Spatial Distribution of Rn, CO$_2$, Hg, and H$_2$ Concentrations in Soil Gas Across a Thrust Fault in Xinjiang, China

Yang Xiang$^{1,2}$, Xiaolong Sun$^{1*}$†, Dongying Liu$^1$, Long Yan$^3$, Bo Wang$^4$ and Xiaqi Gao$^1$

$^1$ National Institute of Natural Hazards, MEMC, Beijing, China, $^2$ College of Geoscience and Surveying Engineering, China University of Mining and Technology, Beijing, China, $^3$ Earthquake Agency of the Xinjiang Uygur Autonomous Region, Ürümqi, China, $^4$ China Earthquake Networks Center, Beijing, China

Spatial distribution characteristics and origin of soil gasses were discussed in this study. We also examine the correlation between the spatial variation of soil gasses and fault activity, based on the measurements of Rn, Hg, H$_2$, and CO$_2$ concentrations in the eastern segment of the BLT fault zone in the southern Tianshan Mountains, Xinjiang, China. The results show that the Rn and CO$_2$ concentrations on the hanging wall were higher than those near the fault zone and on the footwall of the fault. Moreover, the Hg and H$_2$ concentrations on the footwall were also higher than those near the fault and on the hanging wall of the fault. The main factors affecting the variations in soil gas spatial distribution were gaseous origin structure of the crust, fault activity, fault fracture degree, stratigraphic lithology, and the cover layer. The results of active structural fault mapping show that the BLT fault has been active since the Late Quaternary and the thrust has broken the fault surface. Under the influence of tectonic compressive stress, the tension zone was formed on the hanging wall of the fault and fractures were developed. This result is consistent with the characteristics of soil gas concentrations measured in this study, indicating that the concentrations of Rn, Hg, H$_2$, and CO$_2$ are closely related to the fault activity. These findings can be applied to identify seismic precursors from gas monitoring data of the studied area.

Keywords: BLT fault, soil gas, spatial distribution, thrust fault, Xinjiang

INTRODUCTION

A fault zone is a channel for deflation of the crust, and the number of micro-cracks distributed in the fault zone randomly increases under the impact of the tectonic stress field. This accelerates the migration and release of deep gasses (Baubron et al., 2002; Pulinets and Dunajecka, 2007; Fu et al., 2017), and changes the concentration of chemical components near the fault (Wiersberg and Erzinger, 2008). General overviews of the geochemical, structural, and seismic features in tectonically active areas have shown some evidence of a correlation between soil gas geochemistry anomalies and tectonic activities. Evidence also shows that soil gas escaping through the fault and fractures in the active fault zones can be enhanced by fault and earthquake activity (Fu et al., 2008; Sciarra et al., 2017; Yuce et al., 2017). As such, analyzing the geochemical variations of soil gas near...
fault zones has become an important method for investigating earthquake precursors, forecasting earthquakes, and evaluating fault activity (Li et al., 2013; Iovine et al., 2017).

Useful soil gasses include noble gasses, Rn, Hg, H₂, CO₂, and He, which play important roles in fault delineation and earthquake precursory studies (Chyi et al., 2005; Etiope et al., 2007; Caracausi and Paternoster, 2015; Camarda et al., 2016; Fu et al., 2017). Rn has been used by the scientific community as a tracer of natural phenomena related to outgassing from soil located along faults, fractures, and crustal discontinuities (King et al., 1996; Mazur et al., 1999). Rn concentration changes in soil gas and groundwater are commonly observed prior to earthquakes and volcanic eruptions; consequently, they have attracted considerable attention in studies of precursory geochemical signals (Morawska and Phillips, 1993; King et al., 1995; Giammanco et al., 2000; Walia et al., 2009; Iovine et al., 2017). Hg, H₂, He, CO₂, and CH₄ have also been utilized in revealing the relationship among fluid activities in fault zones (Ware et al., 1984; Sugisaki et al., 1996; Jones et al., 2010; Moore and Castro, 2012). Helium isotopes are of particular interest as they can provide unequivocal evidence for the presence in the crust of mantle-derived fluids; ³He is essentially primordial and retained in the Earth’s interior, whereas ⁴He is mainly produced in the crust by the decay of U and Th. Hence, any ³He/⁴He ratio at the Earth’s surface larger than the local and crustal production rates indicates the presence of mantle helium (Sano et al., 2016; Buttitta et al., 2020).

