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Investigation of hot spring gas components and soil gas fluxes in Arxan Holocene volcanic field, Inner Mongolia, NE China

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The latest research results show that there is a unified magma system and heating channel beneath the Arxan volcanic field, indicating a potential risk of eruption. The Arxan volcanic field features multiple gas emission sites (e.g., Jinjianggou hot springs and Yinjianggou hot springs) and exhibits strong hydrothermal activity. In this study, measurements of the hot spring gas composition and soil CO₂ flux in the Arxan Holocene volcanic field were conducted, and the results were combined with previous research results to analyze the degassing characteristics of this region. The results show that the volcanic gases in the Arxan volcanic field are composed of 0.07%–1.09% CO₂, 0.33–12 ppm CH₄, 1.57–53 ppm H₂, 800–30,241 ppm He, and 1.14%–1.86% Ar. The He content in this area is notably higher than that in other dormant volcanoes in China. This difference is possibly caused by U–Th decay in the Mesozoic granodiorite and acidic volcanic rocks in the study area, which can produce substantial radiogenic He. The soil gas concentrations near the Jinjianggou and Yinjianggou hot springs are higher than those of two Holocene volcanoes. The peak CO₂ concentration in the soil near the Jinjianggou hot spring can reach 35,161 ppm. The single-site soil microseepage CO₂ flux in the Arxan volcanic field is 4.66–107.18 g m⁻² d⁻¹, and the estimated annual CO₂ emission flux from the volcanic field to the atmosphere is 0.63 × 10⁵ t, which also demonstrates that soil CO₂ flux of Arxan volcano is comparable to the soil CO₂ emission level of the Iwojima volcano.

KEYWORDS

dormant volcano monitoring, volcanic gas emissions, soil gas fluxes, hot spring gas components, Arxan volcanic field

1 Introduction

Due to the existence of underground high-temperature magma chambers in active volcanic fields, a variety of geothermal fluids quickly escape to the surface along volcanic channels or faults, where they are emitted through hot springs, vents and soils. During the volcanic eruption intervals, large amounts of volcanic gases are emitted to the atmosphere because of the continuous heating of the country rock caused by the high-temperature chambers (Guo et al., 2015; Aiuppa et al., 2015; Tassi et al., 2016; Liu et al., 2021). It has been demonstrated that 14 volcanoes in mainland China erupted during the Holocene (wei et al., 1998; Wei et al., 2003; Pan et al., 2021) and are currently in a dormant state. Among the current dormant volcanoes in China, the Changbaishan, Tengchong, and Wudalianchi

volcanoes have been investigated by numerous studies to determine their fluid backgrounds (Du et al., 1999; Shangguan et al., 2008; Zhang et al., 2011; 2015; 2016; 2018; Liu et al., 2011; Guo et al., 2015; Li, 2015; Zhao, 2012; Wei et al., 2021; Zhao et al., 2019). Some studies on the geothermal fluids in the Arxan volcano have been conducted, but studies focusing on the volcanic greenhouse gas emissions in this area are scarce. Therefore, to ascertain the components and emission levels of hot spring gases, this study investigates the CO₂ emissions in the Arxan volcanic field and analyzes the emission characteristics of greenhouse gases in dormant volcanoes. This study provides significant information for deep magmatism investigations and volcano monitoring in the future.

A vast majority of previous investigations on the Arxan volcano focus on the volcanic geology, geophysical exploration, and geothermal heat in the peripheral area of the volcanic field (Liu, 1987; Bai et al., 2005; Tang, 2005; Zhao and Fan, 2010; Han et al., 2018; Gu, 2018; Cui et al., 2022; Li et al., 2023). The latest research illustrates that the Arxan volcanic cluster consists of 46 volcanoes ranging from Pliocene to Holocene in age, including four active volcanoes that have erupted during the Holocene, namely, the Gaoshan volcanoes, Yanshan volcanoes, Shihaogou basin volcanoes, and Xiaodonggou volcanoes. Among them, Gaoshan and Yanshan volcanoes are considered to be active volcanoes that erupted approximately 2,000 years ago (Bai et al., 2005). In recent years, some magnetotelluric sounding observations have shown that the

region 10–12 km below the active volcanoes retains a high thermal state, and a mantle upwelling channel conducting heat may exist in the region at a depth of 30–50 km (Tang et al., 2005). Han et al. (2018) reports that the Arxan magma system is uniformly composed of arch bridge-shaped magma transportation channels and basaltic magma from the asthenosphere. In addition, two high-conductivity anomalies have been discovered, with burial depths from 40 to 90 km. Recent studies on fluid geochemistry in Arxan show that the excess N₂, Ar, He and CO₂ in hot springs are mainly from the crust and upper mantle, and approximately 3%–23% of the He in crater lake water and bubble gas in hot springs comes from the mantle (Cui et al., 2022).

The purpose of this study is to analyze the degassing characteristics and emission mechanisms of greenhouse gases in the Arxan volcano through the investigation of the relevant gas components, the concentrations of volcanic gas, and the emissions of soil gases. Moreover, this study aims to explore the emission characteristics of volcanic greenhouse gases during the dormant period and compare the results to those of other dormant volcanoes.

