

Geochemical characteristics and environmental implications of loess sequences in the Loess Plateau^①

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Abstract

The major, trace, and rare earth elements of the Duanjiapo (DJP) section in the south of the Loess Plateau, the Jiaxian (JX) section in the north, and the Jiuzhoutai (JZT) section in the west are studied. The results show that the main elemental characteristics of loess in three profiles are consistent with the upper continental crust (UCC). In terms of trace elements, Th, Nb, Zr, Hf, Y, Cs, W, Cr, V, Li, and Pb show relative enrichment compared with UCC; Rb, Ba, Sr and Be exhibit relative depletion. The average of ΣREE is 171.91 ppm with a negative anomaly for δEu and essentially no anomaly for δCe . The results of $\text{K}_2\text{O}/\text{Na}_2\text{O}$, Rb/Sr ratios, as well as the leaching coefficient from three profiles, indicate $\text{DJP} > \text{JX} > \text{JZT}$, suggesting that DJP experiences the strongest weathering leaching effect. The chemical index of alteration (CIA) reveals that all three profiles of loess are in the primary stage of Ca and Na depletion. DJP is generally in the early to moderate stage of chemical weathering, while JX and JZT are both in the early stage.

Key words: loess, chemical weathering, element geochemistry, chemical index of alteration (CIA)

0 Introduction

The supergene environment is a very active system in the earth system, in which the dust series is an important part of the supergene environment. Dust materials not only produce sandstorms and bring negative effects to the environment but also bring positive effects-providing rich nutrients for the ocean, the most important of which is iron. As a dust material, the chemical elements of loess are leaching or enriched in the epigenetic environment, which is closely related to weathering, which is strictly affected by the climate environment. Therefore, the change of loess element content can well record the evolution of the environment^[1-3]. In recent years, in addition to the Loess Plateau^[4], researchers have also conducted a large number of geochemical studies on the loess in the northeast of the Qinghai-Tibet Plateau^[5], the Chengdu Plain^[6], the Xi-

ashu loess in the middle and lower reaches of the Yangtze River^[7] and other areas, and have gained a further understanding of the material composition, chemical weathering degree, provenance, climate and environmental characteristics of the loess^[4,8-12]. There are many studies on the geochemical characteristics of the loess on the Loess Plateau. The geochemical characteristics of the elements, whether they are the major elements or the rare earth element partition mode, reveal that the loess material is more homogeneous, the material source is more stable and can well represent the average composition of upper continental crust (UCC). However, the loess distribution range is relatively large, and the climate conditions vary significantly from north to south and from east to west. Under such conditions, the weathering intensity of loess varies significantly, and the leaching intensity, enrichment degree, and the corresponding relationship with the climate environment are still very meaningful questions.

① Supported by the National Natural Science Foundation of China (No.41561001, 42271007).

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Received on Jan. 9, 2024

Duanjiapo (DJP) in Lantian, Jiaxian (JX), and Jiuzhoutai (JZT) in Lanzhou of China are located in the south, north, and west of the Loess Plateau, respectively. The climate conditions are significantly different. In this semi-arid and semi-humid region, the geochemical characteristics of loess elements are very sensitive to climate change. Based on the element composition of the Duanjiapo, Jiaxian, and Jiuzhoutai profiles, this paper discusses the leaching and enrichment of elements in the three profiles and reveals their corresponding climate and environment characteristics through the geochemical characteristics of the major, trace, and rare earth elements and elemental ratios.

1 Materials and methods

1.1 Overview of the study area

The Loess Plateau is situated within the influence zone of the East Asian monsoon. Winters are cold and dry, while summers are hot and humid. There are distinct seasonal gradients in wind direction, precipitation, and temperature. The range of mean annual precipitation (MAP) and mean annual temperature (MAT) is 300 mm to 730 mm and 8 °C to 14 °C, respectively. The sampling profiles are located at Duanjiapo (DJP, 34°45'N, 109°35'E), Jiaxian (JX, 38°23'N, 110°45'E), and Jiuzhoutai (JZT, 36°03'N, 103°40'E) (Fig. 1). DJP profile is situated approximately 25 km southeast of Xi'an in Lantian County, where the local climate is warm and humid, with an annual precipitation of up to 730 mm and an average annual temperature of 13.5 °C. The Jiaxian profile is located in the transitional zone between the northern Loess Plateau and the southern edge of the MuUs Desert, with an annual average precipitation of 380 mm and an average temperature of 10.9 °C. The Jiuzhoutai profile is situated on the highest terrace gravel layer on the northern bank of the Yellow River in Lanzhou City, with an average annual precipitation of 327 mm and an average temperature of 8.3 °C.

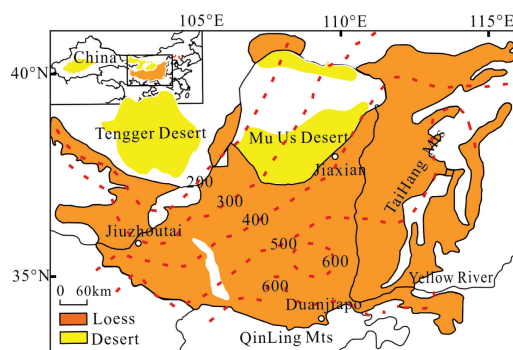


Fig. 1 Sampling location in the Loess Plateau

1.2 Sampling and analysis methods

The depths of the Duanjiapo, Jiaxian, and Jiuzhoutai profiles were 3.6 m, 1.6 m, and 1.5 m, as shown in Table 1. After sampling, the samples were sealed in plastic zip-lock bags and brought back to the laboratory. Pre-processing involved removing any mixed litter and roots from the samples to ensure their purity. Subsequently, the samples were air-dried under constant temperature conditions at 25 °C, ground using an agate mortar and pestle, and sieved through a 200-mesh sieve for analysis. Analysis of major and minor element was conducted by Nanjing Shunke Testing Technology Co., Ltd. The major elements were tested by inductively coupled plasma emission spectrometer (Agilent 5110) with RSD < 3%. The minor elements, including rare earth elements, were tested by inductively coupled plasma mass spectrometer (Agilent 7700x) with RSD < 5%.

