Behaviors of Major and Trace Elements in Soils Developed from Weathering Basalt in Western Guizhou, China

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Abstract: Weathering is a crucial geochemical process for basalt and soil formation, which plays a vital role in restoring the karst region in Guizhou, southwest China. Two regolith profiles (Dougu and Shazi) were selected to investigate the behaviors of major and trace elements developed from advanced to extreme weathering of the Emeishan basalt in the western Guizhou province. These profiles are composed of surficial clay-humus, laterite, loess, and weathered basalt. The two profiles contain very high amounts of silica-alumina ratio (Sa), silica sesquioxide ratio (Saf), and chemical index alteration (CIA), with deficient concentrations of CaO, Na2O, MgO, and K2O compared to that of the fresh basalt. They are also characterized by notable depletion of Sr, K, Ba, P, and enrichment of La and Ce. In general, The two profiles showed enrichment in light rare earth elements. Ce is enriched in the laterite profile of Shazi. The variances in the mobilization of elements in these two profiles and their similar protolith nature indicate that they underwent various supergene geological processes. The Shazi and Dougu profiles have experienced a severe action of alkali dissolution, desilication, and enrichment of iron, aluminum, titanium. The variation characteristics of magnesium and calcium indicate more montmorillonite in the Dougu profile formed in the middle and late stages of weathering. The CIA index also shows that the weathering effect of the Shazi profile is more potent than that of the Dougu profile. The rare earth elements in the Shazi profile have apparent positive δCe anomalies, indicating that the Shazi profile is formed in an intense oxidation environment. The content of scandium (Sc) in the parent rock and its weathering degree limits its amount in weathering crusts. The Sc in the Shazi and the Dougu profiles is rich than the parent rock in the weathering crust, and the enrichment is most visible in the red soil layer. The degree of enrichment of Sc is prominent in the Shazi profile with higher Sc content in the parent rock and even reaches the level of mineralization.
Keywords: trace element, mobilization, soil, weathering basalt, western Guizhou

1. Introduction

Permian Emeishan basalt is mainly distributed in Sichuan, Yunnan, and Guizhou provinces in China, which researchers have named as the Large Igneous Province (abbreviated to LIPs). It is the only internationally recognized Large Igneous Province in China. The rock series is primarily distributed in the western margin of the Yangtze plate, showing a rhomboid shape, with an exposed area of about $3.0-3.5 \times 10^5$ km$^2$ [1][2]. Yigang Xu (2002) [3] briefly expounded on the characteristics of the LIP: it consist of a large covered lava flow. The maximum thickness can reach more than 5 km. They have many types of rock compositions, but are dominated by basaltic lava. In the early period of the Emeishan basaltic magma eruption, a large-scale dome occurred on the western margin of the Yangtze, which is consistent with the theoretical model of surface uplift caused by mantle plume rise [4].

The area of Permian basalts in Guizhou is $4 \times 10^4$ km$^2$ and it is largely distributed in western Guizhou. Basalt contains a variety of trace elements and is rich in these elements. The composition of trace elements from its weathered soil inherits the geochemical characteristics of the parent rock to a certain extent. At present, volcanic ash soil contains high amounts of trace elements and has excellent soil fertility (very arable). Considerable part of it is developed from its basalt parent material, which has attracted soil scientists and agronomists [5]. The migration and redistribution of major elements and trace elements in the process of basalt weathering and soil formation can ascertain the degree of basalt soil development and soil-forming environment [6][7]. At the same time, the differences in geochemical properties of the major and trace elements will cause relative enrichment or leaching. Wu C F (1991) [5] opined that the content of various beneficial trace elements in basalt parent soil is significantly higher than that in granite parent soil. Yang R D (2008) [8] reported that the content of trace elements in the soil formed by weathering basalt is higher than that formed by weathered carbonate rocks, metamorphic rocks, and clastic rocks. Therefore, the soil formed by the weathering of basalt is very conducive for agricultural purposes since it contains substantially beneficial trace elements if considered only from the geochemistry perspective.

To provide a theoretical basis for the adjustment of agricultural structure and the development of characteristic agriculture in Guizhou’s Emeishan basalt distribution area, there is a need to strengthen research on the geochemical characteristics of the basaltic soil and the migration mechanism of trace elements in the weathering process of basalt.

