only counted the changes of hydrogen concentration before several earthquakes to determine the correlation. The influences of earthquakes on observation station are not differentiated. The phenomenon that the hydrogen concentration changed before some earthquakes, but did not change before others earthquakes has not been explained.

2. STUDY AREA AND INSTRUMENTS

Yunnan, China, is located near the junction of the Eurasian Plate and the Indian Ocean Plate. The collision of the two plates leads to frequent earthquakes in this area (Xianfu et al., 1981; Kan et al., 1986). The longitudes and latitudes in Yunnan are approximately $97°-107°$ E and $21°-31°$ N, respectively. To better study the varying characteristics of hydrogen concentrations before earthquakes, this study extends the longitude of earthquakes with Ms≥5 to $94°$ (Fig. 1). Eryuan station is located in northwestern Yunnan Province near the Red River fault, Lijiang-Xiaojinhe fault and other faults. The station has a specially built well that is used to observe underground fluid. This well was originally an artesian well, which was cut off after 2008. It is 196 meters deep, and its water temperature is approximately 31 °C.

The micro-hydrogen monitoring instrument used in this study was produced by the Intelligent (Xiamen) Sensor Company. It uses a chip to directly detect the hydrogen concentration in the gas without the need for gas collection and pumping, and its data is more reliable. The principle is that a change in the concentration leads to a resistance change in the probe and then a change in the current. The current-change data are amplified and finally converted into a digital signal. The probe is placed in the wellhead, approximately 1 meter higher than the maximum water level, and the wellhead is simply covered. The sampling rate was approximately one time per minute. Four sets of instruments were installed in Yunnan around January 2018, and the change only at Eryuan is obvious before the earthquakes. The hydrogen background concentrations of the other three stations are too high, and the hydrogen concentration changes related to the earthquakes may be very weak, so the total concentrations cannot change significantly.

3. RESULTS

In Yunnan, earthquake magnitude prediction mainly uses the Ms scale (Chinese national standard GB 17740−2017). The seismic data used in this paper originate from the fast report catalog, the data in which were measured by the Monitoring Center of the Seismological Bureau of Yunnan Province. The times of the earthquakes and instruments are recorded in Beijing time. From 2018 to 2019, 51 Ms≥4.0 earthquakes occurred in the study area (counting the maximum magnitude of one of the earthquakes 50 kilometers apart within the same day). Earthquakes with Ms values between 4.0 and 4.9 are ranked from 1 to 32, and Ms≥5.0 earthquakes are ranked from A to S. I is equivalent to 6.3, and K is equivalent to 6.0 (Table 1 and Figure 1).

The variation in the hydrogen concentration over time is shown in Fig. 2. The concentration is 0 ppm in a given period of time. It is a cyclic increasing–decreasing pattern of change, showing a peak in the other time period. To avoid the need to calibrate to zero after restart, we upgraded the probe of the instrument in November 2018, resulting in the loss of a section of data. The basic form and trend of the data do not change before and after the probe upgrade. According to statistics, the data continuity rate is approximately 97% (not counting the data from the upgrade period). Therefore, the missing data have little impact on the research.

4. DISCUSSION

4.1 Analysis of the Correspondence of Hydrogen Concentration Changes and Earthquakes

During the period from February 1 to May 15, 2018, hydrogen concentrations were low in Eryuan. However, on February 20, 2018, a magnitude 4.0 earthquake occurred in Jingdong, 200 km away from Eryuan, but there was no significant change in the hydrogen concentration in Eryuan. Considering the small magnitude of this earthquake, this study extends the range slightly and analyzes only the magnitude 4 earthquakes within approximately 250 km. After observation and analysis, the hydrogen concentration in Eryuan should be 0 ppm (background value) during time periods without earthquakes. The specific reasons are as follows: 1. most of the changes in hydrogen concentration consist of an increase from 0 ppm to extreme values and then a decrease to 0 ppm. 2. During the long time period when hydrogen concentrations were 0 ppm (e.g., August 1 to September 31, 2019), there were no earthquakes of Ms>4 in the study area or only distant earthquakes (magnitudes 4-5 250 km away and magnitudes >5 550 km away). Because the background value is 0 ppm, an anomaly period in Eryuan is a time period when the hydrogen concentration increases from 0 ppm and then decreases back to 0 ppm. However, some of these changes are long-lasting, the concentration increases more, and the changes are obvious. The peak-like change from 0 ppm to 0 ppm is defined as an event. After comparative analysis, if the time integral concentration of an event with a maximum value of more than 0.6 ppm and duration of more than 6 days is more than 3 ppm • D, it is regarded as an *effective event*. Based on the statistics of more than 15 events, the author believes that, in the case of Eryuan station, earthquakes are more likely to occur within 40 days after the end of an effective event or during an effective event, which is similar to the conclusions of many researchers.

