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Fluvial geomorphology and weathering crust controls on ion-adsorption rare earth element mineralization in Northwestern Vietnam

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ABSTRACT

Weathering plays an important role in redistributing rare earth elements (REEs) in near-surface environments, particularly within weathering crusts where primary minerals are gradually altered into secondary phases. Evaluating spatial variations in weathering intensity can therefore help identify regions with potential REE enrichment. In this study, provides new constrains on the weathering potential of northwestern Vietnam based on quantitative geomorphologic data, including normalized steepness index (k_{sn}), and erosion rate from fluvial shear stress. The results show that k_{sn} values are significantly higher in the upstream region of the Da River than in downstream areas. Erosion rates calculated from fluvial shear stress display a consistent spatial pattern, showing higher values in the upstream region. Since non-tectonic factors such as lithology play a minor role on the spatial variation of geomorphic analyses, the coincidence of high k_{sn} values and elevated erosion rates suggests relatively stronger tectonic activities and higher weathering potential in the upstream region. Considering the relationship between weathering processes and REE redistribution in weathering crusts, these geomorphic constraints imply differences in REE accumulation along the Da River. We therefore infer that upstream areas, such as Lai Chau, are likely to contain lower REE concentrations than downstream regions where weathering products can accumulate and be preserved more effectively.

Keywords *Northwestern Vietnam region, Normalized steepness index, Fluvial erosional rate, potential weathering process*

1. Introduction

In modern industries, REEs are considered essential metals and valuable natural resources due to their wide applications in high-technology and renewable energy systems (Haxel, 2002). Understanding the processes controlling the distribution and enrichment of REEs is therefore important for resource assessment and exploration. Weathering plays a key role in the redistribution and accumulation of REEs by breaking down REE-bearing minerals, mobilizing these elements, and subsequently concentrating them within weathering crusts and soil profiles. The intensity of weathering can strongly influence the spatial distribution of REEs (e.g., Braun et al., 1998). In regions characterized by intense weathering, prolonged chemical alteration promotes the dissolution of primary REE-bearing minerals and enhances the mobilization and leaching of these elements, often resulting in relatively low REE concentrations (e.g., Braun et al., 1998). In contrast, areas with weaker weathering intensity tend to preserve primary minerals and limit chemical leaching, leading to relatively higher REE concentrations (e.g., Bao and Zhao, 2008). The correlation between weathering process and REE abundance provides an important basis for assessing rare earth element potential based on the evaluation of regional weathering intensity.