2. Materials and methods

2.1. Soil sampling and site description

The profile in this study was collected from Shazi Town, Qinglong County, and Dougu Town, Bijie City. Both of them are weathering profiles of basalt distribution areas in Guizhou (Figure 1). The environment of basalt weathering profiles in different regions varies, such that the weathering degree of each profile is disimilar. No bedrock was found in the lower layer of the Dougu profile. The samples collected from each profile were fresh soil and rock samples.
Figure 1 A tectonic map with location of Shazi and Dougu profiles, modified from Zhang M [9]

(1) The Shazi profile

The Shazi profile is collected from Shazi Town, Qinglong County, Guizhou, Coordinates N25°46′40.72″, E105°09′0.01″, altitude 1464 m, and profile depth 4.9 m. The Shazi profile is complete and composed of weathering crust and basaltic parent rocks. The profile is divided into five layers with different characteristics according to the color, texture, and interlayer contact relationship of soil and rock. They are the topsoil layer, the loess layer, the iron layer, the red soil layer, semiweathered basalt, and basalt in a top to bottom fashion. The iron layer is a thin layer of about 2 cm thick between the loess layer and the red soil layer (Figure 2). The sampling location starts at 10 cm below topsoil layer, and fresh soil samples are collected in a bottom-top order with 10 cm intervals and placed in sealed pockets. In total, 50 samples are collected from the Shazi profile (Numbered SZ-1 to SZ-50 from top to bottom).
Figure 2 Schematic diagram of various layers of the Shazi weathering section
(2) The Dougu profile

The Dougu profile is collected from Dougu Town, Weining County, Bijie City, Guizhou, Coordinates N26°57′59.41″, E103°49′20.62″, altitude 2557 m, and profile depth 3 m. The bedrock is not exposed. The profile is divided into three layers with different characteristics according to the color, texture, and interlayer contact relationship of soil and rock. From top to bottom, they are: the topsoil, red soil, and loess layers (Figure 3). The samples were collected from top to bottom with an interval of 10 cm. A total of 30 profile samples (Numbered DG-1 to DG-30 from top to bottom) were collected. It is worth noting that since the bedrock was not exposed, the parent rock was collected from the exposed bedrock around the profile, numbered DG-31.

![Figure 3 Schematic diagram of various layers of the Dougu weathering section](image)

2.2. Laboratory analysis methods

We collected fresh samples from the field and air-dried them under natural indoor conditions to remove plant roots and organic residues. The air-dried samples were ground to less than 200 mesh with an agate mortar. Anhydrous alcohol was added during grinding and returned into the sample bag after the alcohol had completely evaporated. Before grinding the next sample, quartz is poured into the mortar for cleaning, and then rinsed with clean water. Ground samples were placed in a 105°C oven for about 4 hours and then taken out for testing.

2.2.1 Major elements analysis methods

The testing of major elements is carried out by X-ray fluorescence spectroscopy in the Key Laboratory of Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences. The instrument is the ARL Perform’X 4200 model X-ray fluorescence spectrometer produced by the Thermo Fisher company. First, the crucible to be used is weighed and its mass is recorded as \( M_1 \). 1 gram of the sample is placed in the preweighed crucible and their total weight is recorded as \( M_2 \). The weighed sample is then heated in a muffle oven at 1050°C for at least 3–4 hours, after which it is reweighed when cooled and recorded as \( M_3 \). LOI (Loss on ignition) = \( (M_2 - M_3)/(M_2 - M_1) \times 100\% \).

A calibrated one-millionth balance is used to accurately weigh 0.8 grams of sample and 8.0 grams of flux. The newly weighed samples must then be evenly stirred in a platinum crucible. Next, 0.5 ml of saturated ammonium iodide solution is added to the mix and placed in a sample melting
device bracket for melting. The prepared glass sheet is finally placed in an X-ray fluorescence spectrometer for testing. Also, 1–2 reference materials were tested for each batch of samples, and one parallel sample was added for every 20 samples to be tested. As a result, the test accuracy is better than 3%.

2.2.2 Trace elements analysis methods

The testing of trace elements is carried out in the ICP-MS Laboratory of the Key Laboratory of Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, and the instrument used is the ICP-MS (Plasma Quant MS Elite) produced by the Jena Analytical instrument Co., Ltd. In the experiment, 50 mg of the sample is weighed accurately in a Teflon crucible, and 1 ml HF and 1 ml HNO₃ are added before the sample is sealed in the steel sleeve. It is then placed in the oven and heated at 185°C for 35 hours to digest the sample. After cooling, it is taken out and placed on a low temperature electric hot plate and steam dried before adding 1 ml HNO₃ as it continues to steam dry thoroughly. Add 200 ng Rh internal standard solution, 2 ml HNO₃, 3 ml deionized water, and place it back in the steel sleeve at 140°C for 5 hours. After cooling, it must be adequately shaken. The 0.4 ml of the solution is placed into the centrifuge tube, at a volume level of 10 ml, and determines its plasma mass with a spectrometer (ICP-MS). The relative standard deviation of repetitive tests was better than 10%.