To analyze the correlation between effective events and earthquakes, it is necessary to analyze earthquakes corresponding to effective events first. To ensure that the study is scientific, some logical assumptions need to be established first. 1. When two earthquakes are of the same or similar magnitude, if there is a change in hydrogen concentration before the farther earthquake, there should be a change in the closer earthquake 2. When the two earthquakes have the same distance between the epicenter and Eryuan, there is a change in the hydrogen concentration before the earthquake with a smaller magnitude, and there should be a change in the earthquake with a larger magnitude.

Based on a previous analysis, the author collated the 15 main effective events since the observation and the corresponding earthquake, as shown in Table 1. From May 17 to July 12, 2018, the concentration decreased after increasing and then decreased after increasing again. Although the concentration decreased at the beginning of June but did not reach 0 ppm, the anomaly was still occurring, so the change is counted as an event. In the V event, although the instrument was just upgraded, the trend of the concentration change at the time of upgrading was increasing and decreasing at the completion of the upgrade. Therefore, it is also counted as a valid event.

The events of the above pairings of Ms ≥ 5.0 earthquakes roughly meet the two assumptions above. However, in pairings of Ms 4.0-5.0 earthquakes, earthquake 15 corresponding to event IX is farther than earthquakes 28, 20, 2 and 11; furthermore, the magnitude of earthquake 20 is greater than that of earthquake 15. Regarding earthquake 2, a certain increase in the hydrogen concentration occurred around February 1. Earthquakes 11, 20 and 28 may be the manifestation of many earthquakes with one stress accumulation; for example, a series of Ms 4 and 5 earthquakes occur after a Ms≥6 earthquake. Then, earthquakes 28 and 29, earthquakes 20 and K, and earthquakes 11 and H may be caused by the same activity.

4.2 Correlation Analysis and Area Delimitation

The integral value of the hydrogen concentration represents the total amount of hydrogen diffusing into the atmosphere during a period. The energy released by an earthquake and the magnitude of the earthquake are related as follows: $lgE=1.5Ms+11.8$ (Gutenberg et al., 1955); thus, $E=10^{11.8}\times10^{(1.5Ms)}\approx10^{11.8}\times31.62^{Ms}$. The difference in the energy of two adjacent magnitude earthquakes is approximately 31.62 times, so the energy is positive and linearly correlated with the magnitude power of 31.62.

The concentration changes before the earthquake in every event. Certainly, the change has little connection with the rock fracturing during the earthquake but rather with the energy accumulation before the earthquake. Before the earthquake, the rocks around the epicenter experienced weak elastic deformation with increasing stress, leading to the accumulation of an amount of elastic potential energy. The change in stress may have led to some kind of chemical reaction between the rock and water, such as a water–rock reaction of silicate, and generated some hydrogen. If this explanation is correct, then the change in stress leads to chemical changes in all rocks around the epicenter, and it may occur in a hemisphere centered on the epicenter.

In the integrals of all events, the concentration change of the first event is relatively strange, and its integral value is overly large. This may be related to the situation that corresponds to double earthquakes (two destructive earthquakes with similar magnitudes and very close locations and times). They were not included in the correlation analysis. Dividing the seismic energy of other events by the third, fourth and fifth powers of the distance, the authors constructed three graphs of the results and the integral values. After a comparison, the correlation of the fourth power is the best, the third power is the second, and the fifth power is the worst. Therefore, the third and fourth power results are maintained. Figure 3 shows that, except for the XIII and XIV events, these discrete points have two slopes. The integral value of one type is relatively small, i.e., less than 10 ppm • D, and the other is larger, i.e., greater than 10 ppm • D. The two earthquakes corresponding to the XIII and XIV events are very close to Eryuan, at 30 km and 60 km, respectively. They are quite different from the other points in the figure. This may be another hydrogen concentration state when an earthquake occurs near Eryuan. According to their data, the result of the energy divided by the third or fourth power of the distance is too large, but the amount of escaped hydrogen is small.

Let x be the integral value and y be the seismic energy divided by the third or fourth power of the distance. For the four slope forms of the two calculation methods, the correlation is analyzed in Figure 3.