2 Results and discussion

2.1 Major elements characteristics

Previous researchers have gained a relatively thorough and clear understanding of the geochemical characteristics of major elements in the loess of the Loess Plateau. The main chemical composition of loess is primarily composed of SiO_2 and Al_2O_3 , with their contents often exceeding 60% of the total. Following them are Fe_2O_3 and CaO , while the contents of K_2O and Na_2O are relatively stable, with little fluctuation. The chemical composition characteristics are fully reflected in the three studied profiles of DJP, JX, and JZT. Specifically, the total contents of seven elements, SiO_2 , CaO , Fe_2O_3 , Al_2O_3 , MgO , K_2O , and Na_2O , account for 90.93%, 92.00%, and 88.78% in the DJP, JX, and JZT profiles, respectively. From the data in Table 2, it can be observed that although the content variations of Si and Al are not significant, they still exhibit certain regularities. For example, the SiO_2 content in the JZT profile is significantly lower than that in DJP and JX, which may be related to the lower SiO_2 content in the geological background of JZT itself. The highest Al_2O_3 content is found in the DJP profile, which is related to its location in the southern Loess Plateau with strong weathering. Previous studies indicate that Al is more prone to enrichment in fine-grained materials. The variation in CaO content is relatively large. The overall content in the DJP profile is low, with an average of 3.88%, but some samples show extremely high CaO content, which may be related to the presence of calcium

Table 1 Sampling location, lithology, and sample information

Profile	Soil stratigraphic unit	Sample size	Sampling interval/cm	Sampling depth/cm	Stratigraphic description
DJP	S0LL0	3	40	0 – 120	Holocene paleosol loess interlayer
	S0SS0	2	40	120 – 200	Holocene black oolitic soil; calcium-infiltrated layer, with well-developed vertical fractures
	L1LL1	2	40	200 – 280	Late Pleistocene Malan loess sublayer; the upper part is covered with a layer of calcium plate about 10 cm thick; the lower part has a large number of wormholes and root holes
	L1SS1	2	40	280 – 360	Weak paleosol sublayer of late Pleistocene Malan loess; existence of calcium dipping layer
JX	L1	8	20	0 – 160	Late Pleistocene loess; calcium nodules, calcium plates, and white calcareous mycelium are distributed
JZT	L1	3	50	0 – 150	Late Pleistocene loess; soil is relatively loose, cementation is weak, and soil properties change little in the vertical direction

Table 2 Major element composition (%) in loess-paleosols from the Loess Plateau

Profile	Strata	SiO ₂	CaO	Fe ₂ O ₃	Al ₂ O ₃	MgO	K ₂ O	Na ₂ O	CIA	LOI	
DJP	S0LL0	59.43	5.47	5.29	13.76	1.97	2.42	1.47	64.63	7.76	
		58.67	6.00	5.26	13.88	1.99	2.31	1.45	65.40	6.80	
		53.31	10.87	4.67	12.39	1.83	2.08	1.40	64.14	9.12	
	S0SS0	63.19	1.80	6.03	15.39	1.77	2.49	1.12	70.50	6.61	
		66.20	1.21	5.46	14.45	2.02	2.68	1.67	63.02	5.93	
		59.14	6.18	5.13	13.46	2.01	2.51	1.40	64.54	5.42	
	L1LL1	61.44	1.31	6.65	16.29	2.04	2.57	0.88	64.01	4.55	
		64.23	1.01	5.99	15.24	2.03	2.74	1.30	67.58	6.90	
		65.57	1.09	5.77	14.78	2.02	2.68	1.47	65.42	8.69	
	Average	61.24	3.88	5.58	14.40	1.96	2.50	1.35	65.47	6.86	
	L1SS1	62.49	7.24	3.81	11.28	2.02	2.17	1.99	55.64	9.19	
	JX	L1	63.70	6.30	3.92	11.49	1.99	2.22	2.08	55.14	12.23
59.88			8.89	3.89	11.14	2.11	2.08	1.87	56.74	7.01	
63.80			4.25	4.78	12.91	2.21	2.37	1.74	60.65	4.89	
L1		64.74	3.01	5.04	13.42	2.17	2.48	1.71	61.52	9.03	
		65.85	2.51	5.02	13.44	2.08	2.55	1.73	61.15	7.36	
		66.99	1.43	4.98	13.73	2.12	2.64	1.82	60.57	5.73	
Average		63.16	5.09	4.61	12.83	1.99	2.45	1.76	60.07	5.32	
		63.83	4.84	4.50	12.53	2.09	2.37	1.83	58.94	7.50	
		55.88	8.97	4.41	11.62	2.49	2.25	1.65	59.39	11.67	
JZT		L1	58.59	8.73	4.12	11.22	2.68	2.24	1.93	55.85	9.34
Average		58.83	8.43	4.13	11.22	2.68	2.25	2.02	55.00	9.08	
		57.77	8.71	4.22	11.35	2.62	2.25	1.87	56.75	10.03	
	Max	66.99	10.87	6.65	16.29	2.68	2.74	2.08	73.99	12.23	
	Min	53.31	1.01	3.81	11.14	1.77	2.08	0.88	55.00	4.55	
	Average	61.75	4.99	4.95	13.20	2.11	2.41	1.62	62.18	7.63	
	CV	5.79	62.30	15.45	11.47	11.17	8.19	18.66	8.09	27.29	
	UCC	66.00	4.20	5.00	15.20	2.20	3.40	3.90	47.92		

nodules in the samples. The CaO content in the JZT profile is the highest, reaching 8.71%, which may be due to its proximity to the source of loess, weaker weathering, and higher native carbonate content. The characteristics of Fe are consistent with those of Al because Fe and Al are both stable elements that are easily retained during weathering. The Fe_2O_3 content in the DJP profile is the highest, reaching 5.58%, while the contents in the JX and JZT profiles are relatively lower at 4.50% and 4.22%, respectively, reflecting the higher degree of weathering in the DJP profile. The variation in MgO content is relatively small, but the content in the DJP profile is still lower than that in the JX and JZT profiles, indicating that Mg exhibits certain reactivity, consistent with previous research results. As for K_2O and Na_2O , their content variations are also small, and the overall content is relatively low.