2.3. Calculation of weathering characteristic values

The weathering characteristic values mainly include the coefficient of weathering and migration rate, and it is commonly used to reflect the weathering strength and migration of elements characteristic in weathering profiles.

(1) Coefficient of weathering

The coefficient of weathering is the ratio of oxide content of two or more major elements. At present, the commonly used weathering indexes are silica-alumina ratio (Sa), silica sesquioxide ratio (Saf), and chemical index alteration (CIA).

Silica-alumina ratio (Sa) and silica sesquioxide ratio (Saf) are commonly used to describe the weathering degree of minerals, though it can also be used to describe the degree of desilication and ferrallitization in profile. Therefore, the lower the silica-alumina ratio (Sa) and silica sesquioxide ratio (Saf) is, the higher the laterization degree, and the stronger the weathering degree, thus, the greater the degree of laterization and enrichment of iron and aluminum. Calculation formula is [10][11][12]: Sa = SiO₂/Al₂O₃, Saf = SiO₂/(Fe₂O₃ + Al₂O₃).

Generally speaking, in the process of chemical weathering, active elements such as Na, K, Ca, Mg, etc., are leached by fluid, and Al₂O₃ is stably preserved, and its content is relatively increased. Nesbitt and Young (1982) [13] proposed that the CIA is used to describe the weathering degree of the profile, and the CIA can also be used to describe the weathering environment. The stronger the chemical weathering, the higher the CIA, and the more humid and hot the weathering process. The calculation formula of the chemical alteration index is [13]: CIA = [Al₂O₃/(Al₂O₃ + K₂O + Na₂O + CaO)] × 100.

(2) The mobility of elements

The leaching of elements with active geochemical properties often leads to the enrichment of inert and difficult-to-migrate elements, so it is necessary to select inert elements as a reference to appropriately reflect the geochemical behavior of elements. Generally, there are three kinds of inert and refractory elements: Al, Ti, and Zr. Different parent rocks have different nonmigrating elements. In the weathering profile formed by basic rocks, Ti is usually selected as the nonmigrating element [14][15]. Therefore, this study chooses Ti as the nonmigrating element to calculate the mobility of
constant elements. The mobility of constant elements varies with depth, where the mobility calculation method is [16]:

\[ \Delta\% = 100 \times \left( \frac{C_j/C_{Ti}}{C_j/C_{Ti}} - 1 \right) \]

\( C_j \) and \( C_{Ti} \) are the contents of elements \( j \) and \( Ti \), \( s \) and \( p \) respectively represent the samples and protolith. If \( \Delta > 0 \), element \( j \) is enriched relative to element \( Ti \), and if \( \Delta < 0 \), element \( j \) is depleted relative to element \( Ti \).

3. Results

3.1. Geochemical characteristics of major elements

(1) The Shazi profile

The content of SiO\(_2\), Fe\(_2\)O\(_3\), and Al\(_2\)O\(_3\) in weathering crust is the highest, measuring over 73%, with an average valuation of 80%. The highest component in the iron layer is Fe\(_2\)O\(_3\), contributing up to 65.2%. Compared to bedrock, SiO\(_2\), MgO, Na\(_2\)O, K\(_2\)O, and CaO in weathering profile are reduced, and almost all CaO is leached, registering a compositional value less than 0.1%. However, Fe\(_2\)O\(_3\) and Al\(_2\)O\(_3\) are increased, indicating that the basaltic weathering profile has experienced intense leaching, desilication, and enrichment in iron, and aluminum.