Active faults commonly exhibit anomalously high concentrations of variously terrestrially generated gases in groundwater and soil air (King, 1980, 1986; Sun et al., 2017b). Concentration abnormalities of soil gas were observed in the Tashkent earthquake area in Uzbek, San Andreas Fault in the United States, Hsinhua and Chaochou faults in southern Taiwan, and Longmenshan fault, Beichuan-Yingxiu fault, and Minjiang fault in China (Engle et al., 2001; Li et al., 2006; Fu et al., 2008; Walia et al., 2009; Zhou et al., 2010, 2015). These studies indicate that the application of soil gas concentrations near the fault zone is of great practical significance for studying the fault activity and capturing the precursory information of earthquakes.

In this study, the concentrations of Rn, Hg, H₂, and CO₂ in soil gas were measured in the field along the profiles approximately perpendicular to the BLT fault. The spatial distribution in the soil gas concentrations in the eastern segment of the BLT fault was analyzed. The BLT fault is a long-term successional active fault zone and has been active since the Late Quaternary. It controls the distribution of the Mesozoic and Cenozoic strata in the northern Tarim Basin (Yao et al., 2018). This study is the first to analyze the distribution characteristics of soil gas in the BLT fault.

OVERVIEW OF GEOLOGY AND SEISMOLOGY

The BLT fault is the boundary between the Tarim Basin and the South Tianshan, oriented along the NWW–EW direction. The length of the fault is approximately 300 km, and the fault plane is N-dipping with an inclination of 50–80° (Figure 1). The BLT fault cuts the Late Pleistocene and Holocene alluvial fans and has been active since the Late Quaternary. It forms clear large-scale paleoseismic deformation zones and fault scarps with different heights on the surface. According to the records, only M5.6 earthquakes in 1972 and M5.2 earthquakes in 1988 occurred along the BLT fault, and no large destructive earthquake has ever occurred. In the present study, we examine the Tiemenguan section of the eastern part of the BLT fault (hereinafter referred to as Tiemenguan). As shown in Table 1, since 1970, 12 earthquakes have occurred near the Tiemenguan section, including two earthquakes above M5 and M4 earthquakes. No earthquakes occurred during the study period, only two earthquakes occurred after 2015, M4.6 on April 1, 2018, and M4.4 on May 9, 2020 (Figure 1A). However, these two earthquakes did not occur on the BLT fault. There are multiple terraces where the fault is faulted and the height of fault scarps varies between 2 and 20 m. According to the results of trench profile images, there have been more than two paleoseismic events in the fault segment since the late Pleistocene. The vertical displacement of the stratum caused by the latest paleoseismic event is 1.1 m (Yao et al., 2018). The surface strata near the fault are bent and flexed, forming a large number of bending faults, and the crustal shortening rate of SN is 1.43–1.81 mm/a. Large-scale earthquakes have not occurred in the BLT fault since the earliest recorded history. This indicates the potential for a large-scale earthquake to occur in the future. At the fault, the surface accumulation material is mainly gravel, primarily composed of granite, and also comprises limestone. The fault is exposed on the surface, and the overburden is mostly composed of fine sand or sandy sedimentary layers.

MEASUREMENT AND ANALYSIS METHODS

Figure 2 shows the schematic diagram for measuring Rn, Hg, CO₂, and H₂ concentrations. Before sampling, 0.8 m deep and 0.03 m wide holes were drilled in the soil at each sampling site. A pyramidal gas sampler was inserted into the hole after removing the drill bit. Before each measurement, the foreign gas in the samplers and in the rubber tube connecting the samplers and detector was removed prior to signal counting. The concentration of Rn in the soil gas was measured using AlphaGuard PQ 2000 PRO (AG) Radon Detector and the Hg concentrations were analyzed with portable RA-915+ Zeeman Mercury Analyzer. The error of measurement was 2 ng × m⁻³. The concentration of CO₂ in the soil gas was measured using KG-3010E Portable Infrared CO₂ Analyzer, and the concentration of H₂ in the soil gas was measured by ATG-300H Portable Hydrogen Gauge with a detection limit of 0.01–10,000 ppm. In addition, five gas samples were collected following the drainage gas collection method at the fault zone for helium isotope (³He/⁴He) analysis. The container used for helium isotope detection was a 100 mL saline glass bottle. After the measurement of soil gas concentration, the gas in the sampler, connecting pipe, and air pump was removed using an air pump. The sampling container was cleaned with saturated saltwater three times, and then the gas was collected. The instrument used
TABLE 1 | Catalog of earthquakes occurring in the area near Tiemenguan from January 1, 1970 to May 31, 2020.