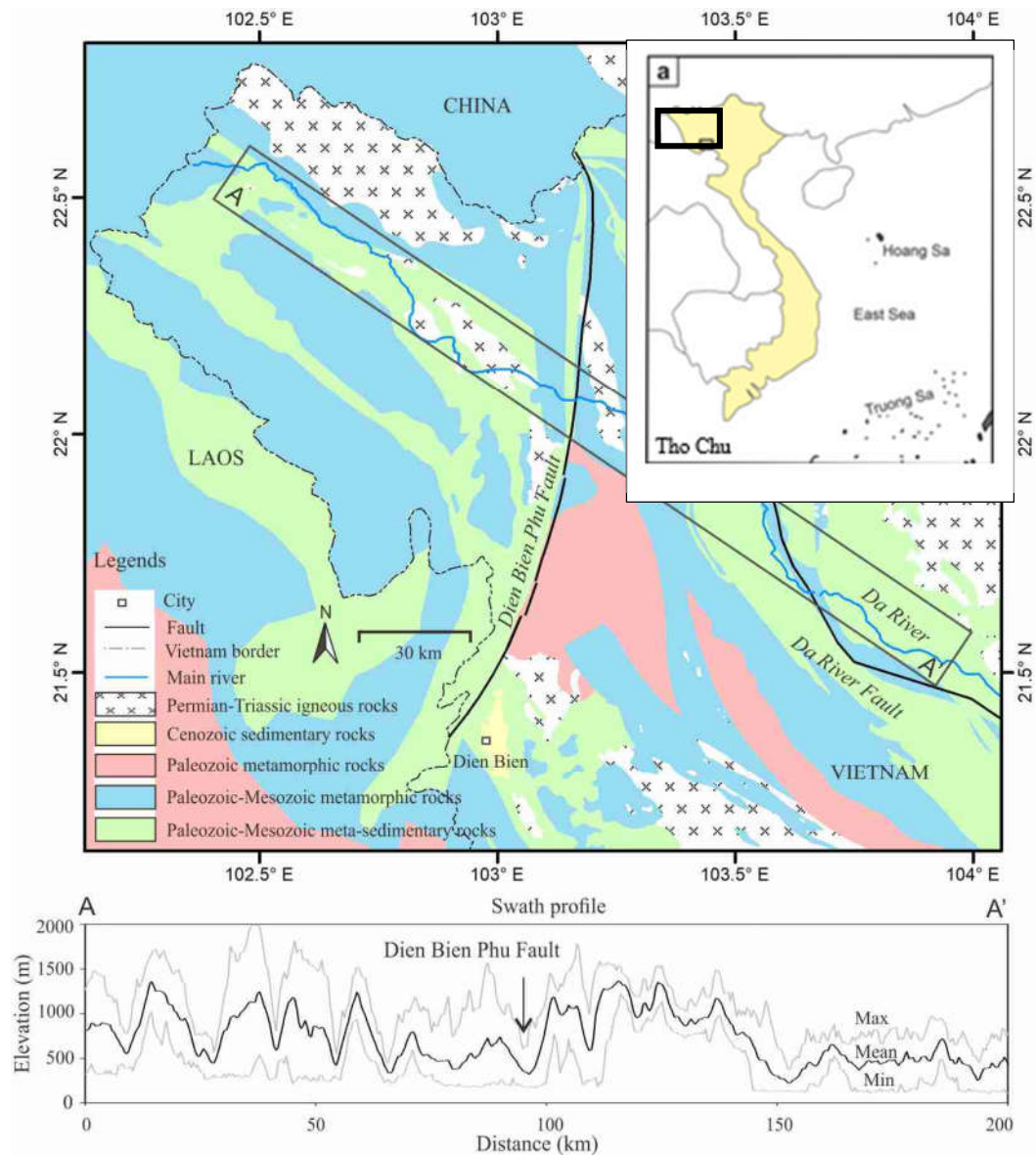


Figure 1. (a) Simplified geological map of the study area with locations of Da River with approximate location of the study area (b) Topographic swath profile AA' along the Da River showing minimum, mean, and maximum altitude and location of the Dien Bien Phu Fault indicated by arrow symbol.

Recent advances in technology have significantly improved our ability to observe and analyze the Earth's surface. In particular, the availability of high-resolution digital elevation model (DEM) data provides unprecedented opportunities to investigate landscape morphology and surface processes. Geomorphic indices derived from DEM data allow researchers to quantify topographic characteristics and infer erosion dynamics and landscape evolution at regional scales. Because surface processes such as erosion and topographic development are closely linked to weathering processes, geomorphic analysis can provide valuable insights into the spatial distribution of weathering intensity. In this study, we apply geomorphic analysis to evaluate the weathering potential of northwestern Vietnam. Specifically, we use geomorphic indicators, including the normalized channel steepness index (k_{sn}) and erosion rate, to identify spatial variations in erosion and landscape dynamics across the region. By analyzing these geomorphic signatures, we aim to infer regional variations in weathering intensity and discuss

their implications for the potential distribution of rare earth elements within weathering crusts in northwestern Vietnam.

2. Methods

2.1. Normalized steepness index analysis

The normalized channel steepness index (k_{sn}) is widely used to extract tectonic information from topography and to infer spatial variations in rock uplift rates (Whipple et al., 2007; Wobus et al., 2006). Higher k_{sn} values generally indicate higher relative uplift rates and have been widely applied to investigate active tectonic regions (e.g., Dinh et al., 2025, 2022, 2021; Nsangou et al., 2022). This method is based on the statement that the change in elevation of a river is the result of interaction between erosion and uplift that can be expressed as the following equation:

$$dz/dt = U(x,t) - KA^m S^n \quad (1)$$

Where dz/dt is the change in elevation through the time; $U(x, t)$ is the rock uplift rate relative to a fix base level; K is the erosion coefficient; A is upstream drainage area; S is gradient; and m, n are positive constants. Under a steady state ($dz/dt=0$), the equation (1) can be rewritten as:

$$S = [U(x,t)/K]^{1/n} A^{-m/n} = k_s A^\Theta \quad (2)$$

Where Θ indicates the concavity index; $[U(x,t)/K]^{1/n}$ is steepness index, k_s . To compare steepness of different rivers, the river steepness can be converted to normalized steepness index (k_{sn}) by using a reference concavity (Θ_{ref}).