Compared with the average chemical composition of the UCC (Fig. 2), Si and Al contents in the three

profiles are relatively close to the UCC but slightly lower. This is likely related to the higher loss on ignition (LOI) of the three profiles, ranging from 7% to 9%, which results in lower elemental contents. The CaO content in all profiles is higher than that of the UCC, indicating the loess's enrichment in carbonates, especially in the JZT profile, reaching 8.71%. DJP is slightly lower than the UCC, reflecting the strong weathering and leaching in DJP. The Fe_2O_3 content in DJP is higher than the UCC, indicating relative enrichment of iron, while JX and JZT are both lower than the UCC, indicating weaker weathering in JX and JZT. Finally, the K_2O and Na_2O contents are lower than the UCC, although they may be related to the higher LOI of the three profiles, resulting in lower content of other elements. However, it still indicates that the three profiles undergo certain weathering processes, with potassium and sodium being leached to a certain extent. The lower Na_2O content in the DJP profile compared with the other two profiles also indicates this.

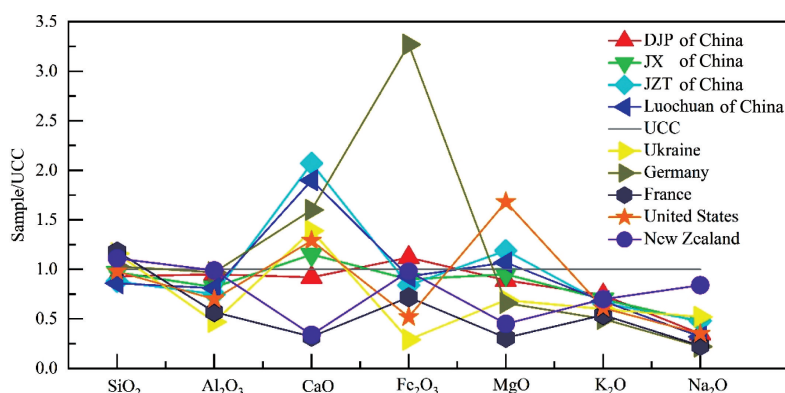


Fig. 2 UCC standardized distribution of major elements in loess in the study area compared to loess in other regions of the world

Comparing the three profiles with loess from different regions worldwide (Table 3), the overall chemical composition of the loess from the three profiles is similar to that of the Luochuan Loess, in Shaanxi, especially with the loess from JZT, reflecting the homogeneity of loess on the Loess Plateau. However, compared with loess from other regions worldwide, the differences are still very noticeable. There are significant differences in major elements such as Si, Al, Fe, Ca, and Mg, reflecting the differences in source materials of loess from different regions^[14]. For example, the loess on the Loess Plateau is rich in Ca, which is related to the higher carbonate content in the desert source areas of loess. In contrast, loess from New Zealand and Germany is calcium-poor. Another example is Mg, loess from the United States has a higher Mg content, while loess from New Zealand and Germany has a

lower Mg content, with loess from China falling in between and closer with the UCC. Ukrainian loess, on the other hand, differs from loess in other regions; it is relatively rich in Ca but lacks Al, Fe, and Mg. Compared with the UCC, all loess samples have relatively low K_2O and Na_2O contents, reflecting that loess from different regions worldwide has undergone weathering to a certain extent, and these two elements have been leached.

2.2 Trace element characteristics

Among the measured trace elements (Table 4), the average contents in the three profiles are as follows: Ba (490.24 $\mu\text{g/g}$) > Zr (257.13 $\mu\text{g/g}$) > Sr (188.75 $\mu\text{g/g}$) > Rb (99.67 $\mu\text{g/g}$) > V (86.41 $\mu\text{g/g}$) > Li (44.75 $\mu\text{g/g}$) > Y (27.90 $\mu\text{g/g}$) > Ga (16.79 $\mu\text{g/g}$) > Pb (21.90 $\mu\text{g/g}$) > Nb

(13.85 $\mu\text{g/g}$) > Th (12.95 $\mu\text{g/g}$) > Cs (8.01 $\mu\text{g/g}$) > Hf (6.57 $\mu\text{g/g}$) > U (2.68 $\mu\text{g/g}$) > Be (2.00 $\mu\text{g/g}$) > Ta (1.04 $\mu\text{g/g}$). The variation coefficients of all trace elements are below 15%, except for Sr and Cs, which exceed 20%, indicating relatively large fluctuations. Overall, the distribution of trace elements in the three profiles is relatively stable, showing a high level of consistency.

Table 3 Comparison of the chemical content of the loess in the study area with the world's major loess areas(%)

Region	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O
DJP of China	61.24	14.40	3.88	5.58	1.96	2.50	1.35
JX of China	63.83	12.53	4.84	4.51	2.09	2.37	1.84
JZT of China	57.77	11.35	8.71	4.22	2.62	2.25	1.87
Luochuan of China	56.94	12.38	7.96	4.64	2.36	2.31	1.26
Ukraine	76.24	7.11	5.82	1.47	1.52	2.03	2.03
Germany	67.79	14.67	6.73	16.37	1.46	1.70	0.87
France	77.96	8.73	1.35	3.59	0.68	1.82	0.91
USA	64.61	10.64	5.41	2.61	3.69	2.06	1.37
New Zealand	73.14	15.02	1.43	4.88	0.99	2.37	3.29

Note: Except for the study area, data in the table are from Refs [15,16].