These data reveal that correlations between the two methods are both good, but the fourth power is better.

The energy of an earthquake divided by the third or fourth power of the epicentral distance of a location is defined as the *impact factor*, which indicates the impact of the earthquake on the generated quantity of hydrogen at the location. Therefore, the impact of an earthquake on Eryuan should decrease with the increase in the third or fourth power of the distance. Through correlation analysis, it can be inferred that the corresponding relationship between events and earthquakes should be roughly correct, and there should be a correlation between them.

The two types of impact factors of earthquakes are obtained by dividing the energy by the third power or the fourth power of distance. The first 27 earthquakes of the third power are 29, 22, C, I, J, K, E, D, F, N, H, 20, M, A, B, O, G, P, L, 7, R, 8, 11, 1, S, 15, and 16 (N, 20, M, O, P, L, R, 8, 1, and 16 are not corresponded). Those of the fourth are 29, 22, C, I, J, E, K, D, 20, F, H, N, 11, A, B, 7, M, G, 15, O, L, P, 8, R, 1, 2, and S (20, N, M, O, L, P, 8, R, 1, and 2 are not corresponded). Earthquakes N, 20 and M may be included by K in the cubic power calculation results. The concentration did not increase before earthquakes O and P and some other earthquakes with large impact factors, but it increased before G, 7, 11, and 15, whose impact factors were smaller than theirs. This result is not very reasonable. In the calculation results of the fourth power, except for earthquake S, there is no obvious contradiction. On December 26, 2019, an earthquake of Ml3.7 (not recorded in the Ms scale) occurred in Yangbi, 54 km from Eryuan. It is preliminarily estimated that the impact factor of this earthquake is between K and D. Therefore, the XV event may correspond to this earthquake, not S. Combined with the correlation calculation results, it is concluded that the integral value of the hydrogen concentration is more likely to be related to seismic energy divided by the fourth power of distance. The impact factor should also be defined as the latter. Based on the corrected earthquake of the XV event, we recalculated the correlations. It is found that there is little change and is not repeated here.

When several earthquakes occur in one event, the earthquake with the largest impact factor should prevail. The impacts of several earthquakes on Eryuan may not be superimposed.

Earthquake with an impact factor greater than 0.0002 (a magnitude greater than 4) in multiple earthquakes corresponding to the same event can be collectively referred to as a same-force earthquake with the largest impact factor. For example, earthquake 20 may be the same-force earthquake of K. Based on the statistical results, the ranges of earthquakes with different magnitudes that can impact Eryuan are obtained. The range of earthquakes of Ms4-5 is approximately 250 km away from Eryuan. The range of earthquakes of Ms5-6 is approximately 550 km away from Eryuan. The range of earthquakes of Ms≥6 cannot be determined at present.

5. CONCLUSION

1. The hydrogen concentration at Eryuan varies significantly before earthquakes within a certain epicentral distance. The distance of earthquakes with a magnitude of 4-5 is approximately 250 kilometers, and the distance of earthquakes with a magnitude of 5-6 is approximately 550 kilometers. Before these earthquakes, the hydrogen concentration at Eryuan increased with a subsequent drop.

2. The impact factor is defined as the released energy of an earthquake divided by the quartic distance between the epicenter and Eryuan station. There is a significant correlation between the integration of concentration and the impact factors. When several earthquakes happen after a change, the specific earthquake corresponding to the change can be determined by comparing their impact factors.

3. Integrals of the anomalistic changes of the underground fluid can be obtained. The correlation between the impact factors and the integrals reveals the relation between the underground fluid and earthquakes.