To better analyze the changes in the major elements in the profile, a related diagram (Figure 4) was developed with the variation of the major elements in the profile. Figure 4 shows that the content of each major element has no obvious change in the basalt layer. At the boundary between the basalt layer and semiweathered basalt, the contents of the major elements distinctively changed. The content of Fe\(_2\)O\(_3\) and Al\(_2\)O\(_3\) increased significantly, and the average values were 4.5%, 22.93%, and 22.03%, respectively. With a decrease in depth, the contents of the three components fluctuated largely. The content of Fe\(_2\)O\(_3\) and Al\(_2\)O\(_3\) in the loose layer and the red soil layer is significantly higher than that in the topsoil layer. The content of Fe\(_2\)O\(_3\) and Al\(_2\)O\(_3\) in the red soil layer is the highest, indicating that Fe and Al in the topsoil layer may leach downward or laterally under the action of strong leaching. The Fe leached into the topsoil layer may not be rich in the loess layer. At 2.25–2.6 m, Fe\(_2\)O\(_3\) content decreased from 65.22% to 19.56% In the range of 2.6 m –3.1 m, the content of Fe\(_2\)O\(_3\) increased from 19.56% to 27.59%, which may be due to the formation of an iron layer. The contents of SiO\(_2\), MgO, Na\(_2\)O, and CaO decreased. With a decrease in depth, the contents of Na\(_2\)O and CaO were approximately constant, approaching zero, while the content of SiO\(_2\) fluctuated between 10.08% and 41.04%. However, the content of K\(_2\)O at the boundary (4.2–4.3 m) is higher than that of the basalt. At 2.2–3.8 m, the content of K\(_2\)O is below 0.5%, which is similar to that of Na\(_2\)O. But above 2.2 m, the content of K\(_2\)O increased again, reaching above 0.74%. Generally speaking, Na and K, as alkali metals, have similar geochemical properties and show deficit characteristics in a supergene earth environment [17]. However, K\(_2\)O is enriched relative to Na\(_2\)O in the weathering profile, which may be due to the increase in clay mineral content.
(2) The Dougu profile

In the Dougu profile, the content of SiO2 is the highest, ranging from 32.61% to 60.88%, with an average of 35.74%. The SiO2 content peaked at 60.88% in DG-5. From the field profile, no quartz vein was found in this depth, which may be caused by presence of siliceous minerals in the sample. The content of Fe2O3 is second only to SiO2, with a slight change, ranging from 12.41% to 25.41%, with an average of 22.08%. The change of Al2O3 content is smaller than that of Fe2O3 but relatively similar, ranging from 12.58% to 22.43%, with an average of 21.25%. According to the content change observed in the samples, Na2O and K2O showed leaching loss in the profile, while the contents of Fe2O3, Al2O3, and CaO in the profile were slightly enriched relative to the parent rock.

Figure 5 shows that the contents of SiO2, Al2O3, and Fe2O3 fluctuate significantly in the vicinity of DG-10, and change stably in loess layer and red soil layer. The contents of SiO2 leached, and the contents of Al2O3 and Fe2O3 are enriched relative to the parent rock. The content of SiO2 in the topsoil layer showed an increasing trend from bottom to top, while Al2O3 and Fe2O3 showed decreasing tendencies. The changes in MgO, CaO, Na2O, and K2O contents in the profile are more complex. The content of CaO in the profile is less, but it is enriched relative to the parent rock; hence, there is no significant leaching loss. In contrast, most of the Na2O leached relative to the parent rock and is relatively enriched at the bottom of the red soil layer, the top of the topsoil layer, and in DG-9. The K2O content in the loess layer is relatively richer in the parent rock. From the loess layer up to the top of the red soil layer, the K2O content decreased, indicating an appreciable leaching loss. The K2O...
content in the topsoil layer tends to increase with the decrease in depth. Most of the MgO content is enriched relative to the parent rock, and only a lower content was observed in the topsoil layer, while the MgO content in the profile decreased and then increased from bottom to top. The enrichment is mainly concentrated in the middle and upper parts of the red soil layer and the bottom of the topsoil layer. Therefore, it is primarily inferred that the weathering, leaching, and desilication of the Dougu profile during weathering were weaker than that of Shazi profile. The enrichment of CaO and MgO contents indicates that the weathering period of the Dougu profile is the montmorillonite stage.

Figure 5 The variation in contents of major elements at various depths of samples from the Dougu profile

3.2. Geochemical characteristics of trace elements

(1) The Shazi profile

Because the formation of the profile has experienced intense weathering and leaching, the content of most trace elements is lower than that of the parent rock, and the content of each element varied largely with depth. The leaching of Sr, Rb, Ba, and other elements relative to the parent rock occurred, and the leaching degree of Sr is the largest. Still, the other three elements are relatively enriched in the upper profile. The elements such as V and Sc are enriched relative to their parent rocks. However, Cr Ni, an iron philic element, shows different content changes than the V element.