| Date       | Time (UTC) | Long (°E) | Lat (°N) | Mag (M) | Date       | Time (UTC) | Long (°E) | Lat (°N) | Mag (M) |
|------------|------------|-----------|----------|---------|------------|------------|-----------|----------|---------|
| 2020/5/9   | 12:11:19   | 85.640    | 42.234   | 4.4     | 1998/4/13  | 23:14:32   | 85.796    | 41.996   | 4       |
| 2018/4/1   | 1:18:36    | 85.580    | 42.256   | 4.6     | 1988/5/25  | 18:21:58   | 85.692    | 42.010   | 5.2     |
| 2014/9/9   | 12:04:57   | 85.196    | 42.319   | 4.4     | 1981/4/21  | 3:22:52    | 85.816    | 41.988   | 4.4     |
| 2013/8/28  | 12:57:41   | 85.776    | 42.076   | 4.5     | 1980/6/14  | 13:01:13   | 85.523    | 41.954   | 4.7     |
| 2013/7/9   | 14:51:55   | 85.276    | 42.210   | 4.3     | 1978/4/22  | 15:04:15   | 85.920    | 42.004   | 5.3     |
| 2005/6/3   | 19:11:23   | 85.770    | 41.983   | 4.1     | 1977/6/5   | 18:19:29   | 85.714    | 42.004   | 4.7     |

FIGURE 1 | Geologic structure map and seismic distribution of Tiemenguan section of BLT fault (a), spatial distribution of soil gas survey lines (b). The red circles indicate the earthquake that occurred after the measurement. SSD, Songshudaban fault; HLS, Huolashan fault; BLT, Beiluntai fault.

FIGURE 2 | Schematic diagram of soil gasses measurement.

was MM5400 mass spectrometer with a sensitivity greater than $1.5 \times 10^{-6}$ a/PA. The gas samples were sent to the Lanzhou Center for Oil and Gas Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, immediately after the collection. Analysis of the samples was completed within 30 days of sampling.

Figure 3A shows that the measured values of Rn concentrations tended to stabilize after the second value of the initial measurement and there was a small amplitude of fluctuation. At each measurement time, 30 readings were taken and analyzed using the boxplot method, yielding a characteristic value of Rn concentration in each measurement site. The other three components, soil gas concentrations of CO$_2$, Hg, and H$_2$ were recorded based on the measurement time and their maximum values were taken. The concentration of soil gas CO$_2$ was relatively stable and the peaks were consistent with repeated measurements (Figure 3B). However, the concentrations of Hg and H$_2$ showed a gradual increase in the measured values and upon reaching the highest value, the concentrations tended to stabilize (Figure 3C) or rapidly decrease (Figure 3D).

RESULTS

In this study, soil gas measurements were obtained twice across the fault at Tiemenguan, the eastern segment of the BLT fault, Xinjiang. The results are shown in Table 2. During the first phase, the measurements of soil gas Rn and CO$_2$ concentrations were completed between April 20 and April 26, 2015. A total of 15 measuring points were identified from south to north. Measuring points 1–9 (P1–P9) were located at the footwall of the fault, and points 10–15 (P10–P15) were located at the hanging wall of the fault. To determine whether there were similar changes in other gasses, we selected more measurement points at hanging wall (P13, P14, and P15), fault zone (P7, P8, and P10), and footwall (P2, P3, and P4) during the first phase from August 11–17, 2015, to conduct the second phase of soil gas measurements. The primary measurements recorded were the concentrations of Hg and H$_2$ in soil gas. As shown in Figure 4, due to the characteristics of H$_2$ (active) and Hg (adsorptive), such as the gas diffusion concentration that changes with time,
FIGURE 3 | The measurement curve of soil gas concentration in different components. The Rn concentration was determined according to the boxplot method to obtain the characteristics of Rn concentration at each site. A total of 30 measurements were acquired for each measurement point (A). The other three components, soil gas concentration of CO₂, Hg and H₂ were recorded based on the measurement time, respectively. The peak of CO₂ concentration was the same after repeated measurements (B). The Hg concentration value showed a steady change after rising to the highest value (C). H₂ concentration characteristics showed a rapid decrease after rising to the highest value (D). Therefore, the maximum value of the gas concentration curve of each component at sampling sites is analyzed.