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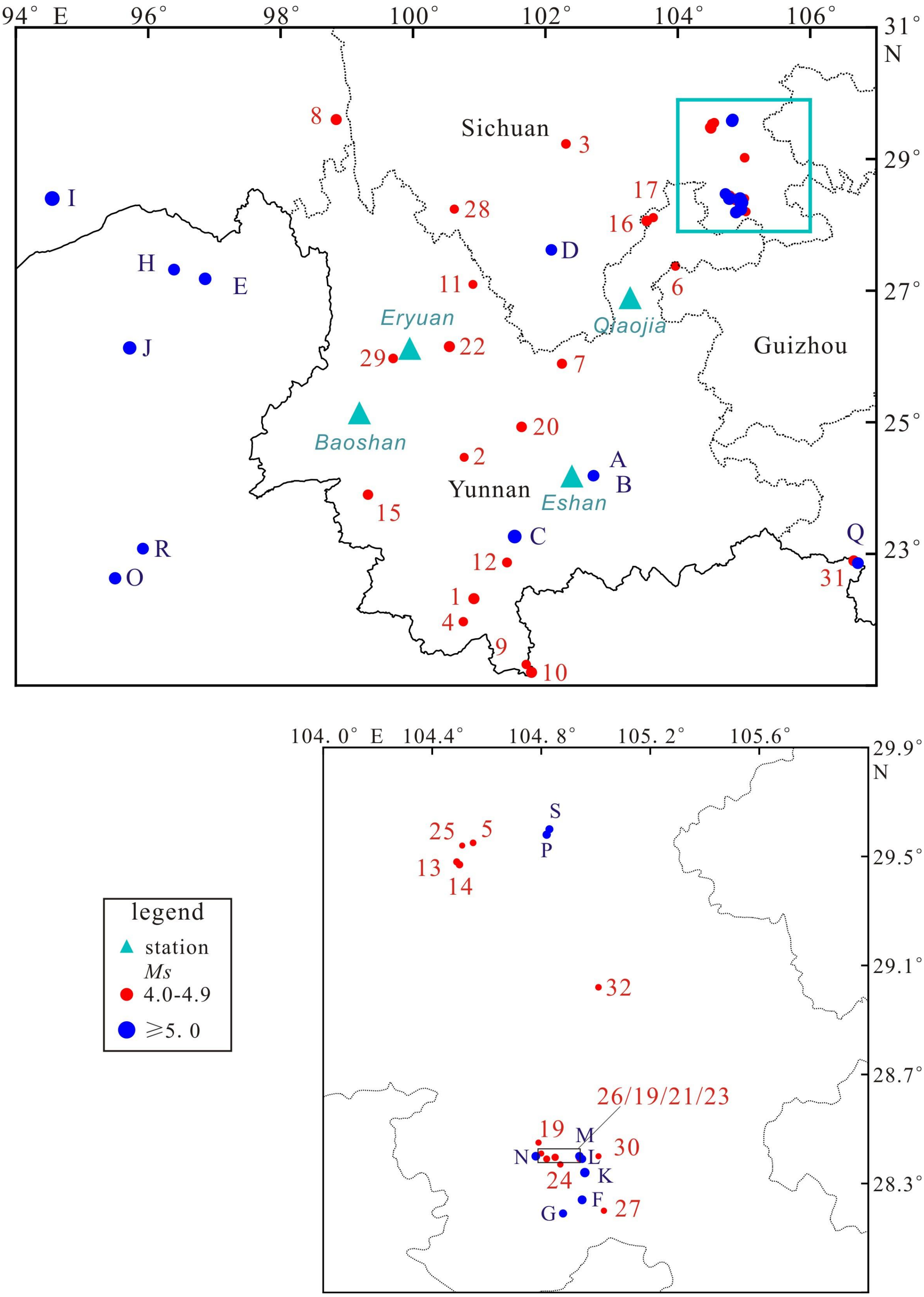
Figure and table captions:

Figure 1. Study area and earthquake epicenters

Figure 2. Hydrogen concentration versus time in Eryuan (c. the daily average hydrogen concentration)

Figure 3. Graph of the impact factor of the third/fourth power and the integral value in Eryuan (a. the third power; b. the fourth power; c. the fourth power, except for events XIII and XIV).