Figure 6 shows that the profiles of elements V and Cr are similar. However, the element Ni is enriched in the semiweathered Black Tortoise strata, and the content of Ni above the iron layer is depleted relative to that of the parent rock. However, the element V is enriched at the bottom of the red soil layer, and the contents of Ni and V decrease with depth. The content of element Cr is less than that of the parent rock, especially at the top of the red soil layer. In comparison, the content of element Cr in the middle of the red soil layer is higher than that in the lower red soil layer and the semiweathered layer. Ni is mainly enriched in the semiweathered layer, while Cr was enriched in the middle of the red soil layer. It was found that the montmorillonite produced by the weathering of Ni
enstatite has the highest Ni content. Previous studies on ultrabasic red soil weathering profiles proposed that Ni is first deposited in the semiweathered layer, followed by Cr at the bottom of the red soil layer [18]. The variation in Ni and Cr in the Shazi profile is consistent with the enrichment rule proposed by the former to a certain extent, which is important for ascertaining the main occurrence location of Ni and Cr in the red soil in future studies.

The content of the Sc element in the parent rock is $28 - 30 \times 10^{-6}$, and the whole soil layer is enriched relative to the parent rock, with an average content of $40.456 \times 10^{-6}$. The enrichment degree in the red soil layer is 1.26–1.96 times that of the parent rock, and the highest content of Sc is $55.9 \times 10^{-6}$, which reaches the industrial grade of large independent Sc deposits. The changing tendency of Rb and Sr element contents is similar to that of the K element, which is relatively enriched in the semiweathered layer and strongly leached in the red soil layer. The content of Sr relatively increased above that of the loess layer. In general, Ba significantly leached relative to the parent rock, where the leaching degree is largest in the red soil layer, with an average content of $185.33 \times 10^{-6}$. Showing that the red soil layer is the principal layer of chemical weathering in the profile.

![Figure 6](image_url)  
**Figure 6** The variation of contents of trace elements with depths of samples in the Shazi profile

(2) The Dougu profile

Sc, V, Cr, Ba, and other elements in the Dougu profile are relatively enriched in the weathering crust. The average content of Sc is $36.91 \times 10^{-6}$, the highest content is $40.9 \times 10^{-6}$, and the content in the parent rock is $27 \times 10^{-6}$. Sc is mainly enriched in the red soil layer, and the enrichment degree is 1.02–1.56 times that of the parent rock, which is lower than that in the Shazi profile. On the other
hand, the content Ba is higher than that in the Shazi profile, with average content measuring to $505 \times 10^{-6}$, which is enriched in the main loess layer.

The trend of V in the Dougu profile is similar to that in the Shazi profile. V is highly enriched at the bottom of the profile, and its content decreased, but it is generally higher than that of the parent rock. The contents of Cr and Ni vary weakly, and there is no enrichment trend of Ni and Cr. The variation trend of Sc shows an enrichment relative to the parent rock, and the main enrichment layers are at the bottom of the topsoil layer and the top of the red soil layer. The variation trends of Rb and K$_2$O content are similar, with a general pattern that decreases initially and then increase from bottom to top, but its content fluctuates highly. Sr content is relatively enriched in the loose layer, yet decreases upward, and fluctuates highly from $30.7 \times 10^{-6}$ to $78.9 \times 10^{-6}$ at 1.1 m. However, Sr leaching is mainly located in the upper part of the red soil layer and the lower part of the topsoil layer. The Ba element content is that with the most tremendous change of trace, mainly enriched in the loose layer, with the content ranging from $730 \times 10^{-6}$ to $1073 \times 10^{-6}$, whereas its content in the red soil layer is mainly distributed from $283 \times 10^{-6}$ to $486 \times 10^{-6}$. As the depth decreases, the Sr element content changes into a decreasing trend (Figure 7).

![Figure 7 The variation of contents of trace elements with depths of samples in the Dougu profile](image)

### 3.3. Variation characteristics of rare earth elements

The $\Sigma$REE of the Shazi profile ranged from $112.2 \times 10^{-6}$ to $400 \times 10^{-6}$, with an average of $180.49 \times 10^{-6}$. $\Sigma$REE content is relatively enriched in topsoil, the bottom of red soil, and the semiweathered layer, but leaching occurs in other horizons. The $\Sigma$LREE/$\Sigma$HREE ranged from 5.20 to 13.47, with an average value of 7.56. Ln/Yb$_{\text{N}}$ ranged from 3.19 to 7.29, with an average of 4.67. The distribution pattern of rare earth elements in the Shazi profile is similar to that of the LREE enrichment. $\delta$Eu ranged from 0.804 to 0.949, with an average of 0.857, showing a weak negative anomaly, and $\delta$Ce
ranged from 0.85 to 5.07, with an average of 1.99, showing a strong positive anomaly (Figure 8). As mentioned above, the Shazi profile suffers from intense leaching, and the REE is relatively leached. The differentiation of light and heavy rare earth metals in the profile is strong, and the light rare earth metals are relatively enriched in the profile. The differentiation of light and heavy rare earths and the enrichment of light rare earths are weaker than those of the Dougu profile.