The results show that in the footwall of the fault, the measured value of soil gas Rn concentration decreases toward the fault. It reaches the lowest value at the fault. However, in the hanging wall of the fault, the measured value increases toward the fault (Figure 5A). As shown in Figure 5B, the measured values of soil gas CO₂ concentration in the footwall of the fault (measuring points 1–9) are generally low, and the measured values decrease toward the exterior of the fault (measuring points 11 to 15). The concentrations of Rn and CO₂ are similar, and the measured values near the fault are high. The measured values gradually decrease with distance from the fault, and the concentration the seasonal influence on soil gas concentrations is minimum in April and August.
TABLE 2 | Main statistic parameters of soil gas data in study area.

| NO | Rn (Bq/L) | CO₂ (ppm) | Hg (ng/L) | H₂ (ppm) | \(^3\text{He}/^4\text{He} \ R) |
|----|-----------|-----------|-----------|----------|-------------------------|
| P1 | 18.1666   | 520       | –         | –        | –                       |
| P2 | 12.3266   | 910       | 59        | 85.36    | –                       |
| P3 | 4.967     | 530       | 50        | 126.16   | –                       |
| P4 | 10.1898   | 460       | 25        | 63.29    | –                       |
| P5 | 4.1443    | 450       | –         | –        | –                       |
| P6 | 2.3079    | 660       | –         | –        | \(1.30 \times 10^{-6}\) |
| P7 | 2.9054    | 470       | 10        | 37.04    | \(1.21 \times 10^{-6}\) |
| P8 | 7.6898    | 610       | 8         | 45.76    | \(1.21 \times 10^{-6}\) |
| P9 | 3.4503    | 480       | –         | –        | \(1.38 \times 10^{-6}\) |
| P10| 17.6658   | 1510      | 7         | 48.64    | \(1.23 \times 10^{-6}\) |
| P11| 13.6639   | 2110      | –         | –        | –                       |
| P12| 12.2356   | 1120      | –         | –        | –                       |
| P13| 8.2745    | 870       | 19        | 35.28    | –                       |
| P14| 8.2222    | 720       | 23        | 22.8     | –                       |
| P15| 6.883     | 360       | 16        | 47.84    | –                       |

measured in the hanging wall of the fault is higher than that in the footwall of the fault.

The Hg concentration of soil gas was the lowest near the fault (P7, P8, and P10) and was relatively high in the two walls of the fault. The concentrations in the footwall (P2–P4) were approximately twice as high as that in the hanging wall (P13–P15) (Figure 5C). The H₂ concentration of soil gas was higher in the footwall (P2–P4) and lower near the fault (P7, P8, and P10) and hanging wall (P13–P15) (Figure 5D).

In addition, helium isotope test results showed that the \(^3\text{He}/^4\text{He} \ R\) ratio ranges from \(1.21 \times 10^{-6}\) to \(1.38 \times 10^{-6}\), which is lower than that of air \((1.4 \times 10^{-6})\).

**DISCUSSION**

The measurement results show that the soil gas concentrations (Rn, CO₂, Hg, and H₂) in the Tiemenguan section in the BLT fault are different on either side of the fault zone. This may be closely related to the physical and chemical characteristics of the gas and its migration mechanism, the geological conditions of the measurement area, and the fracture development degree of the fracture zone.