Table 1. Earthquake parameters and the corresponding effective event and its concentration–time integral value.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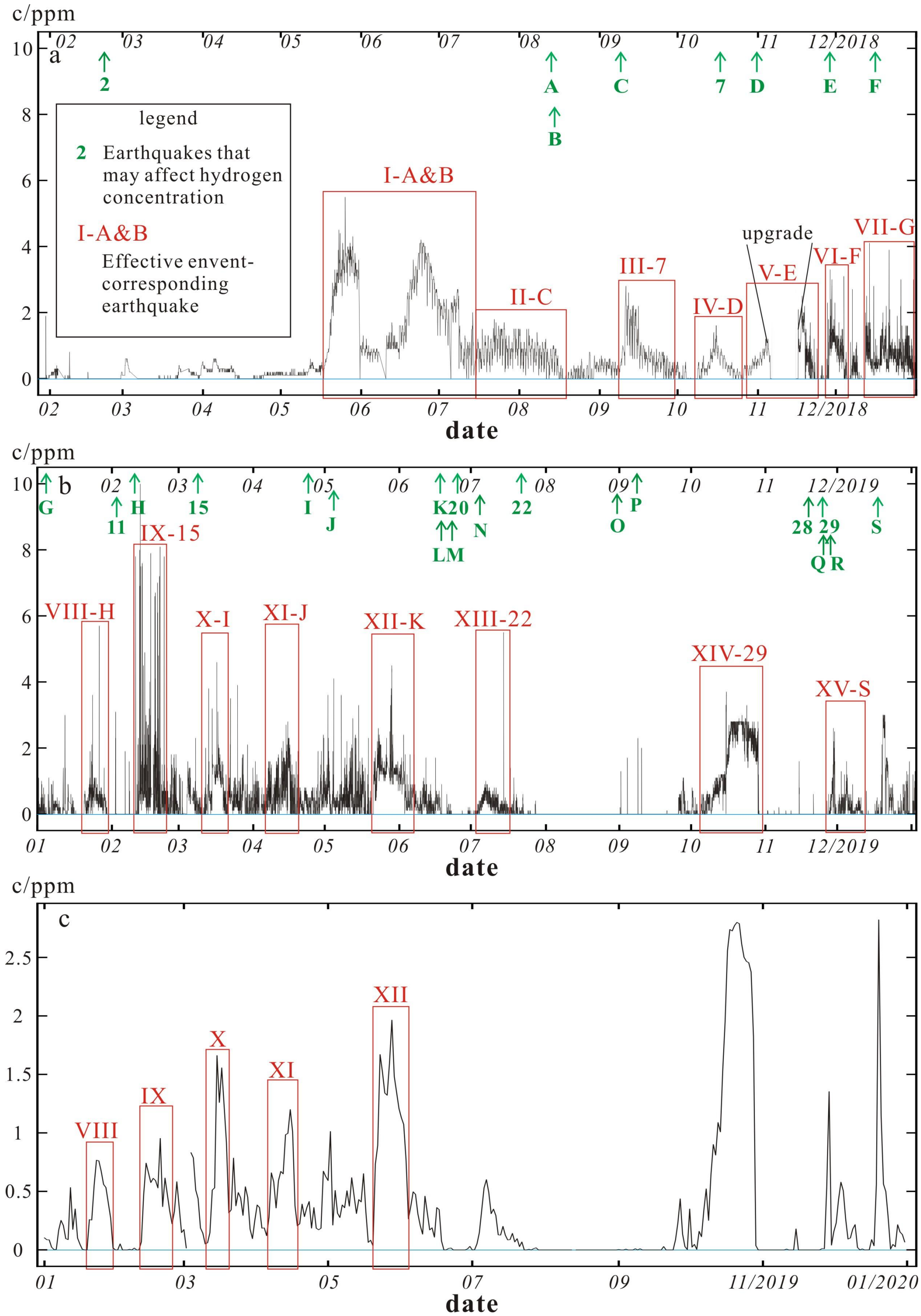
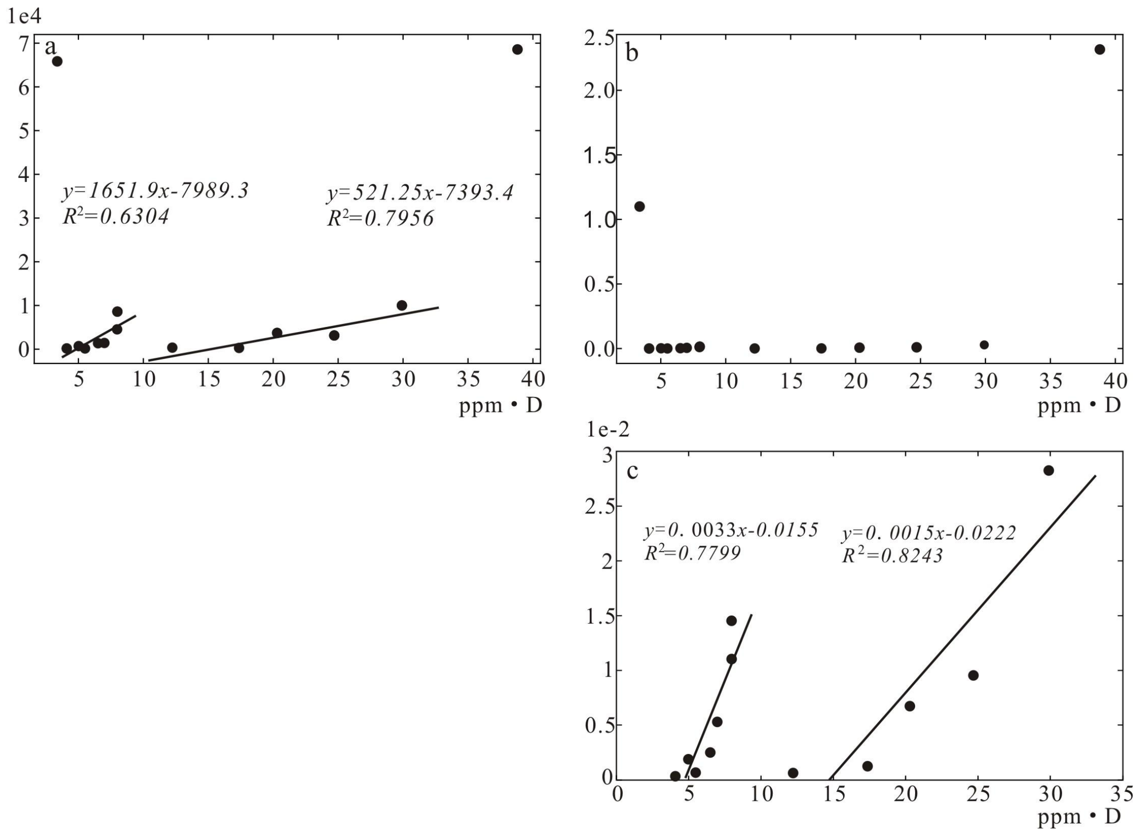


