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# Short-term seismic precursor anomalies in hydrogen concentration at fault gas stations along the Northern Margin Fault of the Yanqing Basin of Beijing, China

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The Northern Margin Fault of the Yanqing Basin (NMYB Fault) is an important active fault at the intersection of the Zhangjiakou–Bohai (Zhang-Bo) Belt and the Shanxi Belt in North China. The Yanqing Basin, controlled by the NMYB Fault, is rich in escaping gas from hot springs, and previous investigations have indicated that the Yanqing Basin is located in the peak area of upwelling deep fluids from the mantle source material within the Zhang-Bo Belt. Hence, the site is suitable for geochemical gas precursor observations; to facilitate this, five new fault soil gas continuous stations were built on different segments of the NMYB Fault to carry out observations of fault gas ($H_2$ and $CO_2$) concentrations. The five new stations were approximately 50–60 m deep in the bedrock to monitor the release of gas from the depths of the fault. This was the first time that such geochemical station arrays were deployed in the same fault zone at a high density and depth. The results of the deep-hole observations of fault gas within the Yanqing Fault zone show that the time series of the hydrogen ($H_2$) escape gas concentration has a close relationship with recent seismic activities, reflecting different physical processes of YFBF fault activity. The $H_2$ concentration at the observatory was more sensitive to the stress-loading response of the NMYB Fault system.

KEYWORDS

**Zhangjiakou–Bohai tectonic zone, gas geochemistry, helium isotope, Yanqing–Huailai basin, earthquake prediction**

## 1 Introduction

Earthquake precursor mechanisms are difficult to understand, which has hindered the development of earthquake prediction (Donald, 1988; Cicerone et al., 2009; Gherardi et al., 2017). The high uncertainty and low predictability of the earthquake forecasting process also make earthquakes one of the most serious natural hazards, often leading to instantaneous loss of life and property (Gupta, 2001; Wen et al., 2008). In recent years, especially in China, Japan, Italy, and the United States, anomalously high concentrations of hydrogen, carbon dioxide, helium, radon, and methane ($H_2$, $CO_2$, He, Rn, and $CH_4$, respectively) in fault and hot spring gases have been extensively studied in seismically active faults in search of a probable earthquake precursor (King, 1986; Sugisaki and Sugiura, 1986; Nagamine, 1994; Cicerone et al., 2009; Babuska et al., 2016; Weinlich et al., 2016; Fischer et al., 2017; Huang et al., 2017; Yang et al., 2022). Temporal anomalous changes in gas concentrations, which could last from a few hours to a few days, have been observed at some monitoring stations before and after some large earthquakes, the epicenters of which were hundreds of kilometers away. The anomalous mechanisms are usually associated with chemical and physical changes occurring in active faults before and after the earthquakes, such as enhanced/decreased water–rock interactions, crustal stresses/strains, and permeability changes (Sugisaki et al., 1983; Sugisaki et al., 1996; Cicerone et al., 2009; Umeda et al., 2013; Weinlich et al., 2016; Chen and Liu, 2023).

The Yanqing Basin is rich in escaping gas from hot springs, making it an ideal site for fault gas monitoring. Previous investigations and studies of the samples of escaping gas from geothermal hot spring wells in the Yanqing North Fault of Beijing [Northern Margin Fault of the Yanqing Basin (NMYB Fault)] had been carried out. The results show that (Table 1) the hot spring escaping gas in the Yanqing Basin controlled by the Yanqing North Fault was rich in helium, and helium isotope ratios were richer, varying from 0.65 to 2.93 Ra. The mantle-sourced He averages 21.95% (maximum: 35.4%), indicating that the Yanqing Basin is located in the area of the upwelling deep fluids. The very good correspondence between the release of mantle-sourced gases and regional seismic activities indicates that the Yanqing Basin is a sensitive area for seismic geochemical observations and also an important active fault at the intersection of the Zhangjiakou–Bohai (Zhang-Bo) Seismic Belt and the Shanxi Seismic Belt of North China.

Therefore, in this paper, six new gas geochemical stations at high density along the NMYB Fault distribution were constructed (Figure 1) as pilots for applied research on gas geochemistry on active faults for an earthquake precursor. The research objectives of the paper include 1) monitoring the $H_2$ concentration changes in the NMYB Fault before and after the earthquake; 2) analyzing hydrogen concentration characterization of short-term anomalies; and 3) investigating the mechanism of the gas precursor of earthquakes at the NMYB Fault.

## 2 Geological background

Beijing is the capital of China with a large population, and it is located at the intersection of the North China Plain and

TABLE 1 Chemical composition and helium and carbon isotope data of hot spring gas in geothermal wells along the Zhangjiakou–Bohai Fault Zone (cited by Yang et al., 2022).

| Date | Temperature (°C) | He (10-6) | $H_2$ (10-6) | $CO_2$ (%) | $CH_4$ (%) | $N_2$ (%) | $O_2$ (%) | $^3He/^4He$ (R/Ra) | $^3He/^4He$ (Rc/Ra) | $^4He/^{20}Ne$ | He mantle-derived % | $\delta^{13}C_{CO2}$ ‰ | $\delta^{13}C_{CH4}$ ‰ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22/10/2020 | 60 | 683 | 2.4 | 0.63 | 0.1 | 99.37 | 0.14 | 2.86 | 2.93 | 8.3 | 0.354 | -14.3 | 0 |
| 26/10/2020 | 44 | 1851 | 5 | 0.23 | 0.14 | 98.98 | 0.29 | 1.38 | 1.382 | 68 | 0.174 | -17.1 | -35.5 |
| 26/10/2020 | 65 | 996 | 0 | 0.11 | - | 96.49 | - | 2.33 | 2.342 | 35 | 0.295 | -14.2 | — |
| 16/11/2020 | 33 | 700 | 0 | 2.7 | 1 | 96.06 | 0 | 1.85 | 1.86 | 29 | 0.233 | -16.2 | -71.3 |
| 23/11/2021 | 44 | 180 | 0 | 0.027 | 13.8 | 85 | 0.06 | 1.49 | 1.5 | 21 | 0.19 | -10.2 | -74.2 |
| 23/11/2021 | 38 | 200 | 320 | 0 | 0.48 | 97.91 | 0.05 | 0.65 | 0.66 | 17 | 0.071 | -10 | -51.2 |