**Effect of Extent of Fracture Development on Soil Gas Concentration**

The differences in soil gas concentrations are closely related to the distribution of fractures. The BLT fault is a thrust fault that is affected by the compressive force caused by regional tectonics. As shown in Figure 1, the bedrock type of BLT fault in the Tiemenguan section is primarily granite. Under regional tectonic compressive stress, a series of bending moment faults were formed in the hanging wall of the fault. Due to differences in the degrees of deformation in the hanging wall and footwall, their fractures exhibit different development degrees (Figure 6). As a result, the amount of deep gas escaping is different. In the hanging wall of the fault, under the regional tension stress environment, the surface at the top of the fault broke and formed a series of bending moment faults with many cracks. These bending moment faults are generally shallow fractures, allowing the gas in the soil to continuously escape to the atmosphere, which is not conducive to the enrichment of soil gas. On the other hand, the footwall topography, which is affected by compressive forces, is quite flat. The surface fractures are mainly closed or semi-closed, which is not suitable for the upward soil gas diffusion from the deep layers and its subsequent emission into the atmosphere. Thus, it is advantageous for the soil gas to be adsorbed on the particle surface of the rock. Then, it gradually accumulates in the soil. In the fault zone, the rock is highly fractured, and the fractures are further developed, which results in upward movement of the gas along the fracture.

**Effect of Geological Conditions on Soil Gas Concentration**

The spatial variation characteristics of soil gas concentration are not only related to the number of fractures on the fault, but also to the rock types and overburden properties. For
example, the surface sediments in the Tiemenguan section are primarily gravel and the rock types are mainly granite and limestone with high uranium and thorium content. This causes the soil gas Rn concentration in this section to be relatively high. Even if the rocks on either side of the fault are of the same type, different soil gas concentration characteristics will be formed if the overburden above the fault is different (Fu et al., 2005). As shown in Figure 6, there are differences in stratum type and overburden thickness between the two sides of the Tiemenguan fault. The hanging wall of the fault is covered with a thin layer of sandy soil; the fault is almost exposed to the surface, which results in the dilution of soil gas by air, and thus the soil gas concentration is low. The gravel layer in the footwall of the fault is comprised of weathered granite particles and medium coarse sand. The overburden layer is mainly sandy soil. It has strong gas sealing and adsorption properties. There are few channels available for the gas to escape and this results in a high gas concentration. This is reflected by the high concentrations of H$_2$ and Hg in the footwall of the fault.

**Effects of Physical and Chemical Properties of Gasses**

Hg is a heavy metal of great concern due to its extreme mobility and absorbability. Hg can be easily enriched in faults due to its special physical and chemical properties, and it can migrate from the interior to the surface along a fault or rock fracture due to fluid carrying or pressure gradient (Yangfen et al., 1989; Zhang et al., 2014; Sun et al., 2017a). H$_2$ is a relatively active
volatile substance and its diffusion speed is much higher than that of other gasses. It can easily migrate upward from the fault. The concentration of soil H$_2$ in the fault zone is closely related to the internal structure of the active fault and the development degree of fracture (Wakita et al., 1980). The sources of H$_2$ are as follows: microbial activity in shallow soil; deep water and abiogenic decomposition of CH$_4$ (King, 1986); and chemical reaction between fresh rock fracture surfaces and water (Sugisaki and Mizutani, 1983). CO$_2$ in the fault zone is usually a mixture of several source emissions. Surface biological activities or decomposition of organic matter may lead to increased CO$_2$ concentrations. However, active fault zones can directly produce a large amount of CO$_2$ and can also act as a channel to release deeply contained CO$_2$ (Ciotoli et al., 2007; Chiodini et al., 2008). Rn – a radioactive but chemically inert gas – is constantly generated all over the earth, normally in minute amount by radium in crustal materials (King et al., 1995). The short half-life of $^{222}$Rn limits its diffusion in the soil; thus, the amount of radon measured at the ground surface cannot be released from a deep origin. Therefore, the concentration of Rn in soil gas is mainly affected by rocks containing radioactive elements U and Th. It also migrates from deep faults to the surface along with other carriers, such as CO$_2$, N$_2$, and CH$_4$ (Etiophe and Martinelli, 2002; Yang et al., 2005; Chyi et al., 2010). The small carrier velocity can cause a large change in the concentration of the surface.