Compared with the UCC (Fig. 3), all trace elements exhibit slight variations, including Th, Nb, Hf,

Ta, Ga, Pb, and Sc. As indicated by their coefficients of variation (CV), fluctuations are relatively small, demonstrating the stability of trace elements in loess, with little deviation from the UCC. Zr is approximately 1.5 times higher than the UCC, indicating relative enrichment of loess. Zr is a high-field-strength element, highly stable, mainly existing in the form of zircon. Therefore, the three profiles of loess are enriched in zircon. Interestingly, the highest content of Zr in the JX profile suggests its proximity to the source area, where the proportion of zircon is higher. Conversely, DJP is farthest from the source area, hence its lowest Zr content. Additionally, Cs and Li contents are much higher compared with the UCC. As both are alkali metals, theoretically, they are prone to be released from minerals. The highest Cs content in DJP may be due to its strong weathering and high clay content, enhancing adsorption by clay minerals. Li is generally less enriched by clay minerals, so its high content may be related to the high content of source materials. V is enriched relative to the UCC, possibly due to the high content of source materials. Sr shows obvious depletion in all three profiles, consistent with results from other loess studies^[8]. Sr is reactive and tends to accumulate in minerals containing Ca. As Ca is leached, Sr also shows leaching. The lower Sr content in the DJP profile compared to JX and JZT may be due to this reason.

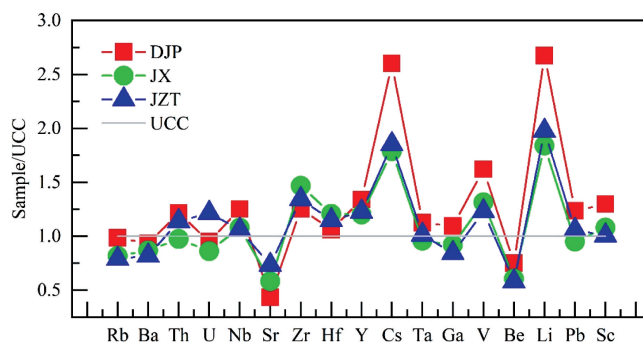


Fig. 3 UCC standardized distribution of trace elements in the study area

2.3 Rare earth element characteristics

Rare earth elements (REEs) are a group of elements with incomplete to filled 4f electron shells. Since the number of outer electrons is 3, most REEs exist in the +3 valence. Due to their similar properties, they often occur together closely in geological processes. In supergene environments, REEs are highly stable and are less affected by weathering, erosion, transportation, sedimentation, diagenesis, and metamorphism. Therefore, they can be used to reflect changes in material sources, geochemical differentiation, and deposi-

tional environments. Previous studies have systematically investigated the REEs in loess and red clay^[9-10,14]. Overall, the REEs content in loess varies within a narrow range, showing homogeneity in distribution. The distribution pattern is similar to that of sedimentary rocks and approaches the crustal average. The distribution pattern of loess is consistent with that of deserts in the northwest, reflecting the consistency of their possible sources. In summary, the geochemical characteristics of REEs in loess reflect the homogeneity of loess materials, and they can represent the average composition of the UCC^[12,14].

In Table 5, the total rare earth element (ΣREE) content of samples from the DJP, JX, and JZT profiles ranges from 150 $\mu\text{g/g}$ to 200 $\mu\text{g/g}$, consistent with other loess regions. However, the ΣREE of the DJP profile is significantly higher than that of JX and JZT. This reflects the higher weathering intensity and higher

content of fine clay minerals in loess in the southern plateau, where clay minerals exhibit stronger adsorption of REEs. In fact, within the same profile, the ΣREE of paleosol layers is higher than that of loess layers. In the DJP profile, the ΣREE of L1SS1 is 196.1 $\mu\text{g/g}$, while L1LL1 is 186.6 $\mu\text{g/g}$.

Table 4 Trace element content ($\mu\text{g/g}$) in three loess profiles on the Loess Plateau

