Research Article

Tectonic Controls on Near-Surface Variations in CH₄ and CO₂ Concentrations along the Northwestern Margin of the Ordos Block, China

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Tectonic controls on near-surface CH₄ and CO₂ concentrations were investigated by measuring CH₄ and CO₂ concentrations at the surface and a height of 1.5 m, in the different tectonic units that comprise the northwestern margin of Ordos Block, China, which has a complex tectonic structure and a history of strong earthquakes. CH₄ and CO₂ concentrations varied from 1905 to 2472 ppb and 397.5 to 458.5 ppm, respectively. Surface CH₄ and CO₂ concentrations were generally higher than those measured at 1.5 m, but showed similar trends, indicating that the measured CH₄ and CO₂ predominantly originated from underground gases. The CH₄ and CO₂ concentrations increased with an increasing strike-slip rate across the faults, and concentrations in the blocks with high internal deformation were much higher than those measured in the stable blocks. Regions of extensional deformation had higher gas concentrations than regions that had experienced compressional deformation. The spatial distribution of CH₄ and CO₂ at the study site had similar trends to faults associated with the Yinchuan Graben. The results of this study indicated that gas source, gas migration pathway, and tectonic stress were the main factors that influenced gas emission. The key factor is tectonic stress, which controlled the formation of tectonic structures, changed the pathway of degassing, and acted as the driving force for gas migration. The results of this study clarify the mechanism of CH₄ and CO₂ degassing in faulted regions and suggest that CH₄ and CO₂ concentrations may be useful precursors in the monitoring of seismic activity. The results may also help inform future assessments of the contribution of geological sources to greenhouse gas emissions.

1. Introduction

Earth degassing is controlled by gas sources, pathways of gas migration, and the driving force for degassing, which is tectonic stress. C-H-O-bearing gases (e.g., CO₂, H₂, CH₄, CO, and H₂O) are important components of the mantle and lower crust [1, 2]. Gases from the solid earth are continuously emitted into the atmosphere, especially through weak zones in the crust, such as the faulted boundaries of tectonic plates and blocks [3–9]. Most faults and fractures in the crust are generated under the action of tectonic stress and provide channels for gases escaping from the crust and mantle into the atmosphere. Therefore, concentrations of

emitted gases are higher at faulted tectonic boundaries, and the gas flux from the lithosphere may vary with changes in tectonic stress.

The correlations between earth degassing and active tectonic units at different scales (local, regional, and continental) have been extensively studied in volcanic regions [10–12], seismic regions [5, 6, 13–16], and fault zones [4, 8, 17–21]. A large number of soil gas observations indicate that higher values of gas concentrations and flux are distributed along fault zones [5, 6, 17, 20, 22]. The results of field investigations [20, 22–24], statistical phenomena [25], and dynamic experiments on rocks [26] have also demonstrated that the stress associated with crustal deformation

FIGURE 1: Topographic map showing active faults and sampling points near the western margin of the Ordos Block, China: (a) location of the study area (modified after [29]); (b) study area. Arabic numerals indicate the sampling point numbers in the different tectonic units: I: Minqin Block; II: Ordos Block; III: Hetao Graben; IV: Yinchuan Graben; V: Haiyuan Block.

affects earth degassing. In addition, atmospheric CH_4 and CO_2 anomalies related to fault zones and the accumulation of tectonic stress have been observed in satellite hyperspectral data [27].

The goals of this paper are (i) to discuss correlations between the extent of earth degassing and specific tectonic features, by investigating spatial variations in surface CH_4 and CO_2 in the different tectonic units around the north-western margin of the Ordos Block, China, and (ii) to assess the contribution of the emitted gases to the local atmospheric environment, because CH_4 and CO_2 are important greenhouse gases.