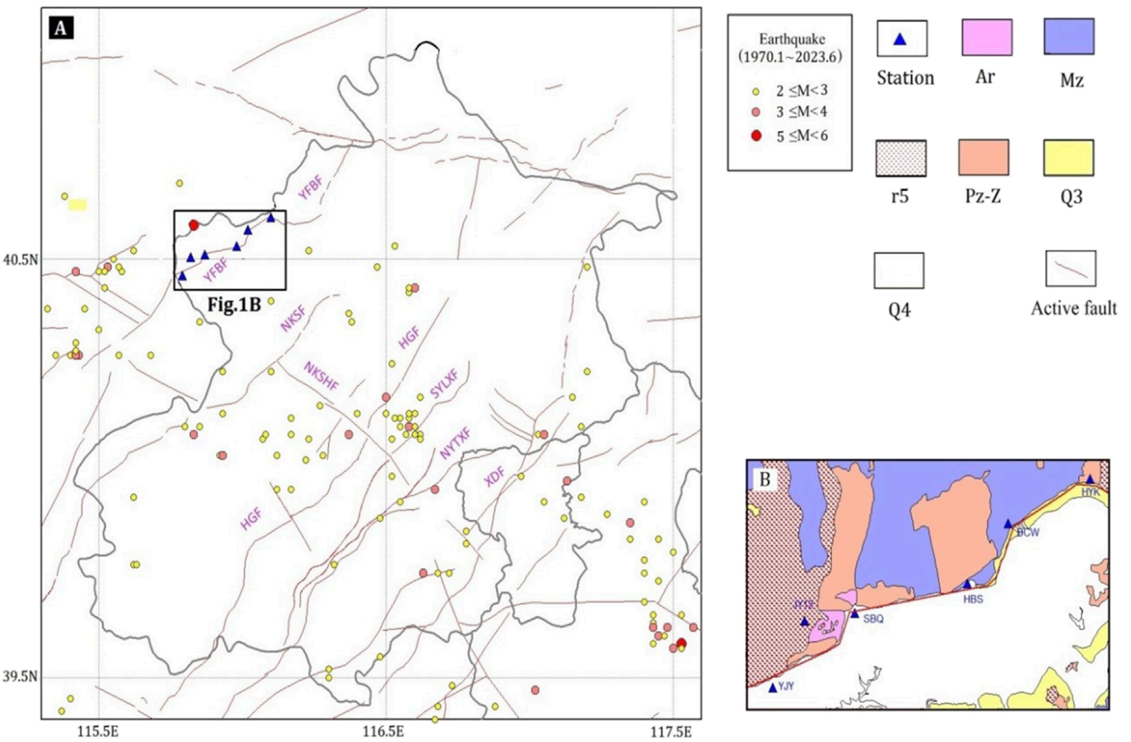


FIGURE 1
Distribution of gas geochemical stations at the Northern Margin Fault of the Yanqing Basin (NMYB Fault). **(A)** Locations of gas stations in the historic earthquake distribution map of Beijing. **(B)** Locations of gas stations in the geological map of the study area.

the Zhang-Bo seismic belt. North China has experienced frequent strong earthquakes over the last few decades (Chen and Liu, 2023; Luo et al., 2024), such as the Xingtai M7.2 earthquake in 1966, Bohai M7.4 earthquake in 1969, Haicheng M7.3 earthquake in 1975, Tangshan M7.8 earthquake in 1976, and Zhangbei M6.2 earthquake in 1998. The Zhang-Bo seismic belt is a group of NW-W orderly active fault zones, starting from the northern margin of the Taihang Mountains in the west and entering the Bohai Sea in the east. It is an important NW seismic activity zone with frequent seismic activity in North China (Yang et al., 2022). Hence, there is a potential risk of damaging earthquakes in Beijing in the following years.

The Yanqing–Huailai (Yan-Huai) sediment basin is in the northwest region of Beijing, where the junction area of the Zhang-Bo seismic belt and Yanshan Mountains is located (Figure 1). Geologically, the basin boundary is mainly controlled by the pre-Cenozoic NNE-oriented positive-tilted and sliding fault groups. The faults continued to be active until the Late Quaternary (Fang et al., 1993). In terms of the overall structure of the basin, the NMYB Fault is the main active fault that controlled the formation and development of this shovel-type fault basin (Yu and Xu, 2004).

Bedrock is exposed in the study area from old to new, based on the stratigraphy of the area (Figure 1), including Archean Gneiss, Meso-Proterozoic carbonate, Mesozoic igneous rock, and Quaternary sediment. Most of the bedrock exposed in the fault zone consists mainly of Cretaceous and Jurassic coarse–facies felsic breccia tuffs, hornblende coarse andesite, gray–green andesite breccia mafic rocks, and volcanic rocks such as granite, which are in angular unconformable contact with the underlying tuffaceous dolomites of the Wumishan Formation in the Jixian System (Calymmian).

The existing geochemical methods from hot springs and gas stations in the Yanqing Basin have many typical earthquake precursor cases. For example, a large number of hot springs and gas anomalies were observed at several underground fluid-monitoring sites in the Yanqing Basin (Che et al., 1999) before the Datong earthquake (19 October 1989), Baotou West earthquake (3 May 1996), and Zhangbei earthquake (10 January 1998), which also suggested that the Yanqing Basin is a typical sensitive area for seismic gas precursors.