Profile	Strata	Rb	Ba	Th	U	Nb	Sr	Zr	Hf	Cs	Ta	Ga	Pb
DJP	S0LL0	106.00	505.00	13.30	2.59	14.40	155.00	243.00	6.15	8.98	1.09	17.90	25.10
		107.00	511.00	13.10	2.47	14.60	156.00	223.00	5.71	9.24	1.10	18.10	23.20
		91.30	448.00	12.00	2.44	13.40	157.00	202.00	5.25	8.03	0.99	16.10	20.90
		117.00	522.00	15.80	2.94	16.00	136.00	260.00	6.67	11.00	1.19	19.70	26.50
	S0SS0	113.00	533.00	14.20	2.52	15.20	180.00	238.00	6.15	9.11	1.14	18.50	24.10
		110.00	507.00	13.40	2.56	14.60	193.00	230.00	5.96	8.95	1.06	17.70	23.30
		121.00	519.00	15.70	2.85	15.10	121.00	244.00	6.37	11.80	1.15	21.00	27.90
		117.00	552.00	15.50	2.83	16.00	132.00	253.00	6.51	10.20	1.19	19.50	26.20
	L1LL1	112.00	538.00	14.70	2.77	15.90	137.00	251.00	6.65	9.43	1.21	19.00	25.20
		81.90	448.00	9.82	2.39	12.20	227.00	300.00	7.49	5.41	0.95	13.80	18.20
		83.90	446.00	10.60	2.37	12.30	226.00	308.00	7.67	5.63	0.89	14.30	17.00
		82.40	424.00	11.40	2.71	12.60	240.00	303.00	7.65	5.66	0.93	14.20	17.00
JX	L1	92.20	487.00	12.10	2.54	13.40	205.00	276.00	7.03	6.99	0.97	16.00	19.50
		100.00	511.00	12.40	2.44	13.80	195.00	284.00	7.15	7.87	1.00	17.10	20.30
		99.70	501.00	12.40	2.32	13.80	177.00	258.00	6.42	7.46	1.01	16.90	20.50
		101.00	515.00	11.30	2.31	13.50	176.00	270.00	6.67	7.30	0.99	17.00	20.30
	L1	92.40	487.00	11.20	2.23	12.10	189.00	233.00	5.95	6.60	0.89	15.90	19.10
		93.10	456.00	12.10	2.98	13.40	235.00	212.00	5.51	8.28	1.10	15.00	22.50
		87.40	451.00	11.50	3.08	12.20	289.00	278.00	7.20	6.26	0.95	13.80	20.60
		85.20	446.00	16.40	4.16	12.60	247.00	276.00	7.28	6.02	0.98	14.10	20.40
JZT	Max	121.40	551.70	16.36	4.16	16.00	289.00	308.20	7.67	11.75	1.21	21.02	27.90
	Min	81.89	424.00	9.82	2.23	12.13	121.00	201.70	5.25	5.41	0.89	13.82	17.01
	Average	99.67	490.20	12.95	2.68	13.85	188.70	257.10	6.57	8.01	1.04	16.79	21.90
	CV	12.37	7.41	14.19	15.54	9.29	23.19	11.31	10.47	22.17	9.39	12.51	14.13
	UCC	112.00	550.00	117.00	28.00	12.00	350.00	190.00	5.80	3.70	1.00	17.00	20.00

Note: UCC element composition is based on Taylor and McLennan^[13].

The LREE/HREE ratio reflects the differentiation characteristics of light and heavy rare earth elements (Table 6). In the three profiles, the LREE/HREE ratio of DJP is 8.29, and JX is 8.34, while JZT is 7.85, showing a slightly lower differentiation. The differentiation of LREE and HREE is closely related to climatic conditions. Under favorable climatic conditions, HREE are easily complexed with CO_3^{2-} and

HCO_3^- and migrate, increasing the LREE/HREE ratio. Previous studies have also shown similar results^[15].

According to Fig. 4, the distribution pattern of REEs in loess is close to the average of the crust, as indicated by the δEu value. The δEu values of the three profiles are 0.62 (DJP), 0.63 (JX), and 0.61 (JZT), showing a more uniform value across the entire Loess Plateau. The δEu values fluctuate more in other

Table 5 Rare earth element contents ($\mu\text{g/g}$) of loess-paleosol profile samples from the Loess Plateau

Profile	Strata	La	Ce	Pr	Nd	Sm	Eu	Gd	Dy	Ho	Er	Tm	Yb	ΣREE
DJP	SOLL0	36.40	74.70	8.41	31.90	6.38	1.24	5.69	5.13	1.03	2.99	0.45	2.86	178.41
		35.10	73.30	8.22	31.40	6.10	1.21	5.52	5.13	1.01	2.93	0.45	2.82	174.42
		33.00	67.50	7.58	29.10	5.65	1.13	5.13	4.75	0.97	2.72	0.43	2.69	161.88
	S0SS0	39.00	81.60	9.02	34.20	6.68	1.33	6.01	5.50	1.09	3.17	0.49	3.07	192.51
		37.10	77.10	8.56	33.00	6.32	1.29	5.88	5.13	1.01	2.94	0.45	2.86	182.91
		36.70	75.80	8.44	32.70	6.32	1.21	5.72	5.07	1.02	2.91	0.46	2.86	180.42
	L1LL1	38.10	84.10	8.90	33.90	6.58	1.29	5.78	5.24	1.05	3.07	0.49	3.02	192.86
		39.90	85.10	9.32	35.80	7.00	1.38	6.28	5.69	1.12	3.29	0.51	3.19	200.01
	L1SS1	39.00	80.30	9.08	34.60	6.86	1.37	5.99	5.60	1.09	3.18	0.49	3.10	192.12
	Average	37.14	77.72	8.61	32.96	6.43	1.27	5.78	5.25	1.04	3.02	0.47	2.94	183.95
	JX	30.90	62.20	7.18	27.50	5.38	1.08	4.60	4.17	0.84	2.44	0.38	2.41	150.25
		31.90	64.10	7.48	28.70	5.62	1.10	4.95	4.41	0.89	2.59	0.40	2.59	155.86
		31.80	64.10	7.29	28.40	5.64	1.12	5.24	5.30	1.07	3.14	0.50	3.08	157.90
		34.70	69.70	7.86	30.20	5.85	1.14	5.15	4.58	0.92	2.63	0.41	2.58	166.87
		34.60	72.80	8.19	31.60	6.20	1.22	5.44	4.78	0.94	2.75	0.42	2.70	172.91
		34.60	71.00	8.16	31.80	5.98	1.20	5.20	4.73	0.94	2.69	0.41	2.63	170.45
		31.50	67.70	7.36	28.00	5.48	1.09	4.77	4.35	0.88	2.55	0.40	2.60	157.74
		34.80	70.20	7.79	29.80	5.47	1.09	4.88	4.37	0.85	2.42	0.38	2.34	165.51
		33.10	67.73	7.66	29.50	5.70	1.13	5.03	4.59	0.92	2.65	0.41	2.62	162.18
		31.60	64.70	7.25	28.10	5.48	1.11	5.06	4.60	0.92	2.70	0.42	2.56	155.59
		31.80	65.90	7.42	28.40	5.57	1.09	5.17	4.70	0.93	2.71	0.41	2.57	157.86
	Average	32.67	67.30	7.57	29.07	5.70	1.12	5.24	4.82	0.97	2.85	0.44	2.75	161.70