2. Tectonic Setting

Mainland China can be divided into many tectonic blocks of different orders that are bordered by active faults [28, 29]. The study area is tectonically located at the intersection of the Qinghai-Tibet Block, the Alxa Block, and the Ordos Block, in the northern part of the north-south-oriented seismic belt in China (Figure 1). The southern boundary of the Qinghai-Tibet Block is the Indo-Eurasian plate boundary fault zone, which has experienced slip rates in the range of 15–18 mm/a and intense seismicity throughout the Holocene [30]. The northern boundary of the Qinghai-Tibet Block is the sinistral Altyn Tagh-Qilian-Haiyuan fault system, along which different fault segments have exhibited a wider range of slip rates, from ~ 3 to 30 mm/a, during the Holocene [28, 29]. The Haiyuan Block is located at the northeastern edge of the Qinghai-Tibet Block, in the southwestern part

of the study area. The Alxa and Ordos Blocks are tectonically stable and have developed from the north China craton. The Alxa Block is separated from the Donghuang Block to the west by the Alkin fault zone, separated from the Ordos Block to the east by the Yinchuan Graben, separated from the Qilianshan orogenic belt to the south-southeast by the Longshoushan fault zone, and separated from the Middle-Asian orogenic belt to the north by the Badanjilin fault zone. The Minqin Block forms the southeastern margin of the Alxa Block. The Ordos Block is bordered by the Qilianshan orogenic belt to the southwest, the Yinchuan Graben (YG in Figure 1(a)) and Hetao Graben (HG in Figure 1(a)) to the northwest, the Yinshan-Yanshan fault block to the north, the Weihe Graben (WG in Figure 1(a)) to the south, and the Shanxi Graben (SG in Figure 1(a)) to the east [28, 31].

Tectonic activity in the study area (Figure 1) has been strong since the start of the Cenozoic, forming a NW-NWW arc-shaped mountain belt characterized by extrusion and strike-slip faulting in the southwestern part of the area. The arc-shaped mountains consist of pull-apart basins and strike-thrust arc-shaped fault belts that are commonly developed in the piedmonts of the mountains. However, NE-extensional grabens of different scales have formed in the northern part of the study area, and large-scale tensile-torsional normal faults have developed at the boundaries of the basins [32, 33].

The study area is classified into five different tectonic units (Figure 1, Table 1). The Minqin Block (I) and Ordos Block (II) are relatively stable with minor internal deformation and slightly sinistral rotation (<3 nanostrain/a). The

TABLE 1: CH₄ and CO₂ concentrations at the surface (0 m) and a height of 1.5 m in different tectonic settings around the western margin of the Ordos Block in China.

Block (area)	No.	Location		CH ₄ (ppb)				CO ₂ (ppm)				Maximum shear strain (10 ⁻⁹ /a)	Tectonic setting
		Longitude (°E)	Latitude (°N)	1.5 m	Mean	0 m	Mean	1.5 m	Mean	0 m	Mean		
Minqin Block (I)	1	105.73	39.87	1905		1909		407.6^b		406.5		1.0 ± 2.5 [34]	Relatively stable
	2	105.40	39.56	1907	1908	1909	1911	404.8	406.0	405.6	406.0		
	3	105.70	39.35	1912		1914		405.5		406.0			
Ordos Block (II)	1	106.89	38.34	1969		1973		415.5		415.9		0.9 ± 0.6 [34]	Relatively stable
	2	107.44	38.17	1965		1969		413.6		415.6			
	3	107.66	38.55	1996	1955	1997	1958	412.4	411.1	413.3	412.4		
	4	108.04	39.08	1916		1919		405.7		407.8			
	5	107.50	39.25	1931		1931		408.6		409.1			
Hetao Graben (III)	1	107.59	40.70	1932		1934		409.5		409.1		409.8	Extensional
	2	107.92	40.77	1936		1946		409.5		410.4			
	3	108.36	40.75	1926	1927	1927	1931	410.0	408.4	410.0	409.8		
	4	108.75	40.59	1927		1929		409.4		410.3			
	6	108.37	41.06	1928		1928		410.0		410.0			
	5	107.59	41.06	1910		1926		402.1		409.3			
Southern part of Yinchuan Graben (IV)		106.18	38.11	2054		2068		427.1		431.0			Extensional
Northwestern part of Yinchuan Graben (line 1+line 2) ^a (IV)	L1-1	106.03	38.50	2021		2028		403.8		405.9		407.3	Extensional
	L1-2	106.05	38.60	1947		2054		400.7		409.2			
	L1-3	106.09	38.66	1951		1956		406.6		405.8			
	L1-4	106.14	38.74	1960	1964	1959	1982	408.6	405.7	408.5	407.3		
	L1-5	106.19	38.83	1992		1993		409.6		410.6		413.5	Extensional
	L1-6	106.25	38.90	1973		1975		409.4		410.3			
	L1-7	106.32	39.00	1909		1912		401.3		400.5			
	L2-7	106.44	39.00	1981		1966		404.6		405.9			
	L2-6	106.38	38.92	1945		1948		410.0		410.6		412.8	Extensional
	L2-5	106.34	38.83	1937		1939		411.7	412.8	412.1	413.5		
	L2-4	106.27	38.74	1975	1969	1978	1966	411.8		411.8			
	L2-3	106.22	38.66	1927		1927		410.5		412.0			
	L2-2	106.18	38.59	1930		1942		412.1		412.3			
	L2-1	106.18	38.50	2087		2062		429.0		430.1			
Middle-northern part of Yinchuan Graben (line 3+line 4) (IV)	L3-1	106.25	38.51	1971		1965		413.8		415.9		440.4	Extensional
	L3-2	106.29	38.58	2091		2079		427.4		432.6			
	L3-3	106.34	38.67	2466		2472		454.8		456.9			
	L3-4	106.36	38.73	2354	2204	2346	2199	439.9	438.6	440.1	440.4		
	L3-5	106.42	38.84	2260		2255		454.4		458.5		421.1	Extensional
	L3-6	106.51	38.93	2161		2153		446.9		446.1			
	L3-7	106.59	39.00	2125		2125		433.2		433.1			
	L4-7	106.69	39.00	2015		2014		423.7		424.1			
	L4-6	106.64	38.92	1983		1981		418.8		419.0			
	L4-5	106.57	38.83	2008		2006		421.2		419.9			
	L4-4	106.50	38.75	2071	2050	2066	2043	420.6	420.3	420.0	421.1		
	L4-3	106.45	38.67	2056		2054		416.7		414.7			
	L4-2	106.39	38.58	2033		1999		406.7		409.3			
	L4-1	106.32	38.50	2184		2179		434.7		440.8			