2.2. Erosional rate from fluvial shear stress

Erosion rates were estimated using the fluvial shear stress method following Ye et al. (2022). The fluvial shear stress of river (τ) depends on water density, gravity, channel slope, discharge, and channel width, while discharge was estimated from drainage area and annual precipitation using a power-law relationship. The fluvial shear stress of river (τ) can be converted to a non-dimensional parameter, Shields stress (τ^*), which is linearly related to erosion rate:

$$I_i = K (\tau^* - \tau_c^*)$$

Where K is erodibility; τ_c^* is the critical Shields stress values (~ 0.03). Using topographic and hydrological parameters, spatial variations in shear stress and erosion rates were calculated.

3. Results

3.1. Normalized steepness index value

To compare different areas along the Da River, the normalized channel steepness index (k_{sn}) has been calculated for the entire river network with a reference concavity of 0.45. To avoid having an anomalously high k_{sn} along the main trunk, we set up the calculated rivers with a stream order smaller than 4 and a drainage area greater than 10^6 m^2 . The spatial distribution of k_{sn} values is shown in Figure 2 and reveals a clear contrast between the upstream and downstream sections of the Da River. The high k_{sn} values of higher than 200 $\text{m}^{0.9}$, shown by the orange and red colors in Figure 2C, mainly concentrated in the upstream region on the NW side of the Dien Bien Phu Fault. In contrast, the downstream area is dominated by relatively low k_{sn} values (50 to 150 $\text{m}^{0.9}$), represented by green to yellow colors. To further constrain about spatial distribution of k_{sn} , the calculation of k_{sn} values was also carried out along the main trunk of the Da River (Figure 2E). The upstream segment on the SW side of the fault has a k_{sn} value of $\sim 22 \text{ m}^{0.9}$, whereas the downstream segment on the NE side shows a lower value of

~10 m/0.9. Overall, the higher k_{sn} values upstream suggest relatively higher uplift rates in the upper Da River region.