# 3 Methods

## 3.1 Gas sampling in the study area

Gas samples were collected from the hot springs and five deep soil holes from the NMYB Fault on 23 December 2022 (see Table 2). The gas samples were immediately sent to the Key Laboratory of the Institute of Earthquake Forecasting, China Earthquake Administration. Measurements of the samples were finished within 30 days. The compositions of the gas samples were analyzed using an Agilent 490 Gas Chromatograph, which measured $H_2$, He, $CO_2$, $N_2$, $O_2$, and $CH_4$. The measurement accuracy was estimated as follows: the relative standard deviation

TABLE 2 Chemical composition of deep soil gas from the Yanqing Basin.

| | He (ppm) | $H_2$ (ppm) | $O_2$ (%) | $N_2$ (%) | $CH_4$ (%) | $CO_2$ (%) | Rn (bq/m3) |
|---|---|---|---|---|---|---|---|
| HYK | 12.42 | 2.09 | 19.66 | 79.23 | 0.112 | 1.001 | 8000 |
| YJY | 11.72 | 467.5 | 17.82 | 80.96 | 0.11 | 1.06 | 150 |
| HBS | 13.65 | 6.09 | 18.63 | 80.1 | 0 | 1.3 | 100 |
| BCW | 16 | 2.9 | 19.47 | 80.53 | 0 | 0 | 2000 |
| SBQ | 12.97 | 12.66 | 18.66 | 81.12 | 0 | 1.2 | 6200 |

was <0.5% when the content was 1%–100%, and the relative standard deviation was <1% when the content was 0.01%–1% (Zhou et al., 2015; Zhou et al., 2020). Helium and neon isotopes were measured using the Noblesse noble gas isotope mass spectrometer. When the R-value in helium isotope measurement was above $1 \times 10^{-7}$, the test error was ±10%, and the measurement data error was at $1 \times 10^{-8}$–$1 \times 10^{-7}$ were ±15% (Cao et al., 2018). The results were normalized to standard atmospheric values. The carbon isotope ratio was analyzed using the DeltaPlusXL mass spectrometer (Thermo Finnigan, United States), consisting of an HP 6890 Gas Chromatograph, a combustion/conversion furnace, and an interface connecting to the DeltaPlusXP mass spectrometer. The stable carbon isotope composition was expressed by $\delta^{13}C$; the accuracy of $^{13}C/^{12}C$ was 0.6‰ (Li et al., 2014).

## 3.2 Gas concentrations at gas geochemical stations

Based on the above concentration characteristics of the soil gas measurement, five new continuous gas monitoring stations were built along the NMYB Fault (Figure 1); these stations aim to monitor the continuous changes in fault gases ($H_2$ and $CO_2$), analyze the spatial differences of the gas characteristics in different fault segments, and observe their changes over time. Furthermore, the five gas stations can monitor the stress adjustments and seismicity of the Beijing area. The five geochemical monitoring sites along the Northern Margin Fault form high-density gas geochemical networks for automatic and continuous gas sampling and observation (Figure 1 shows the distribution of the stations).

In the past, traditional soil/fault gas observations were subject to many disturbing factors, mainly the shallow depth of gas extraction and its susceptibility to biogenic gases and atmospheric disturbances. In order to minimize the influence of these surface factors, the quality of monitoring was improved, the influence of gases produced by biogenic layers and humus in the soil was avoided as much as possible, and the seasonal interference of the ground temperature was avoided. Fault gas fixed monitoring sites were constructed this time, reaching approximately 50–60 m deep into the bedrock. The depth was well beyond the variable temperate zone of the region (the region's variable temperature zone is generally in the range of 20 m).

Hot spring well stations and faulted soil gas stations make the monitoring of additional tectonic activity possible. The monitoring environment is very stable. There is no industrial or mining activity around the monitoring stations. Instead, the fault gas is introduced at a depth of 50–60 m below ground level using sieve-perforated gas collection cylinders. Both hot spring and fault gases are accumulated (Figure 2) and introduced using polytetrafluoroethylene (PTFE) tubes (length: 33–55 m, outer diameter: 3 cm, and inner diameter: 2 cm). Hydrogen concentrations were monitored every 2 h using an ATG-6118H autoanalyzer in the range of 0.01–1,000 ppm with an accuracy of ±5%, and $CO_2$ concentrations were monitored every 2 h using an ATG-C600 $CO_2$ continuous monitor in the measurement range of 0%–60% with a resolution of 0.001%. Both instruments were calibrated and maintained by the instrument manufacturing company (Wen et al., 2018; NOA Certification, 2019). All gas piping was well sealed from the effects of weather, air, and temperature, as well as external humidity and rainfall. The data obtained from this system were transmitted in real time via 5G.

The gas background values of the new deep-bore fault gas wells in the NMYB Fault correlate with the historical earthquakes. According to the curves of the background $H_2$ observation values of the stations when the station was being constructed (Figure 3), it could be seen that the background values of the hydrogen concentration in the area between Yaojiaying (YJY) and Huangbaisi (HBS), where more historical earthquakes had occurred, were higher. In addition, the historical earthquakes of Baicaowa (BCW) and Huangyukou (HYK), located in the northeast of the rupture, were also fewer, and their $H_2$ concentration background values were low at the same time (Sugisaki and Sugiura, 1986; Cheng et al., 1995).

# 4 Results

## 4.1 Gas chemical composition in stations

Gases (isotopic ratios of $CO_2$, He, Ne, and other gas compositions) collected from Yanqing soil gas wells from 1 January 2023 to 31 January 2024 are shown in Table 2. The $N_2$ concentration of the gas samples was ≥79 vol%. Helium and $H_2$ concentrations in the gases were relatively low (≤500 ppm). $O_2$ concentrations in most fugitive gas samples were less than 20%. Methane concentrations were below 3%. Most $CO_2$ concentrations were below 5%.

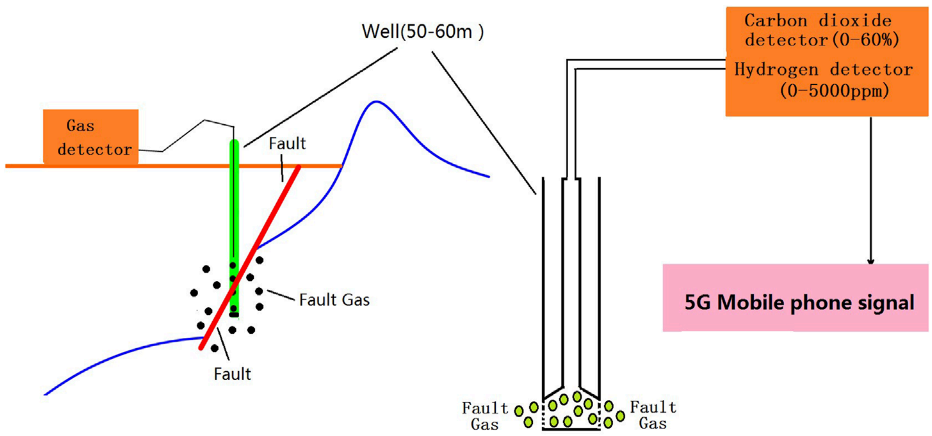


FIGURE 2
Schematic diagram of $H_2$ and $CO_2$ concentration monitoring stations.