TABLE 1: Continued.

Block (area)	No.	Location		CH ₄ (ppb)				CO ₂ (ppm)				Maximum shear strain (10 ⁻⁹ /a)	Tectonic setting
		Longitude (°E)	Latitude (°N)	1.5 m	Mean	0 m	Mean	1.5 m	Mean	0 m	Mean		
Northeastern part of Yinchuan Basin (line 5+line 6) (IV)	L5-1	106.41	38.51	2029		2002		409.4		405.7		Extensional	
	L5-2	106.48	38.58	2240		2274		425.0		434.2			
	L5-3	106.55	38.68	2244		2249		411.7		411.7			
	L5-4	106.60	38.77	2260	2183	2190	2174	439.7	420.7	432.7	421.7		
	L5-5	106.65	38.83	2159		2157		404.8		404.9			
	L5-6	106.75	38.91	2108		2090		407.5		407.8		Extensional	
	L5-7	106.84	39.08	2240		2255		447.0		454.6			
	L6-7	106.93	39.03	2244		2243		452.9		456.6			
	L6-6	106.85	38.91	2208		2219		440.2		444.1			
	L6-5	106.77	38.84	2092		2104		430.2		432.7			
	L6-4	106.72	38.77	1971	2087	1960	2087	403.9	422.4	397.8	423.2		
	L6-3	106.62	38.68	2006		2006		399.7		398.1			
	L6-2	106.59	38.58	2051		2034		411.0		413.2			
	L6-1	106.56	38.49	2040		2042		419.1		419.5			
Haiyuan Block (V)	1	105.69	36.54	1996		1990		404.0		404.2		Extrusion High deformation	
	2	105.89	36.31	2027		1978		426.6		430.7			
	3	105.55	36.27	1971	1987	1968	1976	397.5	408.4	398.2	409.5		
	4	105.74	36.78	1986		1990		408.8		408.9			
	5	105.42	36.83	1955		1952		405.1		405.6			

^aIn the northwestern part of the Yinchuan Graben, the sampling line containing samples line 1-line 6 (abbr. L1-L6) is oriented from west to east. The sampling line containing samples 1-7 is oriented from south to north. ^bConcentrations that are higher at 1.5 m than at 0 m are marked in bold.

Hetao Graben (III) and Yinchuan Graben (IV) are pull-apart basins with shear features caused by dextral strike-slip from north to south [34]. Some faults in the graben basins cut deep into the mantle [35], which is conducive to the upward migration of deep-earth fluids. The Haiyuan Block (V) is characterized by intense regional deformation (17.2 ± 9.23 nanostrain/a) and high rates of left-lateral slip and shortening in the NS direction [34].