### Changes in $^{3}$He/$^{4}$He Isotope Ratio and Soil Gas Concentration

He is an inert gas with a small specific gravity and strong permeability. He in nature is mainly comes from the atmosphere, crust, and mantle. The helium in the atmosphere is mainly composed of $^{4}$He, and the $^{3}$He/$^{4}$He isotopic ratio is almost constant at $1.4 \times 10^{-6}$. The crust is dominated by radioactive atoms in rocks and minerals, such as radiogenic helium, with the $^{3}$He/$^{4}$He value of $2.0 \times 10^{-8}$ and the primary helium in the mantle, with the $^{3}$He/$^{4}$He values ranging from $1.1 \times 10^{-5}$ to $1.4 \times 10^{-5}$. R/Ra can represent the helium isotopic characteristics, where R is the $^{3}$He/$^{4}$He ratio of the sample and Ra is the $^{3}$He/$^{4}$He ratio of the atmosphere, i.e., $1.4 \times 10^{-6}$. When R/Ra <1, it represents the characteristic of shell source helium, while R/Ra >1 represents the characteristic of mantle source helium. As shown in Table 2, the $^{3}$He/$^{4}$He ratio of P6–P10 ranges from $1.21 \times 10^{-6}$ to $1.38 \times 10^{-6}$. The calculation shows that R/Ra <1 indicates that the helium in fault zone is formed from the crust; however, the $^{3}$He/$^{4}$He ratio ($1.21 \times 10^{-6}$–$1.38 \times 10^{-6}$) at the fault zone is smaller than that in the
atmosphere ($1.4 \times 10^{-6}$), which indicates that the helium from the crust has been diluted by atmospheric helium. The main causes of this effect are the U and Th contents in mineral rocks and the sealing characteristics of the system. The higher the content of U and Th in rocks, the more radioactive causes of this effect are the U and Th contents in mineral rocks the crust has been diluted by atmospheric helium. The main

We obtained measurements of soil gas Rn, Hg, H$_2$ and CO$_2$ concentrations from the eastern section of the Beiluntai fault zone in the southern Tianshan Mountains, Xinjiang, China. The geochemical distribution characteristics of the soil gas along the eastern section of the Beiluntai fault were obtained and the possible reasons for the difference in concentrations of soil gas components in the fault were discussed. The following conclusions were drawn:

1. The concentration of the soil gas in the eastern segment of the Beiluntai fault zone in the southern Tianshan Mountains of Xinjiang showed a significant difference on either side of the fault. The concentration of Rn and CO$_2$ was higher on the hanging wall of the fault zone and the concentration of Hg and H$_2$ was higher on the footwall of the fault zone.

2. The soil gas Rn, Hg, H$_2$, and CO$_2$ concentrations of the fault zone are closely related to the physical and chemical characteristics, geological structure, and fracture distribution of the fault zone.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

YX and XS wrote the manuscript. All the authors participated in field measurements.

FUNDING

This research was supported by the research grants (ZDJ2019-06 and ZDJ2017-27) from National Institute of Natural Hazards, MEMC (former Institute of Crustal Dynamics, China Earthquake Administration) and National Natural Science Foundation of China (41972253).

REFERENCES

Baubron, J. C., Rigo, A., and Toutain, J. P. (2002). Soil gas profiles as a tool to characterise active tectonic areas: the Jaunt Pass example (Pyrenees, France). Earth Planet. Sci. Lett. 196, 69–81. doi: 10.1016/s0012-821x(01)00596-9

Butitta, D., Caracausi, A., Chiaraluce, L., Favara, R., and Sulli, A. (2020). Continental degassing of helium in an active tectonic setting (northern Italy): the role of seismicity. Sci. Rep. 10:162.

Camarda, M., De Gregorio, S., Di Martino, R. M. R., and Favara, R. (2016). Temporal and spatial correlations between soil CO$_2$ flux and crustal stress. J. Geophys. Res. Solid Earth 121, 7071–7085. doi: 10.1002/2016jb013297

Caracausi, A., and Paternoster, M. (2015). Radiogenic helium degassing and rock fracturing: a case study of the southern Apennines active tectonic region. J. Geophys. Res. Solid Earth 120, 2200–2211. doi: 10.1002/2014jb011462

Chiodini, G., Caliro, S., Cardellini, C., Avino, R., Granieri, D., and Schmidt, A. (2008). Carbon isotopic composition of soil CO$_2$ efflux, a powerful method to discriminate different sources feeding soil CO$_2$ degassing in volcanic-hydrothermal areas. Earth Planet. Scie. Lett. 274, 372–379. doi: 10.1016/j.epsl.2008.07.051