Figure 8 The characteristic values of rare earth elements of samples in the Shazi profile (ppm)

Note: Chondrite data are based on Taylor and McLennan, (1985) [19].

The $\Sigma$REE of the Dougu profile ranged from $250 \times 10^{-6}$ to $451.3 \times 10^{-6}$, with an average of $383.13 \times 10^{-6}$. $\Sigma$REE content is generally enriched relative to the parent rock, and there is no leaching. $\Sigma$LREE/$\Sigma$HREE ranged from 6.66 to 11.41, with an average value of 7.72. $\text{La}_N/\text{Yb}_N$ ranged from 7.97 to 11.83, with an average of 9.72, and the rare earth distribution pattern of the Dougu profile is similar to the LREE enrichment type. $\delta$Eu ranged from 0.89 to 0.95, with an average of 0.93, showing a weak negative anomaly; $\delta$Ce ranged from 0.46 to 2.14, with an average of 0.91, showing slight negative anomalies in general, and individual weak positive anomalies (Figure 9). Based on the above analysis, the Dougu profile has not suffered intense leaching. The REE is relatively enriched, and the differentiation of light and heavy rare earths is significant in the profile, and light rare earths are enriched in heavier rare earths.
Both Ce and Eu belong to variable valence elements, such that a change in redox environment during weathering can easily cause anomalies in their profile, so they exhibit geochemical behaviors different from other rare earth elements [20][21][22][23]. The Ce has two valence states: Ce³⁺ and Ce⁴⁺. In a relatively oxidizing environment, Ce³⁺ is easily oxidized. The stability of Ce⁴⁺ is higher than that of Ce³⁺, and it is easy to precipitate and cause a δCe positive anomaly. The Eu element has two valence states: Eu³⁺, Eu²⁺. When minerals are chemically precipitated, Eu²⁺ will preferentially enter into the mineral lattice, so the prerequisite for the formation of Eu is the presence of Eu²⁺ in Eu-rich water or aqueous solution [24]. Sverjensky (1984) [25] argued that Eu²⁺ could only appear in an extremely reduced alkaline water environment at 25°C. The Shazi profile shows strong positive anomalies of δCe and weak positive anomalies of δEu, which shows that the profile of Shazi experienced enhanced weathering under a high oxidation environment. However, from the weak negative anomalies of δCe and δEu in the Dougu profile, the redox environment of the Dougu profile is not strong.

4. Discussion

4.1. Mobility of constant elements

(1) Mobility of the Shazi profile

The mobility curves of SiO₂, MgO, Na₂O, K₂O, and CaO in the Shazi profile are similar to their absolute content change curves, and the mobility is all negative, resulting in leaching loss. The mobility of Fe₂O₃, Al₂O₃, SiO₂, and K₂O fluctuates considerably. Starting from the semiweathered
basalt, the mobility of SiO$_2$, MgO, Na$_2$O, and CaO decreases sharply upward. The mobility of SiO$_2$ ranged from 35.93% to 69.11%, with an average of 51.05%. The mobility of Mg ranged from 71.67% to 94.41%, with an average of 90.58%. The mobility of CaO is the largest, approximating 100%, with an average value as high as 99.24%, representing an almost absolute leach loss. The mobility of Na$_2$O ranged from 72.16% to 99.76%, averaging 94.73%. The mobility of K$_2$O ranged from 8.45% to 88.89%, with an average of −50.49%, which is lower than that of Na$_2$O. The mobility of K$_2$O ranged from 16.22% to 44.97% in the loess layer, while Na$_2$O mobility is always less than 90%. It can be seen that K$_2$O is more enriched than Na$_2$O. The mobility of Fe$_2$O$_3$ and Al$_2$O$_3$ are all positive except for a few, with an average of 26.02% and 25.79%. Fe$_2$O$_3$ is significantly enriched in the iron layer, and its mobility is as high as 388.14%. The mobility of SiO$_2$ and Al$_2$O$_3$ reaches the lowest value, which is 77.88% and 30.81% (Figure 10).