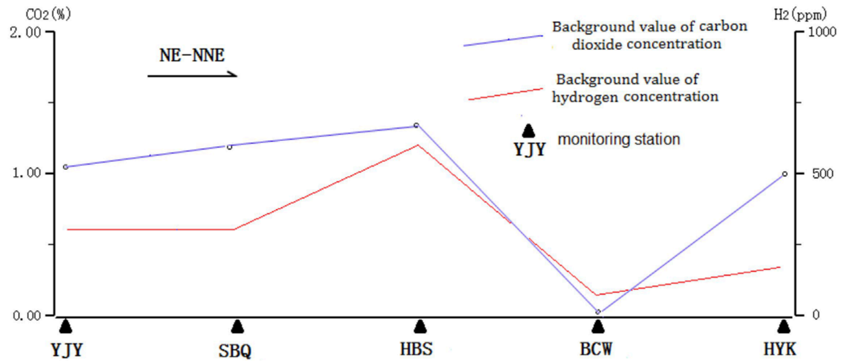


FIGURE 3
Monitoring values of the five $H_2$ and $CO_2$ concentrations were sent to a laboratory in Beijing through cellphone signals.

## 4.2 Concentration of $H_2$ in stations

### 4.2.1 Time-series variation in $H_2$ concentration at the Huangbaisi (HBS) station

From 1 January 2023 to 31 January 2024, there were 4,752 datasets on $H_2$ concentrations (Table 3), which ranged from 0.01 to 501 ppm, with an average of 97 ppm. The anomaly threshold is 170 ppm (Table 3; Figure 4A) according to the Q–Q plot, which is a method of determining the relationship between background and anomalous geochemical data based on the cumulative probability plot delineation of the data threshold (Sinclair, 1991; Zhou et al., 2021). In order to analyze the effect of humidity on the observed values, the correlation coefficient between hydrogen and humidity was calculated to be −0.127 for the 1 January 2023 value of 31 January 2024 at HBS, indicating a very low correlation (see Figure 4B).

### 4.2.2 Time-series variation in $H_2$ at the Shangbanquan (SBQ) station

From 1 January 2023 to 31 January 2024, there were 4,752 datasets on $H_2$ concentrations (Table 3), which ranged from 0.01 to 40 ppm, with an average of 10 ppm. The anomaly threshold was 15 ppm (Table 3; Figure 5A) according to the Q–Q plot. In order to analyze the effect of humidity on the observed values, from 1 January 2023 to 31 January 2024, the correlation coefficient between hydrogen and humidity was calculated to be 0.069 at SBQ, which is also a low correlation (see Figure 5B).

### 4.2.3 Time-series variation in $H_2$ at the Huangyukou (HYK) station

From 1 January 2023 to 31 January 2024, there were 4,752 datasets on $H_2$ concentrations (Table 3), which ranged from 0.01 to 40 ppm, with an average of 9.7 ppm. The anomaly threshold of 16 ppm (Table 3; Figure 6A) was determined by a Q–Q plot. In order to analyze the effect of humidity on the observed values, the correlation coefficient between hydrogen and humidity was calculated to be 0.44 for the 1 January 2023 value of 31 January 2024 at SBQ, which is also a low correlation (see Figure 6B).

# 5 Discussion

## 5.1 Sources of $H_2$

The source of $H_2$ is most likely attributable to (A) $H_2$ produced by water–rock reactions. Abiotic $H_2$ is produced

TABLE 3 Summary of $H_2$ concentrations at three geochemical stations along the NMYB Fault.

| Station name | Number of concentration datasets | Concentration range of $H_2$ (ppm) | Concentration average (ppm) | Abnormal threshold (ppm) | Correlation coefficient with humidity ($r^2$ value) |
|---|---|---|---|---|---|
| HBS | 4,752 | 1–501 | 97 | 170 | 0.016 |
| SBQ | 4,752 | 1–40 | 10 | 15 | 0.005 |
| HYK | 4,752 | 1–70 | 9.7 | 16 | 0.19 |