Chyi, L. L., Quick, T. J., Yang, F. T., and Chen, C. H. (2005). Soil gas radon spectra and earthquakes. Terrest., Atmosph. Oceanic Sci. 16, 763–774. doi: 10.3319/TAO.2005.16.4.763(GIG)

Chyi, L. L., Quick, T. J., Yang, F. T., and Chen, C. H. (2010). The experimental investigation of soil gas radon migration mechanisms and its implication in earthquake forecast. Geofluids 10, 556–563. doi: 10.1111/j.1468-8123.2010.00308.x

Ciotti, G., Lombardi, S., and Annunziatellis, A. (2007). Geostatistical analysis of soil gas data in a high seismic intermontane basin: fucino Plain central Italy. J. Geophys. Res. 112:B05407.
Engle, M. A., Gustin, M. S., and Zhang, H. (2001). Quantifying natural source mercury emissions from the Ivanhoe Mining District, north-central Nevada, USA. *Atmos. Environ.* 35, 5987–5997. doi: 10.1016/s1352-2310(01)00184-4

Etiope, G., and Martinelli, G. (2002). Migration of carrier and trace gases in the geosphere: an overview. *Phys. Earth Planet. Interiors* 129, 185–204. doi: 10.1016/s0031-9201(01)00292-8

Etiope, G., Martinelli, G., Caracausi, A., and Italiano, F. (2007). Methane seeps and mud volcanoes in Italy: gas origin, fractionation and emission to the atmosphere. *Geophys. Res. Lett.* 34:L14303.

Fu, C. C., Yang, T. F., Ju, W., Wang, C. Y., Chen, Y. G., Liu, T. K., et al. (2008). Variations of helium and radon concentrations in soil gases from an active fault zone in southern Taiwan. *Radiat. Meas.* 43, 5348–5352.

Fu, C. C., Yang, T. F., Tsai, M. C., Lee, L. C., Liu, T. K., Wala, V., et al. (2017). Exploring the relationship between soil degassing and seismic activity by continuous radon monitoring in the Longitudinal Valley of eastern Taiwan. *Chem. Geol.* 469, 163–175. doi: 10.1016/j.chemgeo.2016.12.042.

Fu, C. C., Yang, T. F., Wala, V., and Chen, C. H. (2005). Reconnaissance of soil gas composition over the buried fault and fracture zone in Southern Taiwan. *Geochem. J.* 39, 427–439. doi: 10.2343/geochem.39.427

Giammanco, S., Immé, G., Mangano, G., Morelli, D., and Neri, M. (2009). Comparison between different methodologies for detecting radon in soil along an active fault: the case of the Pernicana fault system, Mt. Etna (Italy). *Appl. Radiat. Isot.* 67, 178–185. doi: 10.1016/j.apradiso.2008.09.007

Iovine, G., Guaglardi, I., Bruno, C., Greco, R., Tallarico, A., Falcone, G., et al. (2017). Soil-gas radon anomalies in three study areas of Central-Northern Calabria, (Southern Italy). *Nat. Hazards* 91, 193–219.

Jones, L. C., Rosenbauer, R., Goldsmith, J. I., and Oze, C. (2010). Carbonate control of H2 and CH4 production in serpentinization systems at elevated P-Ts. *Geophys. Res. Lett.* 37, 381–389.

King, C. Y. (1980). Episodic radon changes in subsurface soil gas along active faults and possible relation to earthquakes. *J. Geophys. Res. Solid Earth* 85, 3065–3078. doi: 10.1029/jb091ib12p12269

King, C. Y. (1986). Gas geochemistry applied to earthquake prediction: an overview. *J. Geophys. Res. Solid Earth* 91, 12269–12281. doi: 10.1029/jb091ib12p12269.

King, C. Y., King, B. S., Evans, W. C., and Zhang, W. (1996). Spatial radon monitoring in the 1995 Kobe earthquake. *J. Geophys. Res. Solid Earth* 101, 163–175. doi: 10.1029/95JB00874.607

Large, J. V., Sass, R. A., Ron, E. N., and Esset, R. (2010). Geochemistry of soil gas in the seismic fault zone produced by the Wenchuan earthquake. *Earth Planet. Sci. Lett.* 283, 283–294. doi: 10.1016/j.epsl.2009.09.022