(2) Mobility of the Dougu profile

In the Dougu profile, most major elements, except CaO, have a large leaching loss relative to the parent rock. The mobility of SiO$_2$, Fe$_2$O$_3$, and Al$_2$O$_3$ has a certain similarity with depth. The SiO$_2$ mobility ranged from 47.45% to 51.69%, with an average of 32.9%, indicating that the SiO$_2$ content is leached more than in the parent rock. The Fe$_2$O$_3$ mobility ranged from 27.54% to 63.36%, with an average of 4.1%, some horizon mobility is greater than zero, and most of the mobility is about 10%, which implies no apparent enrichment of Fe elements in the profile. On the contrary, there is a less prominent leaching loss relative to the parent rock. The Al$_2$O$_3$ mobility ranged from 36.25% to 22.82%, with an average of 20.37%. Therefore, there is no enrichment of Al$_2$O$_3$ in the profile, and the degree of leaching is greater than that of Fe$_2$O$_3$. It can be inferred that the weathering process of the profile experienced a strong desilication. The MgO mobility ranged from 46.14% to 15.75%, with an average of 11.52%. The MgO mobility above 1.8 m of the profile ranged from 46.14% to 13.60%, with an average of 9.27%. The MgO mobility ranged from 12.87% to 5.57%, with an average of 2.87%. Therefore, the degree of MgO leaching in the upper profile is more significant than in the lower profile. The CaO mobility ranged from 40.90% to 48.3%, with an average of 49.84%. Except that the mobility of the three layers in the topsoil layer is less than zero, the other layers are all greater than zero, resulting in enrichment relative to the parent rock. The migration rate of Na$_2$O is mainly about 50%, with an average of 30.53%. There is a considerable leaching loss in the profile, and the degree of leaching loss is greater than that of SiO$_2$. The K$_2$O mobility ranged from 70.65% to 17.07%, with an average of 41.81%, depicting that there is a large leaching loss of K$_2$O relative to the parent rock in the profile. The K$_2$O mobility decreased below the red soil layer and increased in the topsoil layer with the decrease in depth, and the lowest K$_2$O mobility is at the top of the red soil layer and the bottom of the topsoil layer, that is, the K$_2$O leaching degree is highest at the top of the red soil layer and the bottom of the topsoil layer. As mentioned above, the whole profile experienced substantial weathering and leaching, and the leaching of SiO$_2$, Na$_2$O, and K$_2$O is great, while that of Fe$_2$O$_3$, Al$_2$O$_3$, and MgO is relatively less and CaO is relatively enriched.

4.2. Weathering strength index

(1) The Shazi profile

The CIA value of the Shazi profile ranged from 83.2% to 97.38%, with an average of 94.75%, and the weathering intensity is enhanced by chemical weathering in a hot and humid environment. Figure 10 shows that from the semiweathered basalt to the topsoil layer, the CIA showed a trend that initially increased and then decreased subsequently. The maximum value of CIA is concentrated in the red soil layer, indicating that the red soil layer is the most weathered area in the profile. The trend of Sa and Saf in the profile is quite complex, with a large fluctuation below 1.9 m and the most obvious fluctuation up and down the iron layer, ranging from 1.61–3.32 to 0.34–2.0, respectively. Yet above 1.9 m, it presents an increasing trend (Figure 10). Although the Sa and Saf content of the profile vary greatly, most of the lowest values are concentrated in the red soil layer, indicating that the degree of
desilication, iron, and aluminum enrichment in the red soil layer is relatively higher than that in other layers. Its weathering degree is also higher than in other layers.

![Figure 10](image)

**Figure 10** The variation of weathering strength characteristics of the Shazi profile

(2) The Dougu profile

The CIA value of the sand profile ranged from 79.76% to 93.85%, with an average of 89.75%. The overall weathering intensity reaches the enhanced academic weathering stage and is lower than the CIA value of the sand weathering profile (94.75%); that is, the weathering intensity of the Dougu profile is lower than that of the sand profile. From the trend of CIA value change, the maximum value of CIA is concentrated in the top of the red soil and the bottom of the topsoil (Figure 11). The values of Sa and Saf vary significantly in the topsoil layer, but with little change below the topsoil layer. The minimum values of Sa and Saf are mainly concentrated at the top of the laterite layer and the bottom of the topsoil layer. Therefore, the top of the red soil layer and the bottom of the topsoil layer are the layers with a substantial weathering degree in the section.