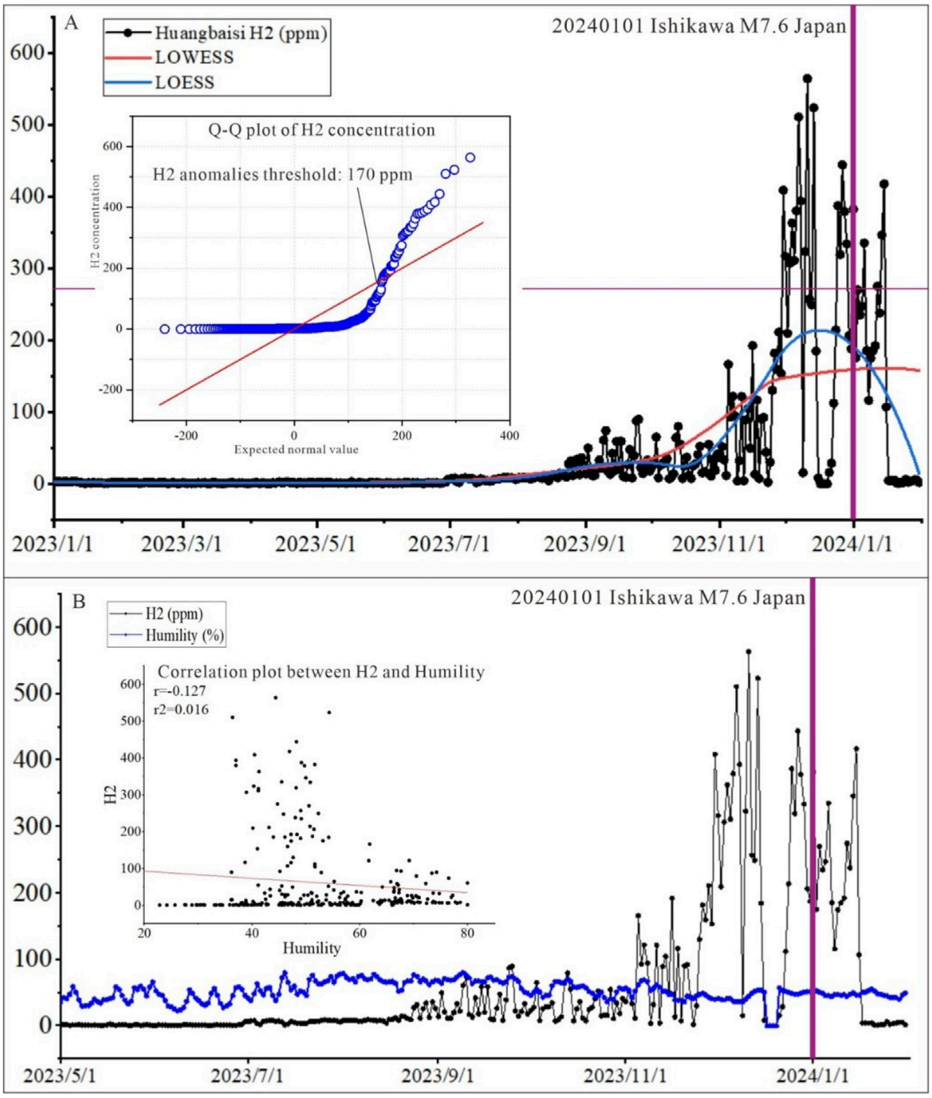


FIGURE 4
**(A)** Q–Q plot of $H_2$ concentration at HBS. **(B)** Correlation between $H_2$ concentration and humidity.

under near-surface conditions when water reacts with ultramafic rocks or serpentinization and migrates from deeper reservoirs (Lollar et al., 2014; Parnell and Blamey, 2017; Irfan et al., 2019; Wang et al., 2019; Wang et al., 2020); (B) water interaction with the newly exposed rock surface (Hirose et al., 2011); and (C) mixing with large amounts of microbial $H_2$ produced by bioactivity and organic matter decomposition (Prinzhofer et al., 2019; Myagkiy et al., 2020).

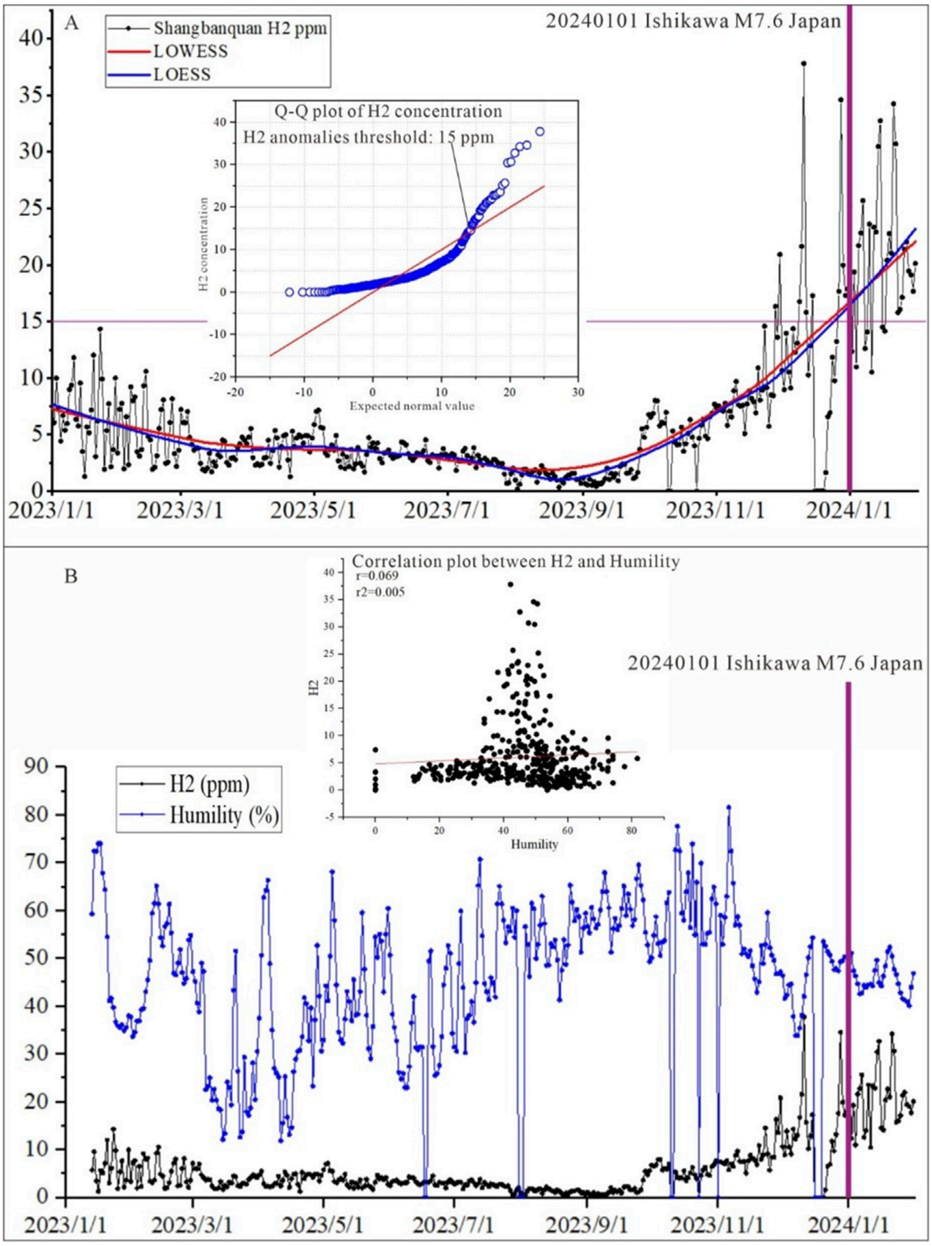


FIGURE 5
**(A)** Q–Q plot of $H_2$ concentration at SBQ. **(B)** Correlation between $H_2$ concentration and humidity.