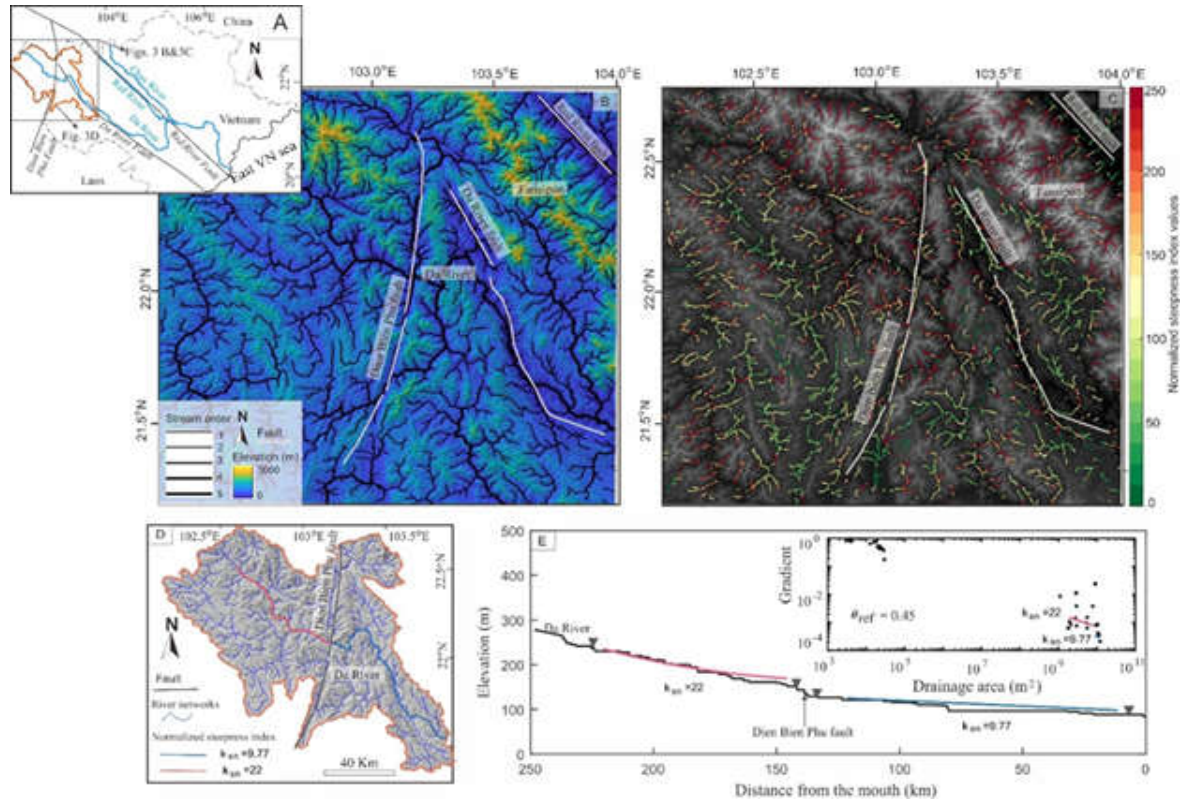


Figure 2. Normalized steepness index for the northwestern Vietnam regions cross the Dien Bien Phu fault. (A) General tectonic sketch of northern Vietnam with distribution of major faults and rivers across the regions. (B) Topographic map showing the stream order of the drainage network. (C) Shaded relief map of normalized steepness index values calculated along all streams with the order lower than 4. (D) Shaded relief map of normalized steepness index values calculated along the Da River. (E) Longitudinal profile of the Da River (black line) and the values of calculated normalized steepness index along the river (color lines). Blue and red lines indicate different values of normalized steepness index. Black triangles indicate the start and the end of the regression segments along the profile. Upper right rectangular represents log-log plots of gradient and drainage area data.

3.2. Erosional rate from fluvial shear stress

The erosional rate values determined from fluvial shear stress were calculated along the Da River across the NW and SE sides of the Dien Bien Phu fault. The results of erosional rate values are presented in Figure 3. In general, the high values of erosional rate, shown by dark blue color, are predominantly observed in the upstream segment on the SW side of the fault. Specifically, erosion rates in the upstream area range from 0 to 2.0 mm/yr, whereas downstream values are significantly lower, ranging from 0 to 0.6 mm/yr. Overall, the higher erosion rates upstream suggest more intense fluvial incision in this sector, likely reflecting stronger tectonic uplift and greater weathering potential.