Table 6 Characteristic parameters of rare earth elements in loess-paleosol profiles of the Loess Plateau

Profile	Strata	LREE	HREE	LREE/HREE	Ce/Ce *	Eu/Eu *	La_N/Yb_N
DJP	SOLL0	159.03	19.43	8.19	1.00	0.61	8.60
		155.33	19.13	8.12	1.01	0.62	8.41
		143.96	17.87	8.06	1.00	0.62	8.29
	S0SS0	171.83	20.69	8.30	1.02	0.62	8.58
		163.37	19.56	8.35	1.02	0.63	8.76
		161.17	19.30	8.35	1.01	0.60	8.67
	L1LL1	172.87	19.99	8.65	1.07	0.62	8.52
		178.50	21.50	8.30	1.04	0.62	8.45
	L1SS1	171.21	20.83	8.22	1.00	0.63	8.50
	Average	164.14	19.81	8.29	1.02	0.62	8.53
	JX	134.24	15.90	8.44	0.98	0.64	8.66
		138.90	16.96	8.19	0.97	0.62	8.32
		138.35	19.61	7.06	0.99	0.61	6.98
		149.45	17.42	8.58	0.99	0.62	9.09
		154.61	18.23	8.48	1.01	0.62	8.66
		152.74	17.78	8.59	0.99	0.64	8.89
		141.13	16.66	8.47	1.04	0.63	8.19
		149.15	16.32	9.14	1.00	0.63	10.05
		144.82	17.36	8.34	1.00	0.63	8.55
		138.24	17.39	7.95	1.00	0.63	8.34
		140.18	17.65	7.94	1.01	0.60	8.36
		151.86	19.77	7.68	1.00	0.60	7.52
	Average	143.43	18.27	7.85	1.00	0.61	8.04

loess profiles. Although the negative anomaly of Eu is generally believed to be due to preferential weathering of its host minerals during weathering, leading to the loss of Eu, the uniformity of this value in the northern and southern loess indicates that the material of loess already exhibited a negative anomaly of Eu before deposition, indicating a certain degree of weathering at that time. The anomalies of Ce in the three profiles are not significant, all around 1, indicating that the environment in which loess formed did not cause Ce migration, which also indicates that the weathering intensity of loess is much lower compared to the current red soil in the south.

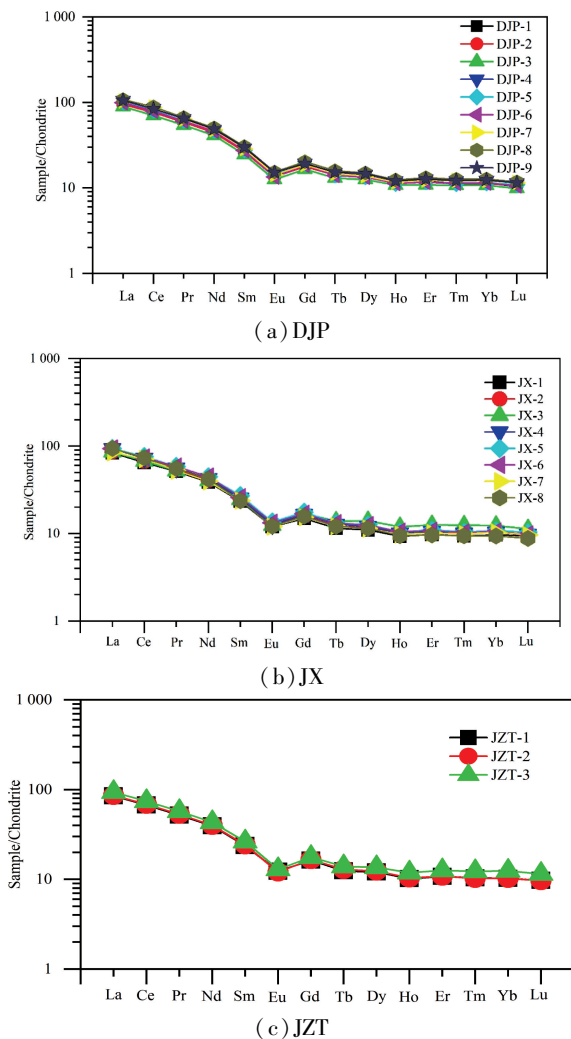


Fig. 4 Rare earth element partitioning of loess profiles on the Loess Plateau

3 Discussion

The geochemical characteristics of major elements, trace elements, and rare earth elements in the three profiles have been well summarized. However,

climate and environmental information in loess are typically reflected using a series of parameters such as elemental ratios because these parameters can more effectively reveal climatic and environmental information. Below, parameters such as Na/K, Rb/Sr, leaching coefficients, residual coefficients are utilized to reflect the leaching and enrichment of elements in loess, thereby revealing climate and environmental information. Additionally, the chemical index of alteration (CIA) is used to elucidate the weathering degree of loess in the three profiles.

3.1 Environmental significance of the ratios and parameters of related elements

The leaching and enrichment of geochemical elements in surface environments are influenced by their chemical properties and stability. This leaching and enrichment of elements are manifested spatially and also reflected over time scales and during the sedimentation process. Therefore, the ratios and correlation characteristics of different elements can reflect the degree of weathering of loess and the process of clay formation. Commonly used elemental ratios and geochemical parameters include K/Na, Rb/Sr ratios, leaching coefficients ($(\text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O})/\text{Al}_2\text{O}_3$), residual coefficients ($(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)/(\text{CaO} + \text{MgO} + \text{Na}_2\text{O})$). These ratios and geochemical parameters can reveal the intensity of weathering experienced by loess, which is closely related to climate.