Laboratory experimental data showed that tectonic stress caused by the reaction of broken minerals and groundwater can produce $H_2$. The observed significant increase in $H_2$ in the high concentration of anomalies before and after many large earthquakes suggests that there is a close relationship between the changes in the concentration of $H_2$ and the earthquakes (Sugiyaki et al., 1983; Zhou et al., 2021). A background investigation on soil was carried out by Li et al. (2014) and Chen et al. (2022) over a larger area including the study area. The results show that there are low-velocity bodies in the upper crust of the eastern part of the Yanqing–Huailai Basin (including the Yanqing Basin), with strong tectonic activity. The investigated gases, including Hg and He, mainly originate from the deeper part of the fault zones, contributing more to the soil gas. $H_2$ also originates from the deeper part but was influenced by the redox environment in the soil deposits, which results in a wide range of variations in the $H_2$ content (Li et al., 2014).

## 5.2 Time-series variation characteristics and anomalies of $H_2$ before earthquakes

Prior to earthquakes from 1 January 2023 to 1 January 2024, there were significant short-term (120–720 h) seismic precursor anomalies in the $H_2$ concentration of fault escape gases at HYK, HBS, and SBQ (Figure 7). Earthquakes occur when stress increases

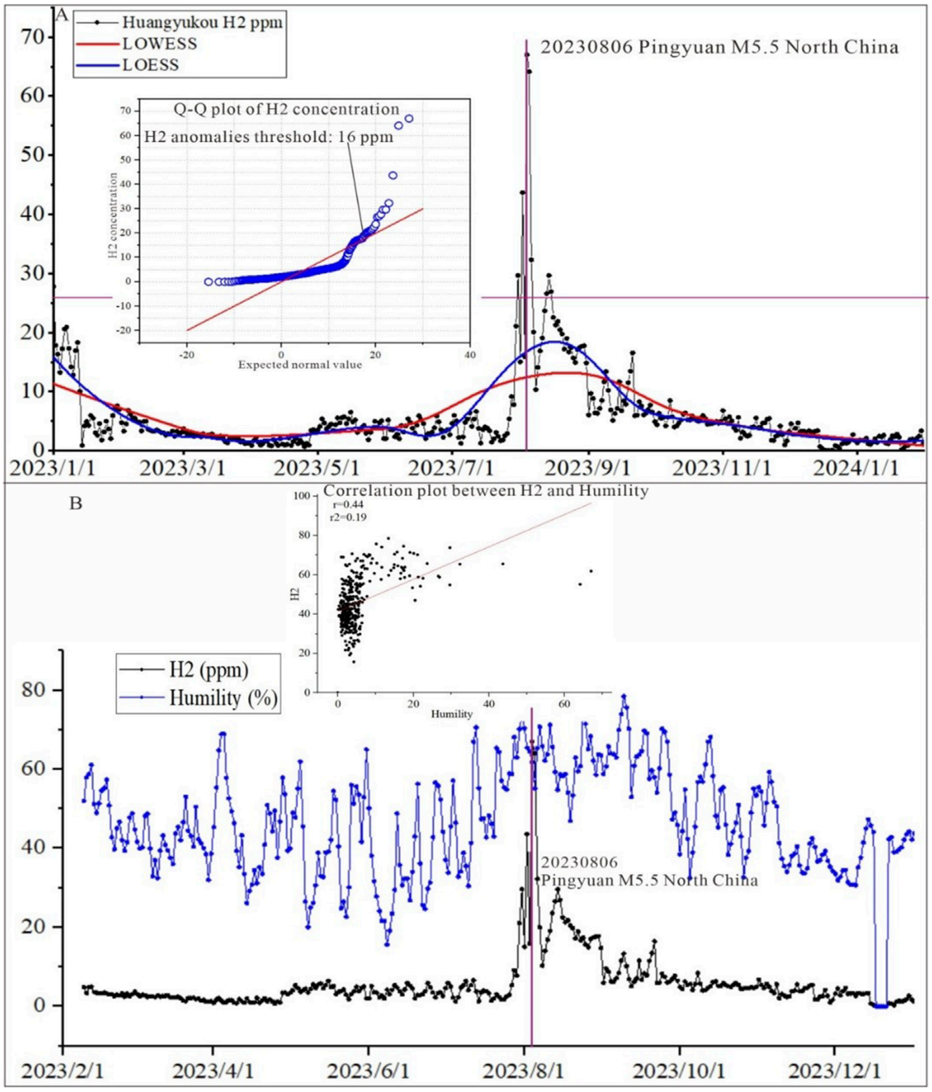


FIGURE 6
**(A)** Q−Q plot of $H_2$ concentration at HYK. **(B)** Correlation between $H_2$ concentration and humidity.

to a state of sub-instability stress on faults (Ma, 2016). The hydrogen concentration in the escaping gas is very sensitive to the increase in stress, which may enhance the openness of microfractures in the fractures along the Northern Margin of the Yanqing Basin.

The anomaly information was reported to the Beijing Earthquake Agency prior to the 5 August 2023 Shandong Pingyuan M5.5 and 1 January 2024 Japan M7.3 earthquakes.

Prior to these two earthquakes, there were significant and persistent precursor anomalies in the $H_2$ concentrations of soil gas in each of the HYK, HBS, and SBQ stations. When the stress increases to a state of sub-instable stress on the faults, the faults misalign to produce earthquakes (Ma, 2016), so the mechanism of precursor anomalies may have been caused by the sustained stress increase prior to the natural seismic events.

The hydrological response to earthquakes depends on the earthquake's magnitude and epicenter (Wang and Manga, 2010; Cox et al., 2015). Therefore, systematic identification of short-term seismic precursor anomalies based on multiple earthquakes using certain criteria is difficult. By drawing on and analyzing the collection of many natural earthquake cases in the same region, the equation of geochemical gas precursor anomalies in relation to magnitude and distance from the epicenter can be summarized, and some criteria can be provided.

