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ORIGINAL ARTICLE

Uranium comminution age responds to erosion rate semi-quantitatively

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Abstract Here we present ($^{234}U/^{238}U$) data from river sediments collected on the Tibetan Plateau. The ($^{234}U/^{238}U$) ratios of a specific grain size fraction show good correlation with erosion rates, which were determined by in-situ–produced cosmogenic nuclides. This correlation has previously been observed in a wide range of geomorphic settings, suggesting that ($^{234}U/^{238}U$) ratios of fluvial sediments have great potential to quantify erosion rates.

Keywords Uranium isotope · Catchment erosion rate · Tibetan Plateau · Surface process

1 Introduction

Quantifying erosion rates are of critical importance in understanding the interaction between tectonic activity, weathering processes, and climate. The Tibetan Plateau (TP) and its bordering mountains cover an area of more than 2.5 million km^2 with an average elevation over 5000 m. Due to its unique geomorphology and recent uplift, the TP has been the favored region for study of erosion processes. Many techniques have been used to study erosion rates on the TP, one of which is based on in situ–produced cosmogenic nuclides (^{10}Be) (Chappell et al. 2006; Li et al. 2014; Ouimet et al. 2009; Pan et al. 2007; West et al. 2014). Cosmogenic ^{10}Be concentration is approximately proportional to its cumulative local production rate and inversely proportional to erosion rate. However, ^{10}Be analysis requires the verification of many assumptions and the process is time-consuming and expensive (Dosseto and Schaller 2016), which may limit its wide application in studying erosion rates.

Uranium isotopes of fine particles, which can record comminution age since particles' separation from bedrock (DePaolo et al. 2006), have potential to quantify regolith production rates. The mechanism is based on the recoiling effect during α-decay of ^{238}U and recoil loss of the decay product ^{234}Th, the precursor of ^{234}Pa and subsequently of ^{234}U (DePaolo et al. 2006). The uranium activity ratio, normally expressed as ($^{234}U/^{238}U$), is expected to decrease with increasing comminution age, according to the following expression (DePaolo et al. 2006):

$$\left({}^{234}\mathrm{U}/{}^{238}\mathrm{U}\right)_{\mathrm{t}} = 1 - f \times \left(1 - \mathrm{e}^{-\lambda_{234} t}\right) \quad (1)$$

where t is the comminution age, f is the fraction of daughter ^{234}Th ejected out of the particle surface, and λ_{234} is the radioactive decay constant of ^{234}U. Because different transport paths correspond to different comminution ages. The ($^{234}U/^{238}U$) ratios of fine particles, which can trace surficial processes of sediments including storage in the weathering profile, hillslope and fluvial transport, and final deposition, have great potential to quantify erosion rates. Here we examine the relationship between ($^{234}U/^{238}U$) and erosion rates using river sediments from the TP.

2 Study area and methods

We collected nine river sediment samples on the TP in locations where erosion rates had previously been calculated by the ^{10}Be method (Table 1).

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The fractional loss rate of ^{234}U is clear only when mineral grains are sufficiently small (DePaolo et al. 2012; Li et al. 2017). Grains with a diameter between 20 and 25 µm were isolated by electroformed sieves. Diluted acetic acid solution and 5% hydrogen peroxide were used to remove carbonate minerals and organic matter, respectively. Fe–Mn oxides were removed through reductive leaching using the citrate-bicarbonate-dithionite method (Mehra and Jackson 1958). The uncertainty of the whole procedure is ±0.004 (2σ) (Li et al. 2017).

About 100 mg of each of the cleaned samples was dissolved in 4 ml 1:1 mixture of HNO_3 and HF solution. Uranium in the digested solution was separated using UTEVA resin. ($^{234}U/^{238}U$) ratios were measured using a newly launched MC-ICP-MS (Neptune plus, Thermo-Fisher Scientific) at MOE Key Laboratory of Surficial Geochemistry, Department of Earth Sciences, Nanjing University. Signals of ^{235}U and ^{238}U were monitored using Faraday cups and that of ^{234}U was monitored using a secondary electron multiplier (SEM). The ($^{234}U/^{238}U$) value was calculated using decay constants of 2.82206×10^{-6} and 1.55125×10^{-10} a^{-1} for ^{234}U and ^{238}U, respectively (Cheng et al. 2013). The 2σ standard deviation of the ($^{234}U/^{238}U$) ratio given by the MC-ICP-MS was 0.001. Instrumental bias between ^{234}U and ^{238}U was corrected by normalizing the $^{238}U/^{235}U$ ratio to 137.84 (Andersen et al. 2017). Repeated measurements of the USGS BCR-2 standard material gave a mean SSB value of 1.001 ± 0.002 (n = 21, Li et al. 2017).