2 Geological setting

The Arxan volcanic cluster is located in the eastern section of the China–Mongolia border. The geographical coordinates are 120°14′–121°20′E, 47°15′–47°45′N. The volcanoes in this cluster

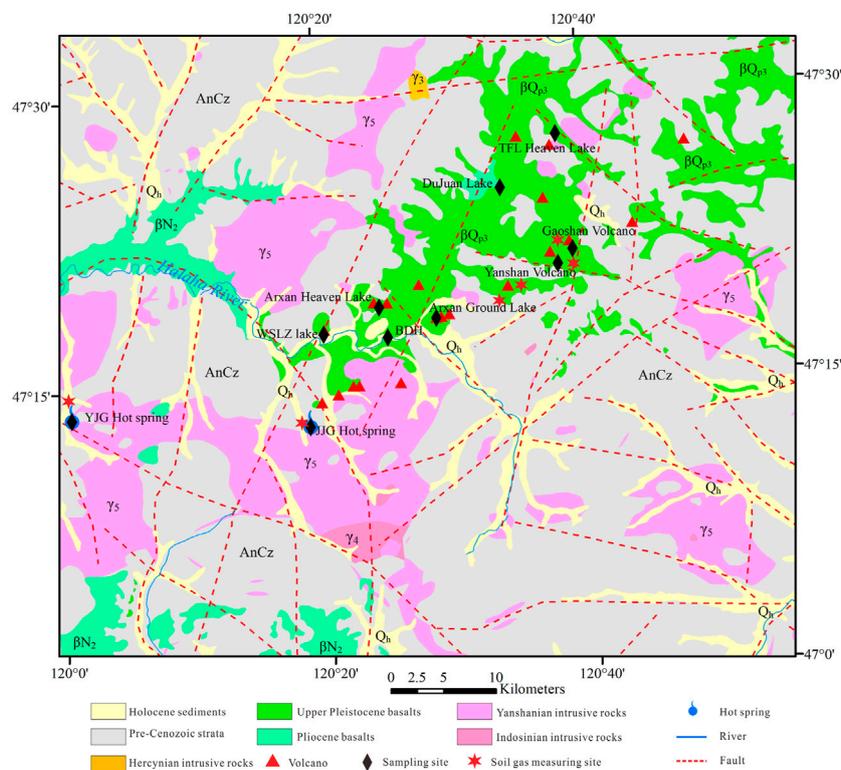


FIGURE 1 Geological map and sampling site locations in the Arxan active volcanic field (modified from 1:250000 geological structure map of Chaihe sheet).



are distributed in the upper reaches of the Halaha River in the southwest of the Greater Khingan Mountains situated in the back-arc region of the subducting western Pacific plate. Since the early Jurassic, affected by the subduction of the Pacific plate and the blocking of the Eurasian plate, a series of NE-oriented faults and volcanic rock belts with different scales have developed. Since the start of the Cenozoic, extensive basaltic magma has violently erupted (Liu, 1987; Liu et al., 2001; Pan et al., 2021). The volcanism in this region is multi-episodic and can be divided into the Pliocene, Pleistocene and Holocene eruption stages. The volcanic products overlie the Jurassic volcanic-intrusive rocks, with an overall NE trending distribution and an exposed area of approximately 1,300 km². The Pliocene series is composed of tholeiite, and the Quaternary rocks are mainly alkaline olivine basalt.

Faults with different directions are developed in the study area (Figure 1). The NE trending Halaha River fault cuts the lithosphere and has a length of approximately 500 km. Furthermore, it provides two channels transporting Quaternary magma from the mantle: one features a high-temperature and fluid-rich mass at a depth of

10–12 km, and the other features a low-temperature mass at a depth of 30 km (Tang et al., 2005). According to previous research (Cui et al., 2022), the hot springs exhibiting fluid derived from a deep mantle source include the Jinjianggou hot spring, Yinjianggou hot spring, Budonghe River, and the two volcanoes active in the Holocene.

3 Sampling and analytical techniques

The hot spring gas samples were collected by the drainage method. At the beginning of our research, the gas-collecting hood was placed in a bubble-free area of hot spring water, and water was filled into a 100 ml syringe to discharge the air inside. Then, the funnel was moved underwater to the bubbling area, and the water in the gas path was drained by the pressure of the hot spring gas itself and the syringe. The collected hot spring gases were subsequently injected into a vacuumized aluminum foil gas sample bag and an inverted water-sealed glass bottle. The gas components were analyzed using a gas chromatograph in the Key Laboratory of Earthquake Prediction, Institute of Earthquake Forecasting, China Earthquake Administration. A total of 11 gas samples were collected from the Jinjianggou hot spring (JJG), Yinjianggou hot spring (YJG), Budonghe river (BDH) and Arxan Tianchi Lake (TC). The locations of the sampling sites are shown in Figure 1.