Li, Y., Du, J. G., Wang, X., Zhou, X. C., Xie, C., and Cui, Y. J. (2013). Spatial variation of soil gas geochemistry in the tangshan Area of Northern China. *Radiat. Measur.* 46, 1190–1201. doi: 10.1016/j.radmeas.2013.08.025

Li, Y. G., Chen, P., Cochran, E. S., Vidale, J. E., and Burdette, T. (2006). Seismic activity and the 1995 Kobe earthquake. *Science* 310, 221–230. doi: 10.1126/science.1120738

Mazur, D., Janik, M., Łoskiewicz, J., Olko, P., and Swako´n, J. (1999). Measurements of hydrogen in fault gases. *Pure Appl. Geophys.* 156, 1226–1245. doi: 10.1007/s000240050161

Munir, M. A. (1989). Change in soil gas radon content variation in water. *J. Geochem. Explorat.* 32, 185–190. doi: 10.1016/0379-8498(89)90067-8

Nakamura, Y., Kata, J., Fujii, N., and Notsu, K. (1980). Hydrogen release: new indicator of fault activity. *Science* 210, 188–190. doi: 10.1126/science.210.4466.188

Walia, V., Yang, T. F., Hong, W. L., Lin, S. J., Fu, C. C., Wen, K. L., et al. (2009). Geochemical variation of soil-gas composition for fault trace and earthquake precursor studies along the Hsinchung fault in NW Taiwan. *Appl. Radiat. Isot.* 67, 1853–1865. doi: 10.1016/j.apradiso.2009.07.004

Ward, R. H., Roecken, C., and Wyss, M. (1984). The detection and interpretation of hydrogen in fault gases. *Pure Appl. Geophys.* 122, 392–402. doi: 10.1007/bf00874607

Wienberg, T., and Erzinger, J. (2008). Origin and spatial distribution of gas at seismicogenic depths of the San Andreas fault from drill-mud gas analysis. *Appl. Geochim.* 23, 1675–1690. doi: 10.1016/j.apgeochem.2008.01.012

Yang, T. F., Wala, V., Chi, L. L., Fu, C. C., Chen, C. H., Liu, T. K., et al. (2005). Variations of soil radon and thoron concentrations in a fault zone and prospective earthquakes in SW Taiwan. *Radiat. Measur.* 40, 496–502. doi: 10.1016/j.radmeas.2005.05.017

Yanget, J., Zhonghua, W., Chunsheng, S., Jiazheng, W., and Hongren, Z. (1989). Earthquake prediction through the observation and measurement of mercury content variation in water. *J. Geomorphol. Explorat.* 33, 195–202. doi: 10.1016/0375-7642(99)00029-0

Yao, Y., Song, H. P., Chen, J. B., Li, S. S., and Jia, H. L. (2018). Late quaternary crustal shortening rate of the Beulunai fault in southern. *Seismol. Geol.* 40, 71–86.

Yuce, G., Fu, C. C., D’Alessandro, W., Gulbay, A. H., Lai, C. W., Bellomo, S., et al. (2017). Geochemical characteristics of soil radon and carbon dioxide within the Dead Sea fault and Karasu fault in the Amik basin, (Hatay), Turkey. *Chem. Geol.* 469, 129–146. doi: 10.1016/j.chemgeo.2017.01.003

Zhang, L., Liu, Y., Guo, L., Yang, D., Fang, Z., Chen, T., et al. (2014). Isotope geochemistry of mercury and its relation to earthquake in the Wenchuan Earthquake Fault Scientific drilling project hole-1. *Tectonophysics* 619–620, 79–85. doi: 10.1016/j.tecto.2013.08.025

Zhou, X., Wang, W., Chen, Z., Yi, L., Liu, L., Xie, C., et al. (2015). Hot spring gas geochemistry in western sichuan province, China after the wenchuan ms 8.0 earthquake. *Terr. Atmos. Ocean. Sci.* 26, 361–373. doi: 10.3319/tas.2015.01.05.01(tt)

Zhou, X. C., Du, J. G., Chen, Z., Cheng, J. W., Yang, Y., Yang, L. M., et al. (2010). Geochemistry of soil gas in the seismic fault zone produced by the Wenchuan Ms = 8.0 earthquake, southwestern China. *Geochim. Trans.* 11(5).

**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.

Copyright © 2020 Xiang, Sun, Liu, Yan, Wang and Gao. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.