3 Results and discussion

The ($^{234}U/^{238}U$) of river sediments and catchment erosion rates measured by the ^{10}Be method are listed in Table 1. A good correlation was observed between ($^{234}U/^{238}U$) and erosion rates (Fig. 1a), suggesting that uranium comminution age of fine particles can reflect the erosion rate of the catchment. However, there was an outlier (site 8), whose erosion rate calculated from ($^{234}U/^{238}U$) was conspicuously higher than that determined by the ^{10}Be method. The large drainage area (3340 km^2) of this river may be

Table 1 Positions, measured ($^{234}U/^{238}U$), and erosion rates of river sediment sample sites on the Tibetan Plateau

Sample ID	Latitude (°N)	Longitude (°E)	($^{234}U/^{238}U$)	Erosion rate (mm/year)	Reference[a]
Site 1	31.03	101.86	0.995	0.364 ± 0.036	Ouimet et al. (2009)
Site 2	31.42	102.05	0.967	0.156 ± 0.012	
Site 3	30.95	101.72	0.995	0.256 ± 0.023	
Site 4	30.68	101.74	1.001	0.489 ± 0.057	
Site 5	29.73	101.51	0.954	0.056 ± 0.017	
Site 6	29.51	101.43	0.985	0.225 ± 0.067	
Site 7	32.93	103.28	0.941	0.05 ± 0.005	Ansberque et al. (2015)
Site 8	35.89	94.36	0.981	0.0217 ± 0.002	Li et al. (2014)
Site 9	33.87	92.36	0.937	0.0368 ± 0.003	

[a] The references wherein erosion rate was determined

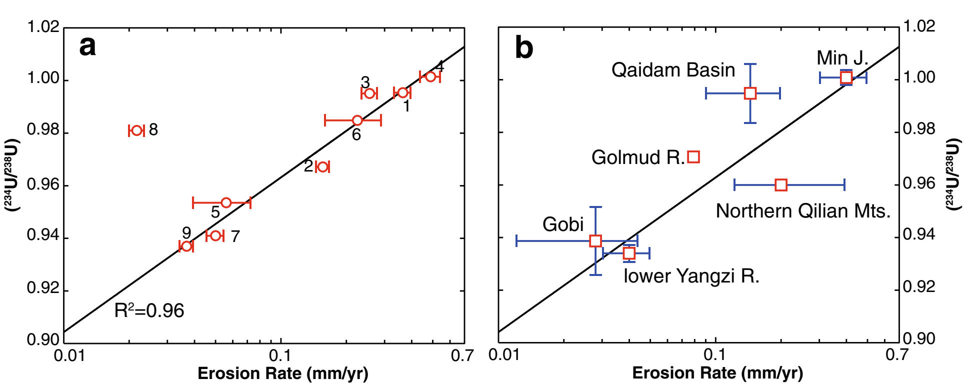

Fig. 1 Correlation between ($^{234}U/^{238}U$) and erosion rates. **a** *Red circles* are samples from the Tibetan Plateau. The *black line* is the best fit to all samples excluding site 8; **b** data sources of erosion rates: Min Jiang (West et al. 2014); Qaidam Basin (Rohrmann et al. 2013); Golmud River (Li et al. 2014); Northern Qilian mountains (Palumbo et al. 2011); Gobi (Jolivet et al. 2007); Lower Yangzi River (Chappell et al. 2006). The *black line* is the same as that in **a**. *Error bars* in **a**, **b** show 2× standard deviation of the mean (2σ)

responsible for the inconsistency (Li et al. 2014). In site 8, shallow landslides and anthropogenic disturbance (farming, roads, mining, etc.), may have led to relatively high ($^{234}U/^{238}U$) values due to sediments' having been exposed for a long time, but only having broken very recently.

We also measured ($^{234}U/^{238}U$) ratios of samples from other regions where erosion rates had been previously determined by cosmogenic nuclides. We found that the variation of ($^{234}U/^{238}U$) was consistent with erosion rates determined by the ^{10}Be method, albeit with a more scattered pattern (Fig. 1b), which can be attributed to the different clock mechanisms of the two methods (Dosseto and Schaller 2016). For uranium, when the fine particles are separated from bedrock, the U-isotope clock starts "ticking". In contrast, in situ–produced cosmogenic nuclides start accumulating in the regolith only when the particles are brought within 2–3 m of the Earth's surface (Dosseto and Schaller 2016). As a result, the combination of uranium isotopes and cosmogenic nuclides may contribute to a more comprehensive understanding of the Earth's surface system.

4 Conclusions

Uranium comminution age may have great potential to quantify erosion rates; further investigation is necessary.

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