Soil gas observation in the volcanic field was conducted using an EDK6900-X-type portable greenhouse gas analyzer, which can measure the concentrations of CO₂ and CH₄ with a range of 0–100,000 ppm and a measurement accuracy of less than ±1%. The instrument completes an air inflow observation every 3 min. Before the measurements, a pit with a depth of approximately 50 cm and a diameter of approximately 40 cm was dug in the surface soil layer. Then, the aluminum gas collector with a diameter of 35 cm and a height of 50 cm was buried in the pit, and the soil was backfilled to seal the gas collector (Figure 2). Then, the air inlet of the instrument was connected with the air inlet and outlet of the gas collecting hood, forming a closed loop. The instrument software can display the test results in real-time. After the real-time test data stabilized, the soil gas at this site was considered to have reached equilibrium. This study observed the soil gas of Gaoshan volcano, Yanshan volcano, and the Jinjianggou and Yinjianggou hot springs. The sample collection and field observations were conducted in August 2022.

The field work of this study mainly includes soil CO₂ and CH₄ gas observations (measured with a EDK6900-X portable greenhouse gas analyzer) in Gaoshan volcano, Yanshan volcano, and the Jinjianggou and Yinjianggou hot springs in the Arxan volcanic field. CO₂ is one of the primary components of volcanic gases, and the results are easy to compare with those of other volcanoes. The field work of this study was carried out during sunny days in July and August. During the observations, the atmospheric temperature was approximately 29°C, the atmospheric pressure was approximately 88 kPa, and the soil moisture content was 5%. For the soil gas observations in the hot spring areas, we selected regions with loose soil and soil thicknesses greater than 80 cm. For the volcanic soil gas observations, the volcanic cone and the pyroclastic-covered peripheral area were selected. This field work

TABLE 1 Gas compositions of the Arxan volcanic field.

Location	T	Sampling date	N ₂	O ₂	Ar	CO ₂	N*	Ar*	CH ₄	H ₂	He	³ He/ ⁴ He	³ He/ ⁴ He*	δ ¹³ C _{CO2}	δ ¹⁵ N	²⁰ Ne/ ²² Ne	²¹ Ne/ ²² Ne	⁴ He/ ²⁰ Ne
	°C																	
Dichi ^a	19.20	08.2010	95.55	2.15	1.86	0.34	91.65	1.76			6.00	1.41	1.02			9.96	0.028	0.44
TFL TC ^a	18.60	08.2010									7.00	1.64	1.53			11.50	0.028	0.36
Tianchi ^a	21.80	08.2010									4.00	1.12	0.27	-15.9		9.77	0.025	0.34
BDH ^a	7.50	08.2010									9.00	0.92	0.44			10.06	0.027	0.62
JJG HS ^a	37.50	08.2010									8212	0.29	0.21	-18.4		9.72	0.026	385.30
JJG HS ^a	19.90	08.2010	97.19	0.56	1.73	0.41	96.17	1.70	12.00		7338	0.30	0.22	-21.0		10.05	0.023	293.45
HSM No. 34 ^a	27.40	08.2010									6469	0.23	0.16	-18.2		10.54	0.026	257.79
HSM No. 0 ^a	3.50	08.2010									1.00	0.27	0.16	-22.3		9.80	0.025	7.03
JJG HS ^b	36.60	09.2018	96.70	1.45	1.45	0.18	94.07	1.38			3191	0.24	0.17	-6.2	1.9			334
JJG HS ^b	36.60	09.2018	95.83	1.83	1.14	0.26	92.51	1.05			2840	0.20	0.14	-8.7	1.3			152
JJG HS ^b	24.80	09.2018	96.60	1.93	1.19	0.14	93.10	1.10			1457	0.25	0.18	-10.7	1.6			306
JJG HS ^b	24.80	09.2018	96.53	2.01	1.18	0.12	92.88	1.08			1585	0.22	0.16	-13.7	1.7			384
JJG HS ^b	24.80	09.2018	96.56	1.97	1.19	0.13	92.99	1.09										
JJG river	10.00	31.07.2022	74.62	22.00		0.07	34.71		0.60	53.00	19.64							
JJG-1	38.40	01.08.2022	77.58	17.80		0.37	45.29		0.52	34.76	899.86							
JJG-2	38.40	01.08.2022	75.13	19.70		0.19	39.39		0.33	11.67	800.60							
JJG-3	38.40	01.08.2022	89.36	5.25		0.29	79.84		0.64	7.85	9254.40							
JJG-4	38.40	01.08.2022	89.18	5.57		0.28	79.08		0.56	8.11	9261.70							
YJG-1	37.70	04.08.2022	84.35	2.38		0.93	80.03		0.62	7.60	18996							
YJG-2	37.70	04.08.2022	86.49	2.11		1.09	82.66		0.66	1.57	30241							
YJG-3	37.70	04.08.2022	77.91	16.3		0.39	48.34		0.67	9.80	5736.70							
YJG-4	37.70	04.08.2022	86.18	2.48		0.92	81.68		0.58	2.75	20718							

(Continued on following page)

TABLE 1 (Continued) Gas compositions of the Arxan volcanic field.