3. Methods and Data Processing

Concentrations of CH₄ and CO₂ at the surface and 1.5 m above the surface, at 62 sites located in the five tectonic units of the study area (Figure 1), were measured in the field during the period of 19–26 October 2018 with a high-accuracy Picarro G4301 CO₂/CH₄/H₂O analyzer. In order to understand the mechanisms of tectonic CH₄ and CO₂ degassing in different tectonic settings, approximately 5 sampling points were evenly distributed across each tectonic setting (except for Yinchuan Graben), because the gas concentration in air at a single point is representative of a large region containing the same geological and geomorphological features. 42 sampling points were defined in the northern part of the Yinchuan Graben, in order to correlate the spatial distribution of CH₄ and CO₂ concentrations with faults in the graben [35].

The Picarro G4301 CO₂/CH₄/H₂O analyzer was designed based on the principle of wavelength scanning cavity ring-down spectroscopy (CRDS) technology, meaning air samples

do not need to be dried, and in-flight calibrations are not required [36, 37]. Measurement of CH₄ and CO₂ concentrations contains errors of 0.3 ppb and 0.03 ppm for 5-minute sampling, and 3 ppb and 0.4 ppm for 5-second sampling, respectively. We measured CH₄ and CO₂ concentrations at 0 m and 1.5 m at each site for two minutes, and the mean values at each sampling site were used as representative concentrations. CH₄ and CO₂ concentrations in the northern part of the Yinchuan Graben were mapped, to show the spatial variation in concentration values at different levels.

4. Results

4.1. CH₄ and CO₂ Concentrations. CH₄ concentrations in the different tectonic units of the study area ranged from 1905 to 2466 ppb at 1.5 m and from 1909 to 2472 ppb at 0 m. CO₂ concentrations ranged from 397.5 to 454.8 ppm at 1.5 m and 397.8 to 458.5 ppm at 0 m (Table 1). The mean values of surface CH₄ concentrations in the different tectonic units varied between 1908 ppb and 2183 ppb, and mean values of surface CO₂ concentrations varied between 405.7 ppm and 440.4 ppm (Table 1).

Concentrations of CO₂ at 0 m were higher than those at 1.5 m, except for some sites (Table 1) near villages or roads, which were likely to have been affected by human activities. Concentrations of CH₄ at 0 m in the Ordos Block, Minqin Block, and Hetao Graben were higher than that at 1.5 m, while the concentrations were higher at 1.5 m than at 0 m in the Haiyuan Block, except for point No. 4 (Table 1).

FIGURE 2: Distributions of CH_4 concentrations at (a) a height of 1.5 m and (b) the surface (0 m), for different tectonic settings along the western margin of the Ordos Block.

Higher concentrations were observed at 0 m at most survey sites in the western part of the Yinchuan Graben, but higher concentrations of CH_4 were obtained at 1.5 m at most survey sites in the central and eastern parts of the graben (Table 1).

4.2. Distribution of CH_4 and CO_2 Concentrations. The spatial variation in CH_4 concentrations at a height of 1.5 m (Figure 2(a)) showed a similar tendency distribution to variation in surface concentrations (0 m, Figure 2(b)) across the different tectonic settings. Spatial variation in CO_2 concentrations followed the same pattern (Figure 3). The results showed that CH_4 concentrations increased in the five surveyed regions, in the following order: Minqin Block (I) < Hetao Graben (III) < Ordos Block (II) < Haiyuan Block (V) < Yinchuan Graben (IV). CO_2 concentrations increased in a slightly different order: Minqin Block (I) < Hetao Graben (III), Haiyuan Block (V) < Ordos Block (II) < Yinchuan Graben (IV).

5. Discussion

5.1. Variations in CH_4 and CO_2 Concentrations in Different Tectonic Settings. Different fault blocks in the study region are under the action of different tectonic stresses, so the gases that are emitted in each region have different geochemical characteristics. The five fault blocks in the study area are characterized by different movement styles and directions, and GPS data inversion has revealed that each has a different stress field [34].