Figure 2. Hydrogen concentration versus time in Eryuan (c. the daily average hydrogen concentration in 2019)



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No.	Date	Ms	Epicentral distance (km)	Focal depth (km)	Effective event	Integral value (ppm●D)
Ms 4.0-4.9						
1	2018/2/9	4.9	433	12		
2	2018/2/20	4	200	7		
3	2018/5/16	4.3	417	10		
4	2018/5/20	4.2	468	10		
5	2018/7/23	4.4	592	14		
6	2018/8/15	4.2	422	5		

7	2018/10/17	4.5	231	10	III	17.37
8	2018/12/13	4.9	403	10		
9	2019/1/10	4.2	562	20		
10	2019/1/14	4.9	577	17		
11	2019/2/2	4	145	12		
12	2019/2/12	4.4	390	5		
13	2019/2/24	4.7	583	5		
14	2019/2/25	4.9	583	5		
15	2019/3/8	4.4	250	11	IX	5.51
16	2019/5/16	4.7	415	10		
17	2019/6/5	4.1	427	8		
18	2019/6/23	4.6	544	7		
19	2019/6/24	4.1	544	8		
20	2019/6/24	4.7	214	10		
21	2019/7/3	4.8	547	9		
22	2019/7/21	4.9	60	10	XIII	3.37
23	2019/7/22	4.1	554	8		
24	2019/8/13	4.2	547	10		
25	2019/9/10	4	588	10		
26	2019/9/12	4	543	10		
27	2019/11/10	4.1	553	10		
28	2019/11/19	4.1	246	14		
29	2019/11/25	4.3	30	12	XIV	38.81
30	2019/11/27	4	561	10		
31	2019/11/28	4.8	767	8		
32	2020/1/1	4.3	594	21		
Ms≥5.0						
A	2018/8/13	5	351	14	I	111.64
B	2018/8/14	5	352	6	I	

C	2018/9/8	5.9	355	17	II	29.91
D	2018/10/31	5.1	270	20	IV	7.00
E	2018/11/28	5.5	330	9	V	24.70
F	2018/12/16	5.7	548	12	VI	6.51
G	2019/1/3	5.3	540	15	VII	12.23
H	2019/2/10	5.2	379	43	VIII	5.02
I	2019/4/24	6.3	592	10	X	8.00
J	2019/5/4	5.8	423	102	XI	7.98
K	2019/6/17	6	554	8	XII	20.30
L	2019/6/18	5.3	555	9		
M	2019/6/22	5.5	555	10		
N	2019/7/4	5.6	541	8		
O	2019/8/31	5.4	594	14		
P	2019/9/8	5.4	615	10		
Q	2019/11/25	5.2	774	10		
R	2019/11/28	5.2	529	19		
S	2019/12/18	5.2	617	14	XV	4.10