Location	T °C	Sampling date	N ₂	O ₂	Ar	CO ₂	N*	Ar*	CH ₄	H ₂	He	³ He/ ⁴ He	³ He/ ⁴ He*	δ ¹³ C _{CO2}	δ ¹⁵ N	²⁰ Ne/ ²² Ne	²¹ Ne/ ²² Ne	⁴ He/ ²⁰ Ne	
																			%
BDH	10.60	02.08.2022	75.26	21.7		0.10	35.90		0.59	10.04	18.59								
TC	29.70	02.08.2022	75.66	22.0		0.10	35.75		0.49	2.99	4.67								

*After Cui et al., 2022.

^aAfter Zhao et al., 2021.

An empty cell indicates no data.

N*: excess N₂ corrected by the N₂/O₂ ratio of ASW at 3°C, N* = N₂-1.814 O₂.

Ar*: excess Ar corrected by the O₂/Ar ratio of ASW at 3°C, Ar* = Ar-O₂/20.5.

³He/⁴He*: ASW-corrected ³He/⁴He ratio; Atm: percentage of atmospheric He in the total He of the hot spring gases (Cui et al., 2022).

was conducted based on previous studies and geological surveys. In the measurement process, we selected areas far from ponds, rivers, and regions with dense vegetation and human activities. Faults are highly developed in the study area, and the formation of hot springs is the result of the interaction between groundwater and faults. Some appropriate soil gas observation sites near the Jinjianggou and Yinjianggou hot springs were selected to determine the soil gas emission characteristics in the fault zone. Additionally, two sites on the cone and peripheral area of the two Holocene volcanoes (i.e., the Gaoshan and Yanshan volcanoes) were selected to show the level of soil gas emission in the volcanic field.

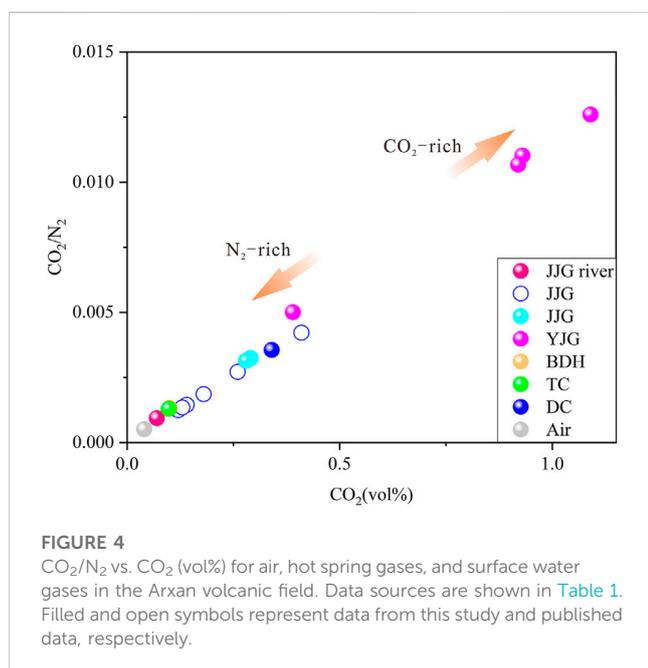
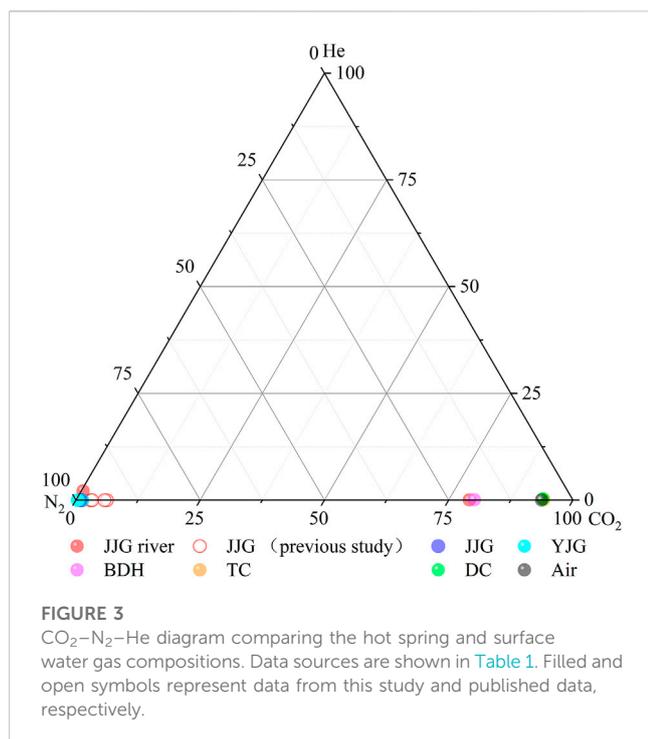
4 Results

4.1 Volcanic gas composition and content

The upward migration of magmatic gases is one of the most significant observable factors preceding volcanic eruptions. Due to the early and rapid upward gas migration, eruptions can be predicted earlier. Therefore, most volcanic monitoring studies focus on the gas geochemistry in dormant volcanic fields. In this study, we tested the gas components in Jinjianggou and Yinjianggou hot springs, Budonghe river and Tianchi volcanic field. The gas composition of the Arxan volcanic field is shown in Table 1, and previous observation data were also collected.