### 5.2.1 $H_2$ concentration at HYK

Before the 5 August 2023 Pingyuan County M5.5 earthquake in Dezhou city of Shandong Province of China, the $H_2$ concentration anomaly increased at Huangyukou (Figure 7), which appeared 5 days before the earthquake and ended before the earthquake. Details were as follows: it began to rise abruptly on July 30, reaching a first peak of 65.65 ppm on the July 31, a second peak of 91.56 ppm at 11:40 on August 2, and a third peak of 174.6 ppm at 00:40 on August 5, and then, it returned to a low point of 19.568 ppm at 18:40 on August 5. The M5.5 earthquake in Shandong Pingyuan occurred at

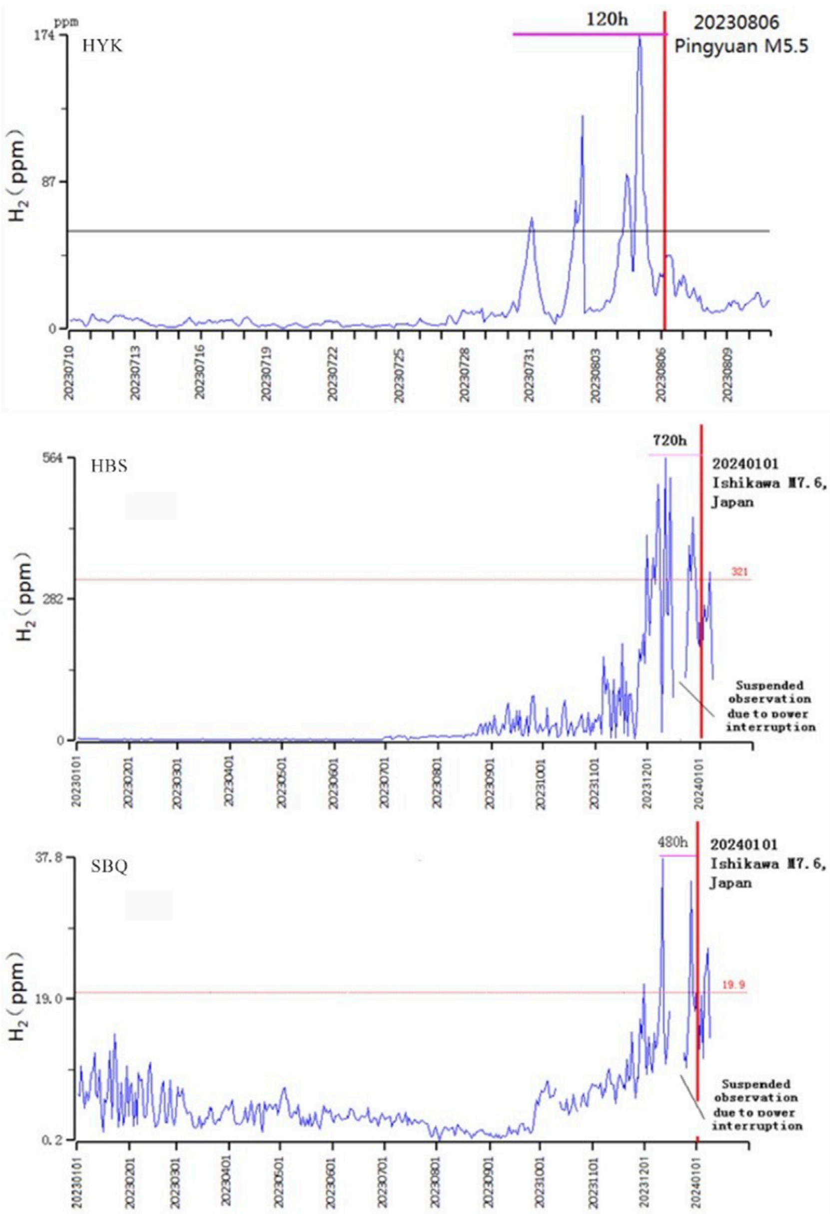


FIGURE 7
$H_2$ concentration anomalies prior to earthquakes at HYK, HBS, and SBQ.

02:33 on August 6 and returned to normal at 18:40 on August 7 (Figure 7; Table 4).

### 5.2.2 $H_2$ concentration at HBS and SBQ

Before the 1 January 2024 M7.6 earthquake in Ishikawa, Japan, there were significant short-term anomalies in the hydrogen concentration in HBS and SBQ (occurring 30 days and 20 days before the earthquake, respectively, and the anomalies decreased significantly after the earthquake), and the parameters of the precursor anomalies for the earthquakes are shown in Figure 7; Table 4.

Analyzing the $H_2$ anomaly magnitude, it was found that the $H_2$ anomaly magnitude at HYK before Shandong Pingyuan M5.5 was larger than that at SBQ and HBS before the Japan M7.6 earthquake. The anomaly amplitude before the Shandong Pingyuan M5.5 earthquake was as high as seven times, while the anomaly amplitudes before the Japan M7.6 earthquake were four and five times, respectively (Figure 7). From another point of view, it indicates that the loading effect of the stress field of the earthquakes with far epicentral distance has a significantly weaker relation with the earthquakes within the North China region.

TABLE 4 Seismic precursor parameters of three geochemical stations on the NMYB Fault.

| Time | Earthquake magnitude | Location | Epicentral distance of HYK | Epicentral distance of HBS | Epicentral distance of SBQ | Latitude | Longitude | Focal depth | Abnormal duration |
|---|---|---|---|---|---|---|---|---|---|
| August 6, 2023 at 14:33 | M5.5 | Pingyuan, China | 380 km | — | — | 37.16°N | 116.34 | 10 km | 5 days |
| January 01, 2024 at 15:10 | M7.4 | Nengdeng, Japan | — | — | 1,890 km | 37.55°N | 137.49°E | 59 km | 24 days |
| January 01, 2024 at 15:10 | M7.4 | Nengdeng, Japan | — | 1890 km | — | 37.55°N | 137.49°E | 59 km | 30 days |

## 5.3 Simulation of gas concentration migration in faults

Chen et al. (2022) investigated the relationship between the gas release characteristics of the major active fault zones within the North China Craton and the regional tectonic framework. The results show that in the Zhang-Bo tectonic belt, the release of soil gas Rn and $CO_2$ and the contribution of crustal or mantle sources in the escaping gas from hot springs are significantly higher than in other tectonic zones in the region. A comprehensive analysis combining the results of the shear strain rate field, GPS horizontal velocity field, and S-wave velocity imaging reveals that the region was characterized by strong tectonic activities, and the development of nascent fractures may be widespread in the subsurface, and mantle-source fluids may be present in the subsurface of the Zhang-Bo tectonic belt for 20–40 km. It was also found that the peak region of helium from the mantle source material in the Zhang-Bo belt in the Yanqing Basin region showed increased deep fluid upwelling.