CO_2 and CH_4 concentrations at most measurement sites in the Minqin Block (I) and Ordos Block (II) were

higher at the surface than at a height of 1.5 m (Table 1), indicating that underground gases contributed most of the CH_4 and CO_2 . The Minqin and Ordos Blocks are stable blocks with little or no (<3 nanostrain/a, Table 1) internal deformation [28, 34], so crustal fractures are not well developed in these regions and therefore do not act as pathways for gas emission. Therefore, CH_4 and CO_2 concentrations were lower in these stable blocks than at other sites (Figures 2 and 3).

The stress field associated with crustal deformation led to geochemical variation in emitted gases. Rates of active fault movement depend on local tectonic stresses and can control the upward migration of gases along fault zones. CH_4 and CO_2 concentrations increased with faster strike-slip rates across faults, which showed an increasing trend from north to south (strike-slip rates across the faults in Hetao Graben < Ordos Block < Haiyuan Block) in the study area [29, 34]. In the Haiyuan Block, CH_4 and CO_2 concentrations increased from southwest to northeast (Figures 2 and 3), due to relatively rapid left-lateral slip along its northern boundary, compared to moderate strain accumulation on its southern boundary [34].

The average surface concentrations of CH_4 (1958 ppb) and CO_2 (412.4 ppm) were higher in the Ordos Block than those in the Minqin Block (CH_4 = 1911 ppb, CO_2 = 406.0 ppm; Table 1), even though both blocks are tectonically stable [28], with little internal deformation [34]. Greater emission of gases from the Ordos Block occurs because it is more enriched in petroleum and natural gas than the Minqin Block, as demonstrated by its many gas and oil fields. In addition, the Minqin Block is a desert region with loose soil and a

FIGURE 3: Distributions of CO_2 concentrations at (a) a height of 1.5 m and (b) the surface (0 m), for different tectonic settings along the western margin of the Ordos Block.

FIGURE 4: Models of earth degassing throughout (a) the Yinchuan Graben and (b) the Haiyuan Block. In (a), the extensional tectonic setting provides pathways (fractures) of gas migration (modified after [35]). In (b), the compressional tectonic setting creates overlapping structures that inhibit the rise of deep gases (modified after [6]).

thin cover, which is not conducive to the accumulation of underground gas sources.

Most surface concentrations of CO_2 and CH_4 measured in the western parts of the Yinchuan and Hetao Grabens were higher than those measured at a height of 1.5 m (Table 1), indicating the presence of underground gas sources. CH_4 concentrations in the central and eastern parts of Yinchuan Graben were higher at 1.5 m, due to CH_4 release from rice fields.

Extensional tectonic stress in the region has produced faults and fractures that provided the pathways for gas migration (Figure 4, [6]). Gas from the mantle and asthenosphere can be emitted to the atmosphere along faults that

cut deep into the mantle in the Yinchuan Graben, which explains why CH_4 and CO_2 concentrations are much higher in this graben (IV) than in other tectonic blocks (Figures 2 and 3; [35]).

The Hetao Graben (III) is a shear-stretched basin with a tensile strength that became much weaker in the Quaternary. Petroleum exploration has indicated that there are large amounts of natural gas beneath the measurement sites in the Hetao Graben and at its boundary with the Ordos Block. However, underground gas in the Hetao Graben finds it more difficult to escape due to poor pathways, because the rocks in this graben have a lower permeability and faults

FIGURE 5: Contour maps of CH_4 and CO_2 concentrations in the northern part of the Yinchuan Graben, which show that variations in CH_4 and CO_2 distribution fit the trend of tectonic features in the survey area.

are sealed. As a result, the average surface concentrations of CH_4 (1931 ppb) and CO_2 (409.8 ppm) in the Hetao Graben were much lower than surface concentrations measured in the Yinchuan Graben ($\text{CH}_4 = 1966 - 2199$ ppb, $\text{CO}_2 = 407.3 - 440.4$ ppm; Figure 4 and Table 1).