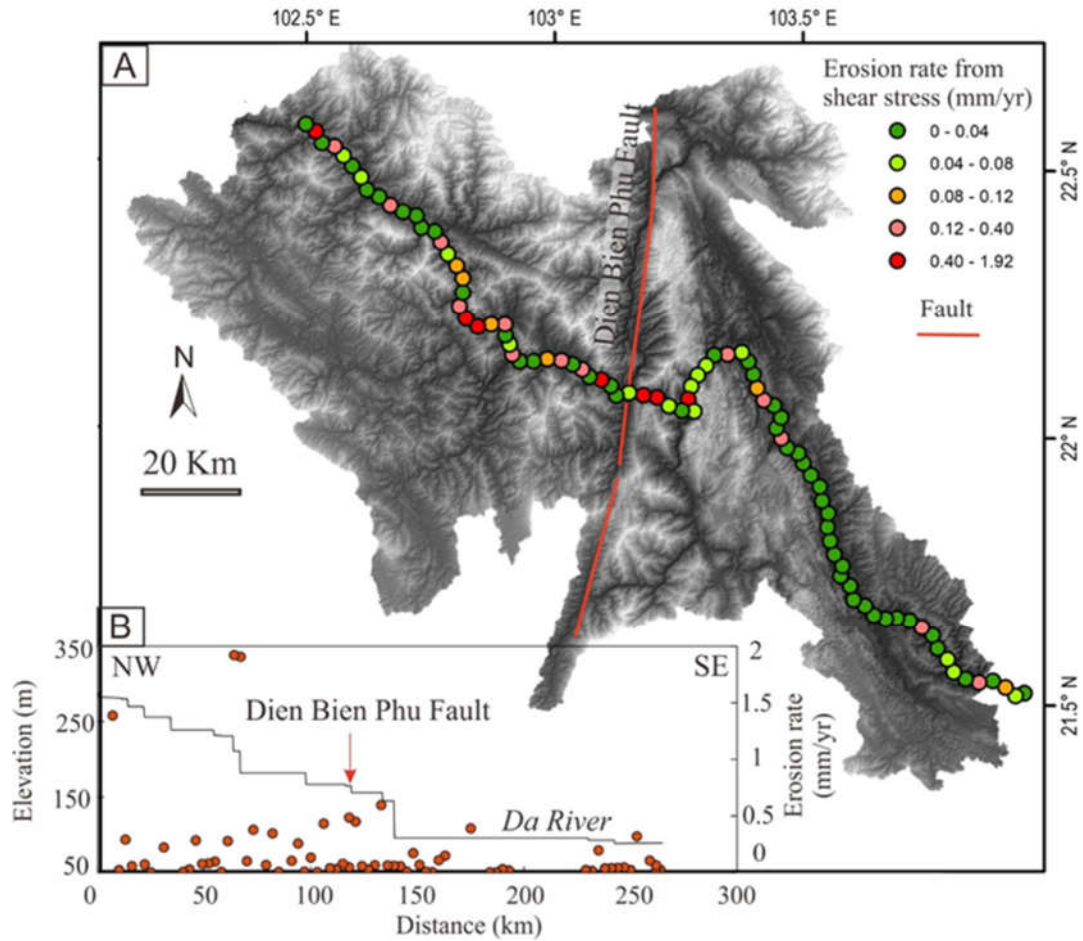


Figure 3. Erosion rate from shear stress along the Da River. (A) Shaded relief map with distribution of erosion rate values across the Dien Bien Phu fault. Different colors of circles represent different values of erosion rate. (B) Longitudinal river profile of Da River (black line) with distribution of erosion rate values (orange circle) across the Dien Bien Phu fault.

4. Discussion

Key observations emerging from our geomorphic analyses include: (1) high k_{sn} values are predominantly concentrated in the upstream region of the Da River, located on the NW side of the Dien Bien Phu Fault (Figure 2); and (2) erosion rates estimated from fluvial shear stress are higher on the NW side of the fault than on the opposite side (Figure 3). Besides tectonic factors, effects from lithology and climate have to be discussed for the spatial variation of normalized steepness index. Different lithology and climate (particularly precipitation variations) settings can alter the shape of river profile and thus may affect values of k_{sn} in the study area. Data compiled from the official geological map (Figure 1) and the published literatures (e.g., Lai et al., 2012; Roger et al., 2014) show that metasedimentary rocks are common rock type distributed in almost all the entire study area; therefore, lithology effects are considered insignificant in the variations of k_{sn} values. Regional precipitation data (Do et al., 2020) demonstrates that no substantial changes exist in rainfall amount across northwestern Vietnam with an average annual precipitation value of around 1500-1800 mm/yr. Therefore, non-tectonic factors including lithology and climate alone are unable to account for the observed k_{sn} value changes in our study area. In other words, tectonics is likely to be the main factor for differential k_{sn} values in the study area and thus, the concentrated distribution of high k_{sn} values on upstream regions implies a relatively higher uplift rate on upstream compared to

downstream. The spatial correspondence between regions of high uplift rates and elevated erosion rates on upstream of Da River is consistent with the widely documented positive relationship between tectonic uplift and erosion in many active orogenic systems, such as along the eastern margin of the Tibetan Plateau (e.g., Cook et al., 2018) and in the northern Andes (e.g., Ott et al., 2023). This relationship reflects the tendency for landscapes to approach a dynamic equilibrium between tectonic uplift and erosional denudation, whereby increased rock uplift is accompanied by enhanced erosion. Accordingly, the elevated erosion rates and normalized channel steepness indices observed in the upstream portion of the Da River may also indicate intensified weathering processes in these areas. In regions with high weathering intensity, stronger chemical alteration and surface denudation accelerate the breakdown of REE-bearing primary minerals and enhance the leaching and transport of released elements. These processes can increase the removal of REEs from the weathering profile through runoff and sediment transport, thereby limiting their local concentration. Consequently, regions characterized by high erosion rates and strong weathering are less favorable for REE accumulation. In this context, the upstream region of the Da River- where elevated k_{sn} values and erosion rates are observed- may represent areas with relatively low potential for REE enrichment due to the enhanced removal and redistribution of REEs during intense weathering and erosion processes. Based on these geomorphic observations, we propose preliminary inferences regarding the spatial potential for REE enrichment derived from geomorphic analysis. However, these interpretations remain indirect and should be considered as a first-order assessment. More detailed investigations, such as direct measurements of REE concentrations in soils, regolith, and sediments across different geomorphic settings, are necessary to further evaluate and validate these interpretations. Such geochemical analyses, combined with detailed field investigations, would provide a more comprehensive understanding of the distribution and enrichment potential of rare earth elements in Vietnam.

Conclusion

Geomorphic analyses of the Da River region show that high k_{sn} values and elevated erosion rates are predominantly concentrated in the upstream area, on the northwestern side of the Dien Bien Phu Fault. This spatial correspondence likely reflects zones of intensified weathering processes in the upstream region. Enhanced weathering may accelerate the breakdown of REE-bearing minerals and increase the leaching and transport of rare earth elements (REEs), thereby limiting their local accumulation. Consequently, areas characterized by high k_{sn} values and strong erosion are likely to have relatively low potential for REE enrichment. These results provide a first insight on spatial distribution of REE potential in northwestern Vietnam. However, further studies, including direct geochemical measurements of REE concentrations are necessary to better constrain the distribution and enrichment potential of REEs in the region.

Acknowledgements

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