The NMYB Fault is located in the northern part of the central orogenic belt of the North China Craton, which consists of two east–west grade blocks of the North China Craton collided and spliced in the Paleoproterozoic (Liu and Zhao, 2012). After experiencing many geologic effects, a large number of faults were developed under the stresses of Cenozoic tensile-slip, and basin–mountain coupling tectonics were formed in the adjacent basins blocked by the mountain system (Xu et al., 1998), and the Yanqing Basin is one of them (Yang et al., 2022).

Subduction of the paleo-Pacific plate sheet is the geodynamic mechanism leading to the thinning and destruction of the lithospheric mantle of the North China Craton (Zhu et al., 2017). The destruction of the North China Craton occurred mainly in the area east of the Taihang Mountains in North China, resulting in the intrusion of magma, earthquakes, and volcanism in the area, including the Zhang-Bo belt, which are closely related to the geologic activities. The Yanhuai Basin, located in the Zhang-Bo Belt, is one of the areas with the potential danger of strong earthquakes in the eastern part of mainland China. The mechanism of earthquake occurrence in the Yanhuai Basin and basin–mountain interaction, the monitoring and prediction of future strong earthquakes, and other scientific and applied issues have also been attracting the attention of earthquake scientists.

Hence, in the broader context of tectonically active and fracture development in the Zhang-Bo belt region, combined with gas observation anomalies in this region, a model was designed to explain the anomalies. The model assumes that the NMYB Fault is a gas source system capable of responding to external stress loading and that during the anomalous time period, there was stress loading from the periphery of the fault, and anomalous gas rises, along with increases in the $H_2$ concentration, were observed at the observatory stations (see Figure 8).

This can be explained by the fact that in the fracture system, the hydrogen concentration in the escaping gas is very sensitive to the increase in stress, which has the potential to enhance the openness of the microfracture under the Yanqing Fracture, leading to an increase in the concentration of the gas originating from the depth.

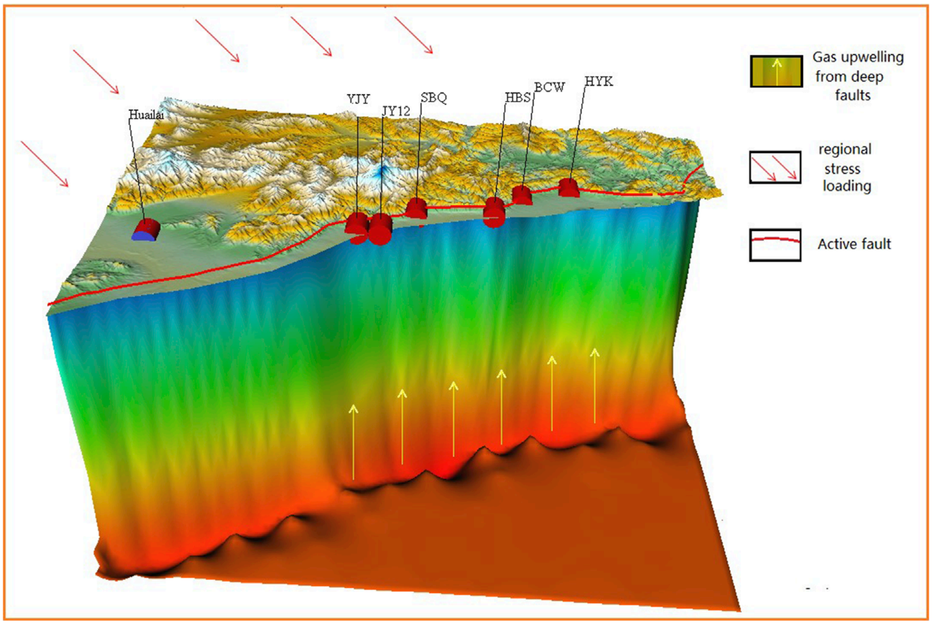


FIGURE 8
Modeling of the stress loading and gas transportation process in the fracture at the Northern Margin of the Yanqing Basin.

At the same time, during stress loading, hydrogen released from rock fragmentation and hydrogen generated by water–rock chemistry at the active fault site make hydrogen more concentrated near the active fault, so some hydrogen anomalies can be observed at the location of the active fault at the surface.

# 6 Conclusion

1. The high-density geochemical observatory stations near the fractures at the Northern Margin of the Yanqing Basin are a preferable site for pilot research on gas geochemistry in active faults.
2. The time series of $H_2$ concentration observations exhibit complex temporal patterns, reflecting a wide range of different physical processes. Observatories located along the rupture showed significant short-term hydrogen concentration anomalies (5–30 days) prior to the earthquake, which may be related to regional stress loading.
3. The use of high-precision automatic continuous monitoring stations to observe hydrogen concentration and other concentrations ($CO_2$, He, radon, water temperature, and ion concentrations) at active rupture locations can be analyzed to determine the physical process of rupture zone activity; the next step is to combine and synthesize the time series and spatial characteristics of hydrogen concentrations and multiple fault gases from observation stations in the same rupture zone. This approach could be a valuable tool for further unraveling the mechanism of earthquakes and predicting earthquakes.

# Data availability statement

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

# Author contributions

MY: conceptualization, funding acquisition, investigation, methodology, writing–original draft, and writing–review and editing. GL: conceptualization, funding acquisition, supervision, and writing–review and editing. YC: methodology, visualization, and writing–review and editing. PH: investigation and writing–review and editing. LH: writing–review and editing. ZW: writing–review and editing. SW: investigation and writing–review and editing. XS: writing–review and editing. YoZ: writing–review and editing. HZ: methodology, investigation, writing–review and editing. GF: methodology, investigation, writing–review and editing. XG: methodology, investigation, writing–review and editing. YZ: formal analysis, writing–review and editing.


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## Conflict of interest

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

## Publisher's note



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