The Haiyuan Block (V), which experienced strong deformation and so contains well-developed fractures (Deng et al. 2013; [34]), showed evidence for the efficient emission of deep gases. The average concentration of CH_4 (1976 ppb) was higher in the Haiyuan Block than that measured in the Ordos (1958 ppb) and Minqin (1911 ppb) Blocks in which internal deformation was weaker (the Ordos and Minqin Blocks showed a maximum shear strain of 1.0 ± 2.5 and $0.9 \pm 0.6 \cdot 10^{-9}/a$, respectively; Table 1, [34]). Average CO_2 concentrations were slightly higher in the Haiyuan Block (409.5 ppm) than in the Minqin Block (406.0 ppm; Figure 3). However, many overlapping structures were produced in the Haiyuan Block due to compression caused by the Qinghai-Tibet Plateau (Figures 1(a) and 4(b), [29]), which inhibited the migration of deep gases [6]. In addition, the Haiyuan Block contains less underground gas than the Yinchuan Graben, which is enriched in oil and gas. Consequently, the average concentrations of CH_4 (1976 ppb) and CO_2 (409.5 ppm) were much lower in the compressional Haiyuan Block (V) than those ($\text{CH}_4 = 1966 - 2199$ ppb, $\text{CO}_2 = 407.3$

$- 440.4$ ppm) in the extensional Yinchuan Graben (IV) (Figures 2 and 3, Table 1).

Tectonic stress affects gas emission in complex ways, although a good correlation exists between the soil gas concentration and stress in the crust [23, 24]. Degassing can be enhanced by a large number of fractures formed under the action of stress, while pathways of gas emission can shrink or even become blocked when stress is concentrated, thereby inhibiting emission, for example, little gas emissions from the Longmenshan fault zone before the Wenchuan M_s 8.0 earthquake of May 12, 2008, which was caused by the locked fault hardly without deformation under the long-term strain accumulation [27, 38, 39]. Correlations between fault stress and geochemical and fluid-related earthquake precursors were studied by Martinelli & Dadomo [25], and their results suggested that greater seismic precursory phenomena occur at faults under lower stresses.

5.2. Correlation of CH_4 and CO_2 Concentrations with Faults in the Yinchuan Graben. Fault systems are the expression of continuous planar defects in rocks, which is why a direct link was observed between extensional faults and gas emission. The maps of CH_4 and CO_2 concentrations fit well with the trends of tectonic features in the northern part of the Yinchuan Graben (Figures 5 and 6), because active faults in

FIGURE 6: Sectional view of CH_4 degassing in the Yinchuan Graben (modified after [6, 35]).

the region acted as pathways for gas discharge. This indicates that high CH_4 and CO_2 concentrations correlate well with active faults. The phenomenon of gas anomalies distributed along faults has also been observed in other regions, such as the Tangshan area of Northern China [20], the Lateral caldera in central Italy [17], the Amik Basin (Hatay) in Turkey [22], and the Eastern Rift of the East African Rift System [40].

Faults become younger from the west to east in the Yinchuan Graben, which results in greater gas emission in the east than in the west. However, the Yellow River is located in the eastern part of the graben, meaning soil porosity and permeability are low in this region. In addition, normal fault activity under tectonic stress might dilute the gas concentrations by air mixing that occurs within the fault (Figure 4(a)). Thus, CH_4 and CO_2 concentrations on the east and west sides of the Yinchuan Graben were lower than those measured in the middle part (Figures 5 and 6).

6. Conclusions

- (1) CH_4 and CO_2 concentrations in the northwestern margin of the Ordos Block, China, varied from 1905 to 2472 ppb and 397.5 to 458.5 ppm, respectively. Most sampling points in the Ordos Block, Minqin Block, Hetao Graben, and the western part of Yinchuan Graben displayed higher surface concentrations of CO_2 and CH_4 than those measured at a height of 1.5 m, indicating that measured concentrations had a contribution from underground gases.
- (2) The distribution of surface CH_4 and CO_2 concentrations was similar to those measured at a height of 1.5 m for all tectonic settings in the study area. CH_4 concentrations in the Minqin Block (I) < Hetao Graben (III) < Ordos Block (II) < Haiyuan Block (V) < Yinchuan Graben (IV) and CO_2 concentrations in the Minqin Block (I) < Hetao Graben (III) < Haiyuan Block (V) < Ordos Block (II) < Yinchuan Graben (IV).
- (3) The distributions of CH_4 and CO_2 concentrations were affected by the gas source, migration pathway,

and tectonic stress regime and are highly correlated with the local tectonic setting and stress state.

The results of this study clarify the mechanism of CH_4 and CO_2 degassing in faulted regions and suggest that CH_4 and CO_2 concentrations may be useful precursors in the monitoring of seismic activity. The results may also help inform future assessments of the contribution of geological sources to greenhouse gas emissions.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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