We analyzed the O₂/N₂ ratio (air = 0.268, Holland, 1987) of the hot spring gas components in the Arxan volcanic field. It can be found that the O₂/N₂ ratios of the samples JYG-1 and JYG-2 are close to that of the air. The Jinjianggou river, Budong river, and Arxan Tianchi lake samples are all surface water, which may be seriously contaminated by the atmosphere. The hot spring gases (Jinjianggou and Yinjianggou hot springs and Budonghe river) in the Arxan volcanic field are mainly composed of N₂ (Figures 3, 4), accounting for 86.2%–97.2%. For volcanic gases, the CO₂ content is low (0.07%–1.09%), while the He (800 × 10⁻⁶–30241 × 10⁻⁶) and Ar (1.14%–1.86%) contents are relatively high (Table 1). The ratios of He–CO₂–N₂ (Figure 3) in the triangular diagram show that the hot spring and surface water gases feature different components and that the hot spring gases are mainly enriched in N₂. Specifically, the CO₂/N₂ ratio of the Jinjianggou hot spring gases is 0.001–0.004, while that of the Yinjianggou hot spring gases is 0.005–0.01. The Yinjianggou hot spring gases are more enriched in CO₂ than the Jinjianggou hot spring gases. In addition, the hot spring gases in the volcanic field are generally enriched in N₂, similar to the surface water in the Jinjianggou River, Arxan Tianchi and Dichi (DC) (Figure 5). The N₂/Ar ratio (67–84) of the volcanic gases is close to that of the air (83.6, Hilton, 1996), but the O₂ content (1.45%–5.57%) is low, and the ⁴He/²⁰Ne ratio (152–384) is much higher than that of the air (0.32, Magro et al., 2013). The surface water in the Arxan volcanic field is characterized by high N₂ contents (95.55%), low CO₂ contents (0.34%) and low He contents (6%–9%), which is different from the hot spring samples.

Previous investigations into the isotopic compositions of hot spring gases in the Arxan volcanic field have demonstrated that the ³He/⁴He ratio of the Arxan volcanic gas is low, ranging from 0.20 to 0.92 R_A (Table 1). This value is higher than that of the crustal source (0.02 R_A, Ballentine et al., 2002) but significantly lower than that of



gas from the upper mantle or lithospheric mantle. This pattern suggests that the crustal source is the major contributor (Zhao et al., 2021). The ⁴He/²⁰Ne ratio of surface water in the Arxan volcanic field is close to the atmospheric value (0.32, Ozima and Podosek, 2002), while the ⁴He/²⁰Ne ratio of hot spring water is much higher than the atmospheric value. The δ¹³C ranges from -22.3‰ to -6.2‰, indicating that the CO₂ in the hot springs may come from the mantle or be associated with biogenic and metamorphic gases in the crust (Cui et al., 2022). The excess N₂, Ar, He, and CO₂

in hot springs in the study area are mainly from the crust and upper mantle, and approximately 12%–63% of the He in the hot spring gas comes from the mantle (Cui et al., 2022). The CO₂ content of the Arxan volcanic field is lower than that of the Changbaishan, Wudalianchi, and Tengchong volcanoes in China, where the CO₂ contents are higher than 90%. The CH₄ concentration of the Arxan volcano (1,900–4,300 ppm) but lower than that of the Tengchong volcano (300–16,900 ppm); the H₂ concentration is close to that of the Changbaishan volcano (1.1–29.2 ppm). However, the He concentrations in the gas from the Jinjianggou and Yinjianggou hot springs are prominently higher than those of the Changbaishan (7.6–53 ppm), Wudalianchi (10–330 ppm) (Gao and Li, 1999), and Tengchong (10–380 ppm) volcanoes (Wei et al., 2016).

4.2 Gas flux measurement

The curve of soil gas concentration measured in the field is shown in Figure 5. The accumulation chamber methodology (Figure 2) was employed in the gas flux observation to measure the diffusive emission of CO₂ in the soil (Chiodini et al., 1998; Mazot et al., 2009; Mazot et al., 2011; Pérez et al., 2011). According to the methods described in Mazot et al. (2009) and Mazot et al. (2015), the soil temperature, atmospheric pressure and water temperature were measured during the field work. Moreover, we calibrated the instrument based on the atmospheric concentration before measurement. The gas diffusing through the soil accumulates and circulates in the closed-circuit system, migrating from the soil to the observation instrument and then returning to the collecting hood through the connecting tube. The soil CO₂ flux was calculated using the following formula (Sun et al., 2018):

$$F_{(CO_2)} = \rho \cdot H \cdot (T_0/T_s) \cdot \left(\frac{P_s}{P_0}\right) \cdot \left(\frac{d_c}{d_t}\right), \quad (1)$$

where T_0 and P_0 are the temperature and atmospheric pressure under standard temperature and pressure, respectively. T_s and P_s denote the soil temperature (°C) and atmospheric pressure (kPa) of each measurement site, respectively. dc/dt represents the concentration change rate for each measurement site.