![Figure 11](image)

**Figure 11** The variation of weathering strength characteristics of the Dougu profile

4.3. The relationship between rare earth element content and major elements

The content of ΣREE in the Shazi and the Dougu profiles is significantly different from that of the Ce element, and the content of the Ce element has a good correlation with the major elements. The strong positive anomaly of δCe in the Shazi profile also indicates differences in properties between Ce and other rare earth elements. Therefore, this study did not consider the Ce element content in the correlation analysis of the ΣREE element content and the constant element.
Table 1 Correlation coefficients ($R^2$) between REE contents and respective contents of K$_2$O, Al$_2$O$_3$, TiO$_2$, Fe$_2$O$_3$ of samples

| Shazi profile     | Al$_2$O$_3$ | Fe$_2$O$_3$ | TiO$_2$ | K$_2$O |
|-------------------|-------------|-------------|---------|--------|
| Ce                | 0.21396     | 0.14598     | 0.33807 | 0.09206|
| ΣREE              | 0.02854     | 0.00115     | 0.03596 | 0.092  |
| ΣREE (except Ce)  | 0.08463     | 0.2412      | 0.2948  | 0.25147|

| Dougu profile     | Al$_2$O$_3$ | Fe$_2$O$_3$ | TiO$_2$ | K$_2$O |
|-------------------|-------------|-------------|---------|--------|
| Ce                | 0.05271     | 0.2383      | 0.21467 | 0.05649|
| ΣREE              | 0.27515     | 0.38799     | 0.32299 | 0.02952|
| ΣREE (except Ce)  | 0.2784      | 0.4299      | 0.50977 | 0.00751|

The content of ΣREE (without Ce) in the Shazi profile does not correlate with Al$_2$O$_3$. Still, it has a significant positive correlation with K$_2$O ($p > 0$) and a weaker negative correlation with Fe$_2$O$_3$ and TiO$_2$ content ($p < 0$) (Figure 12). On the other hand, the content of Σ REE. The different correlations between REE and other elements in the two profiles suggests significant differences in secondary minerals, especially clay minerals, and the weathering intensity of the profiles is different.

The contents of Sc elements in the Shazi profile and the Dougu profiles are significantly positively correlated with Fe$_2$O$_3$, Al$_2$O$_3$, and TiO$_2$ ($p > 0$), particularly with TiO$_2$. In the Shazi profile, the order of correlation from high to low is TiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$ (Figure 13). Fe, Al, Ti, and Sc are typical inert elements. During weathering, the leaching of Si, Ca, Mg, Na, and K, Fe, Al, Ti, and Sc are relatively enriched in the weathering crust, but their geochemical behaviors are slightly different. In basalt, Fe and Al are the basic components of pyroxene and plagioclase, respectively. Fe forms iron oxide and iron hydroxide with the decomposition of pyroxene and plagioclase, while Al mainly exists in clay minerals such as montmorillonite and kaolinite, forming weathered residual deposits. Before and after basalt weathering, Ti primarily exists in the form of titanium oxide, so Ti is the most stable existence and can form weathering residual-slope deposit. Scandium in basalt exists mainly as isomorphism in pyroxene [26][27]. In the process of weathering, Sc can exist not only in montmorillonite in isomorphism but also as iron oxide or hydroxide in the form of adsorption. Its deposit type is residual. According to Figure 13, the relationship between Sc and Ti is the closest, indicated during weathering. Although the geochemical behaviors of Sc and Ti are not consistent, the enriched horizons are the same.
Figure 12 Correlations between ΣREE (without Ce) contents and respective contents of some major elements of samples

Note: a, b, c, and d are Shazi profile samples, e, f, g, and h are Dougu profile samples.
Figure 13 Correlations between Sc contents and respective contents of different major elements of samples

Note: a, b, c, and d are Shazi profile samples, e, f, g, and h are Dougu profile samples.
5. Conclusions

(1) The results on major elements showed that both the Shazi and the Dougu profiles have experienced an intense action of alkali dissolution, desilication, and enrichment of iron, aluminum, titanium.

(2) The two profiles exhibited very high values of silica-alumina ratio (Sa), silica sesquioxide ratio (Saf), and CIA, with extremely low concentrations of CaO, Na₂O, MgO, and K₂O compared to that of the fresh basalt.

(3) The rare earth elements in the Shazi profile have significant positive δCe anomalies, indicating that the Shazi profile is formed in a strong oxidation environment. However, from the weak negative anomalies of δCe and δEu in the Dougu profile, the redox environment of the Dougu profile is not indicative of a strong oxidation environment.

(4) The Sc in the Shazi and the Dougu profiles is enriched relative to its parent rock in the weathering crust, and the enrichment is most visible in the red soil layer. The enrichment degree of Sc is more substantial in the Shazi profile with higher Sc content in the parent rock.

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