The K/Na ratio can assess the chemical weathering degree of feldspar minerals in sediment^[3]. Due to the susceptibility of plagioclase compared with orthoclase to weathering, the leaching rate of Na is significantly higher than that of K. Potassium tends to be adsorbed by clay minerals, thus exhibiting higher stability. The K/Na ratio can effectively reflect the intensity of weathering. The Rb/Sr ratio was one of the earliest parameters used in loess research. Due to the significant difference in the geochemical behavior of Rb and Sr, with Sr being more mobile than Rb, and Rb being an active element but easily adsorbed by clay minerals due to its large ionic radius, when climate conditions are humid and hot, Sr is easily released and migrates while Rb is adsorbed, leading to an increase in the Rb/Sr ratio.

According to Table 7, the K/Na and Rb/Sr ratios in the DJP profile are significantly higher than those in the JX and JZT profiles. The average values of these two ratios in the DJP profile are 1.90 and 0.75, respectively, while for JX, they are 1.30 and 0.46, and for JZT, they are 1.21 and 0.35. Thus, the element mobility in the DJP profile is stronger, indicating more

favorable weathering conditions. The ratios in JX and JZT are both low, indicating poor climate conditions,

with JX having slightly better climate conditions compared to JZT, especially in terms of the Rb/Sr ratio.

Table 7 Environmental coefficient index

Profile	Strata	K ₂ O /Na ₂ O	Leaching coefficient	Residual coefficient	Rb/Sr	
DJP	SOLL0	1.65	0.68	3.09	0.68	
	S0SS0	1.59	0.70	2.94	0.68	
	L1LL1	1.49	1.16	1.76	0.58	
	L1SS1	2.22	0.35	6.55	0.86	
		1.60	0.39	5.89	0.63	
		1.79	0.75	2.81	0.57	
		2.92	0.29	7.69	1.00	
		2.11	0.33	7.02	0.89	
		1.82	0.35	6.45	0.82	
		1.09	1.01	2.01	0.36	
		1.07	0.92	2.21	0.37	
		1.11	1.15	1.73	0.34	
	JX	L1	1.36	0.65	3.15	0.45
			1.45	0.54	3.90	0.51
1.47			0.51	4.25	0.56	
1.45			0.43	5.12	0.57	
1.39			0.72	2.91	0.49	
JZT	L1	1.36	1.11	1.77	0.40	
		1.16	1.15	1.68	0.30	
		1.11	1.13	1.71	0.34	

The leaching coefficient $(\text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O})/\text{Al}_2\text{O}_3$ emphasizes the leaching of active elements. On the other hand, the residual coefficient $(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)/(\text{CaO} + \text{MgO} + \text{Na}_2\text{O})$ indicates the enrichment degree of stable elements, with its denominator comprising active elements such as Ca, Mg, and Na. During the process of weathering and leaching, these three elements are prone to leaching, while the numerator includes stable elements like Al and Fe, which are less mobile. The stronger the weathering, the higher the residual coefficient, showing an inverse correlation with the leaching coefficient. From the results of these parameters of the three profiles, it is still shown that the leaching coefficient of DJP is the lowest, and the residual coefficient is the highest; the leaching coefficient of JX and JZT is higher, and the residual coefficient is lower, still indicating that DJP has the strongest weathering leaching effect. Additionally, compared to the JZT profile, the leaching coefficient of JX profile is lower, while the residual coefficient is higher, once again indicating that the northern part of the Loess Plateau undergoes stronger weathering compared with the western JZT.

Furthermore, there are certain variations in the

leaching coefficient and residual coefficient in each profile. In the paleosol layer, the leaching coefficient is lower, while the residual coefficient is higher. In the DJP profile, which is easily distinguished between loess and paleosol layers, the leaching coefficient of the Holocene loess layer (SOLL0) is higher, whereas the residual coefficient is lower. Conversely, in the Holocene paleosol layer (SOSS0), the situation is reversed, indicating that these parameter values can effectively reflect the variation in weathering intensity along the profile. Interestingly, in the JX profile, although it is difficult to identify poorly developed soil layers in the field, there are significant differences in the values of these parameters between the upper three samples and the lower five samples. The leaching coefficient of the upper samples is 1.03, while that of the lower samples is 0.57. The residual coefficient of the upper samples is 1.98, whereas that of the lower samples is 3.87, indicating weaker weathering in the upper part and stronger weathering in the lower part. In the JZT profile, there are also notable differences between the surface samples and the two lower samples. The leaching coefficient (1.11) of the surface samples is lower, with a higher residual coefficient (1.77).

Conversely, the leaching coefficient (1.14) of the lower samples is higher, with a lower residual coefficient (1.70). Vegetation development on the surface samples during field sampling indicates stronger weathering and leaching effects.

3.2 Degrees of chemical weathering

The Loess Plateau has abundant calcium carbonate nodules and calcium crust layers, indicating that elements associated with carbonate (represented by Ca) undergo deposition after leaching. However, the chemical weathering and environmental conditions reflected by these element contents may exhibit a lag effect. Therefore, a more reliable indicator is needed to determine the degree of chemical weathering in loess. CIA is generally used to indicate the degree of feldspar weathering and the formation of clay minerals. During the weathering and leaching of feldspar, mobile elements such as K, Na, and Ca are easily leached and transported, while Al, being relatively stable, tends to accumulate. Therefore, a higher CIA value indicates a stronger chemical weathering and leaching process, reflecting relatively warm and humid climatic conditions. In loess studies, CIA is often used as an indicator of the summer monsoon^[16]. Nesbitt proposed the following formula for calculating CIA^[17]:

$$\text{CIA} = \text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}^*) \times 100 \quad (1)$$

where, the content of each oxide is expressed in mole units, CaO^* represents the CaO in silicates. Corrections based on the content of carbonates and apatite were proposed by McLennan^[18]. If the CaO content is less than the Na_2O content, then the CaO^* content is used; if the CaO content is greater than the Na_2O content, then the CaO^* content is considered equivalent to the Na_2O content. A higher CIA value indicates a greater amount of K, Na, and Ca elements leached from the silicate minerals of the bedrock, indicating stronger chemical weathering of feldspar. Generally, CIA values between 80–100 reflect intense chemical weathering under hot and humid tropical or subtropical conditions; CIA values between 65–80 indicate moderate chemical weathering under warm, moist conditions; CIA values between 50–65 indicate low chemical weathering under cold, dry climatic conditions^[17].