The single-site soil microseepage CO₂ fluxes in the Arxan volcanic field range from 4.66 to 107.18 g m⁻² d⁻¹, as shown in Table 2. Previous studies have shown that soil microseepage CO₂ flux data in the range of 0.2–10,000 g m⁻² d⁻¹ are credible when adopting the closed-chamber method (Chiodini et al., 1998; Guo et al., 2014). Thus, the observed data in this study conform to the CO₂ emission level of soil microseepage in most quiescent volcanoes. The CO₂ fluxes in the Jinjianggou and Yinjianggou hot springs are high, whereas the soil CO₂ fluxes in the two Holocene active volcanic non-volcanic fields are 4–13 times lower than those of the hot springs. Figure 1 shows that the faults of the entire Arxan volcanic field are highly developed, and the hot springs and active volcanic non-volcanic fields are all dissected or partially dissected by faults, providing channel for the release of deeply sourced gases.

Vegetation may have an effect on soil CO₂ emissions, and the soil gas measurement sites of Gaoshan and Yanshan volcanoes had more vegetation cover, such as weeds and shrubs. We reviewed some

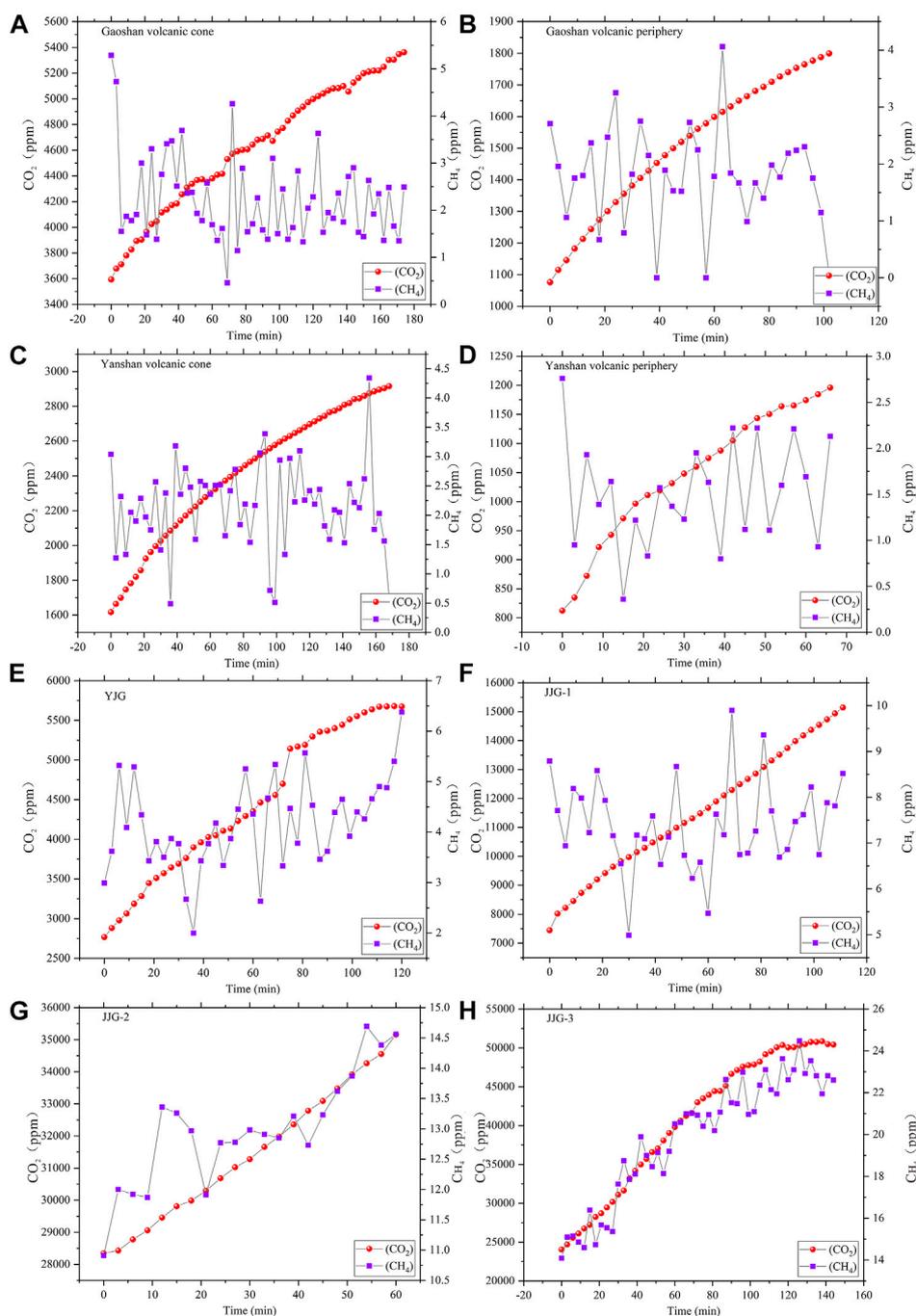


FIGURE 5

The measured curve of soil gas concentration in the volcanic field [(A) Gaoshan volcanic cone, (B) Gaoshan volcanic periphery, (C) Yanshan volcanic cone, (D) Yanshan volcanic periphery, (E) Yinjianggou hot spring, (F) Jinjianggou hot spring-1, (G) Jinjianggou hot spring-2, (H) Jinjianggou hot spring-3].

relevant studies on CO_2 fluxes emitted from non-volcanic soil vegetation. Norman et al. (1992) measured CO_2 fluxes from a large number of vegetated soils in Wisconsin and obtained an average CO_2 flux of $0.6 \text{ g m}^{-2} \text{ d}^{-1}$ (Norman et al., 1992). Mäki et al. (2019) conducted a soil CO_2 flux study in a coniferous forest at Hyytiälä (Juupajoki, Finland) and observed fluxes of $0.72\text{--}5.04 \mu\text{g m}^{-2} \text{ d}^{-1}$ (Mäki et al., 2019). Other scholars have

performed a study on CO_2 fluxes from natural vegetation in the Xilin River basin in the grasslands of Inner Mongolia, China, which has a similar geological background and climatic environment to the study area. Thus, our data can be compared to the CO_2 emissions from natural vegetation in non-volcanic fields. That study found that the natural vegetation in the grasslands of the Xilin River basin in Inner Mongolia is associated with a CO_2 flux of $2.4\text{--}12 \text{ g m}^{-2} \text{ d}^{-1}$

TABLE 2 Results of soil CO₂ flux in the Arxan volcanic field.

Measurement site	Atmospheric pressure/kPa	Temperature/°C	CO ₂ flux/g m ⁻² d ⁻¹	Area/m ²	CO ₂ output/t·a ⁻¹
Gaoshan volcanic cone	85.80	29.3	8.73	4.195 × 10 ⁶	13367.16
Gaoshan volcanic periphery	85.83	31.9	4.66		
Yanshan volcanic cone	85.98	31.6	6.30	3.892 × 10 ⁶	8949.65
Yanshan volcanic periphery	86.01	34.3	5.32		
YJG	89.06	23.4	31.82	233445	2706.13
JJG-1	88.13	26.0	42.32	981537	38338.30
JJG-2	88.13	26.0	45.11		
JJG-3	88.36	29.4	107.18		

TABLE 3 Comparison of CO₂ emission fluxes between the Arxan volcano and similar volcanoes.

Volcano	Region	Type	CO ₂ soil flux/ ×10 ⁵ t·a ⁻¹	Area/ km ⁻²	CO ₂ soil flux/Area (×10 ⁵ t km ⁻² a ⁻¹)	Measurement time	References
Arxan	China	Intraplate	0.63	9.3	0.068	2022	
Changbaishan	China	Intraplate	9.4	110	0.085	2010, 2011, 2016	Zhang et al. (2011), Guo et al. (2014), Sun et al. (2018), Zhao et al. (2021)
Wudalianchi	China	Intraplate	12	215	0.056	2010, 2011, 2017	Guo et al. (2014), Zhao et al. (2021)
Tengchong	China	subduction-related	70	790	0.089	2012, 2013	Cheng et al. (2014)
St. Helens	United States	subduction-related	115	90	1.27	1980	Harris et al. (1996)
Yellowstone	United States	mantle plume-related	1.5	1	1.5	2006	Werner et al. (2008)
White Island	New Zealand	subduction-related	0.032	0.2	0.16	1998	Wardell et al. (2001)
Iwojima	Japan	Island arc	1.64	22	0.07	2000	Notsu et al. (2005)

(Ma, 2006). We can see that the CO₂ fluxes of natural vegetation in non-volcanic fields are all relatively low, and the CO₂ fluxes near the Jinjianggou and Yinjianggou hot springs are markedly higher than those released by vegetation in the above non-volcanic fields. However, the CO₂ fluxes in the Arxan and Yanshan volcanic fields are close to the levels released by natural vegetation in the grasslands of the Xilin River basin in Inner Mongolia. For the above reasons, it is likely that the surface faults of Gaoshan and Yanshan volcanoes are not well developed, and deep gases do not easily pass through the volcanic cones to reach the surface directly.

5 Discussion

We identified some unique characteristics of the hot spring gases in our study area during the sampling and observation process. The hot spring gas in the Arxan volcanic field is characterized by abnormally high He concentrations. The faults in the study area are highly developed, especially the NNE and NE oriented ones. Tang et al.

(2005) observed two deep faults that acted as channels for the upward migration of magma from the mantle. One fault shows high temperatures and fluid enrichment at a depth of 10–12 km, and the other shows low temperatures at a depth of 30 km. The He content in the study area is significantly higher than that in other dormant volcanoes in China. According to previous studies on the petrological and geochemical characteristics of the volcanic rocks in the Yinjianggou of the Arxan volcanic field, the most remarkable feature is the anomalously strong enrichment of U in the regional volcanic rocks (the U content reaches 4.27–7.82 ug/g), which may be associated with the evolution of crust-derived magma (Wu et al., 2010). Thus, we speculate that the high He content is likely caused by the decay of U and Th in the Mesozoic granodiorite and acidic volcanic rocks.