According to Table 2, the CIA values of the DJP profile range from 53.02 to 73.99, with an average of 66.58; for the JX profile, CIA values range from 55.14 to 61.52, with an average of 58.93; and for the JZT profile, CIA values range from 55.00 to 59.39,

with an average of 56.75. Overall, the CIA value of the loess-paleosol sequences in the study area ranges from a minimum of 55.00 to a maximum of 73.99, with an average of 62.18, indicating an overall low degree of chemical weathering. The average CIA value for the DJP profile's S0 layer is 66.76, for the S0LL0 layer it is 64.72, for the L1LL1 layer it is 65.01, and for the L1SS1 layer it is 66.50. The CIA values of different layers are in the order of S0SS0 > L1SS1 > L1LL1 > S0LL0, indicating that the CIA value of the paleosol layer is greater than that of the loess layer. The profile as a whole is in a stage of relatively low chemical weathering under semi-arid to arid conditions. Only the S0SS0 layer is in a stage of moderate chemical weathering, indicating a period of relatively humid climate.

Nesbitt et al.^[17] proposed the A-CN-K ternary diagram model for predicting continental weathering trends, where A represents Al_2O_3 , CN represents $\text{CaO} + \text{Na}_2\text{O}$, and K represents K_2O . This model effectively reveals the degree of surface weathering of materials. The results of samples from the DJP, JX, and JZT profiles on this ternary diagram (Fig. 5) show that all samples align with the composition of the UCC, pointing towards the Paleoproterozoic Australian Shale (PAAS), consistent with the direction of the A-CN line. This indicates that the weathering of loess is still in the primary stage of decalcification and modification, consistent with the findings of other researchers^[11]. However, the ternary diagram still reflects differences in the weathering intensity among the three profiles. Both JX and JZT are in the early weathering

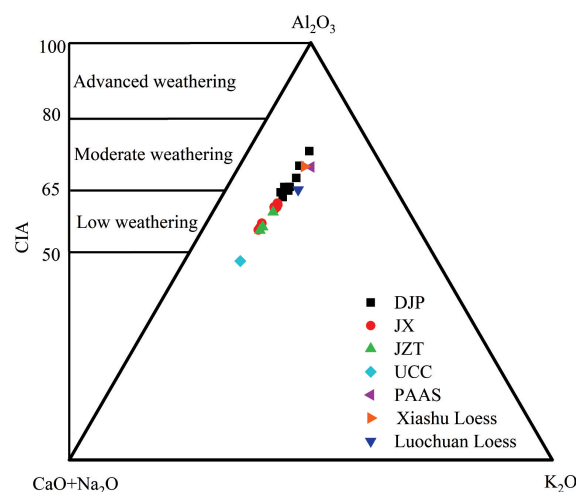


Fig. 5 A-CN-K diagram of loess in the study area, other regions, and reference materials

stage, with JX slightly higher in weathering intensity compared to JZT. DJP, on the other hand, is already in the early to moderate weathering stage, with significantly higher weathering intensity than JX and JZT, approaching the degree of weathering of the Xiashu Loess. It should be noted that the average weathering degree of DJP on the ternary diagram is close to that of the representative loess of the Loess Plateau —the Luochuan Loess. However, the actual weathering degree of DJP should be higher, and the lower result of DJP on the diagram may be related to the presence of a large number of calcium nodules in the profile.

4 Conclusion

Through comparative analysis of the elemental geochemical characteristics and related parameters such as elemental ratios of the three loess profiles in Duanjiapo, Jiaxian, and Jiuzhoutai on the Loess Plateau of China, several insights are obtained.

(1) SiO_2 , Al_2O_3 , CaO , Fe_2O_3 , MgO , K_2O , and Na_2O are the main components of loess, accounting for 90.57% of the total content. Relative to the UCC, they exhibit characteristics of low Al, K, Na, and high Ca. Compared with UCC, elements such as Th, Nb, Zr, Hf, Y, Cs, V, Li, and Pb are relatively enriched, while elements like Rb, Ba, Sr, and Be are relatively depleted. The average ΣREE content is $171.91 \mu\text{g/g}$, with a negative anomaly in δEu and generally no anomaly in δCe . The differentiation of rare earth elements is significant, with the strongest LREE/HREE differentiation observed in Duanjiapo, indicating the most intense weathering leaching action.

(2) The results of $\text{K}_2\text{O}/\text{Na}_2\text{O}$, Rb/Sr, as well as leaching coefficients in the three profiles indicate the following trend: $\text{DJP} > \text{JX} > \text{JZT}$, suggesting that Duanjiapo has experienced the strongest weathering leaching, while JZT is the weakest. The results for the residual coefficients are opposite, but their significance aligns with the indicators above and the parameters.

(3) The CIA values reveal that all three loess profiles are in the primary stage of Ca and Na removal. DJP is generally in the low to moderate stage of chemical weathering, while JX and JZT are both in the primary stage, with JX showing slightly higher weathering intensity compared with JZT. The CIA values of the paleosol layer in the DJP profile are higher than those of the corresponding loess layer.

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