Furthermore, the soil CO₂ concentrations near the Jinjianggou and Yinjianggou hot springs are much higher than those in the Holocene volcanic field. The results of previous magnetotelluric and seismic surveys (Han et al., 2018; Li et al., 2023) have shown that NE and NNE trending faults are located in the vicinity of the two hot springs and may act as underlying magma channels. Therefore, the soil CO₂

and the gases present in the two springs are remarkably higher in concentration than those in other regions. In contrast, the soil CO₂ and CH₄ concentrations in the Holocene Gaoshan and Yanshan volcanoes are lower than those in the Jinjianggou and Yinjianggou hot springs. These lower concentrations of volcanic gases at the surface may be due to the seal formed by lava flows generated by the eruption 2,000 years ago. The geological surveys of the volcanic cone and adjacent areas have not observed any obvious fault exposure.

Compared with the monitoring of erupting volcanoes, it is equally important to investigate the characteristics of gas release from dormant ones. The volcanic degassing trend is related to the type of volcanic gases. Previous studies have proposed that in response to the rise of magma, volcanic gases preferentially exsolve in the order of CO₂, S, H₂, HCl and HF (Werner et al., 2013). The analysis of the Arxan volcanic hot springs shows that the gas composition of the volcanic non-volcanic field is characterized by high N₂, He, and Ar contents and low CO₂ contents. In the hot spring gases, the δ¹⁵N value ranges from 1.3‰–1.9‰, and the N₂/He ratio ranges from 303 to 663. The results suggest the existence of a high proportion of N₂-rich organic matter (Zhao et al., 2021). Additionally, both the ³He/⁴He and CO₂/³He ratios of the hot spring gas samples in the study area are low and differ from the patterns of the mantle endmember (high ³He/⁴He, low CO₂/³He) and subduction recycling endmember (low ³He/⁴He, high CO₂/³He). Furthermore, these values are far lower than the values of the volcanic and geothermal gases in volcanic arcs and mid-ocean ridges (Sano and Marty, 1995). The He concentrations in hot spring gases in the Arxan volcanic field (1,457 × 10⁻⁶ ~ 30,241 × 10⁻⁶) are much higher than the atmospheric value (5.24 × 10⁻⁶), indicating a deep origin, i.e., a crustal and/or mantle source.

Several active volcanoes with the same tectonic background are compared to the Arxan volcanic field. Arxan, Changbaishan and Wudalianchi are all intraplate volcanoes, whereas Tengchong, Mount St. Helens and White Island are all subduction-related volcanoes. Additionally, Arxan, Changbaishan, Mount St. Helens, and Yellowstone are all currently dormant, while the White Island volcano has been in a slightly active state (2019 eruption, VEI = 2). Due to the large difference in the area of each volcanic field, it is not reasonable to directly compare the annual total flux of volcanic CO₂. Therefore, the annual CO₂ flux of each volcanic field was divided by the corresponding area in this study. According to Table 3, it can be seen that the soil CO₂ flux of the Arxan volcano is approximately 20 times lower than that of the Mount St. Helens and Yellowstone volcanoes and approximately 2 times lower than that of the White Island volcano in New Zealand during the eruption stage. Iwo Jima volcano has erupted intermittently since 1922, with the most recent eruption occurring in July–August 2022. The historical eruption VEI maximum of one also indicates that soil CO₂ fluxes from Alsan volcano are comparable to soil CO₂ emission levels from Iwo Jima volcano, which is active and has erupted frequently in recent years (e.g., 2001, 2020, 2021 and 2022).

6 Conclusion

Based on the observation of soil gases and the composition of the gases escaping from hot springs, we analyzed the degassing characteristics of the Arxan volcanic field. The major conclusions include the following:

- (1) In the studied hot springs in the Arxan volcanic field, the concentrations of CO₂, CH₄, H₂, He, and Ar are 0.07%–1.09%, 0.33–12 ppm, 1.57–53 ppm, 800–30,241 ppm, and 1.14%–1.86%, respectively. The notably high He content is likely due to U–Th decay in the Mesozoic granodiorite and acidic volcanic rocks in the study area.
- (2) The soil gas concentrations near the Jinjianggou and Yinjianggou hot springs are higher than those near two Holocene volcanoes. The peak CO₂ concentration in the soil near the Jinjianggou hot spring can reach 35,161 ppm. The single-site soil microseepage CO₂ flux in the Arxan volcanic field is 4.66–107.18 gm⁻² d⁻¹, and the estimated annual CO₂ emission flux from the volcanic non-volcanic field to the atmosphere is 0.63 × 10⁵ t, which also demonstrates that soil CO₂ flux of Arxan volcano is comparable to the soil CO₂ emission level of the Iwojima volcano.

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 author.

Author contributions

XP, GG, DH, BB, and SG conducted the field survey. XP and YS processed the data and prepared the first draft. All authors contributed to the article and approved the submitted version.

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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.

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