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# Regolith evolution on the millennial timescale from combined U–Th–Ra isotopes and in situ cosmogenic $^{10}Be$ analysis in a weathering profile (Strengbach catchment, France)

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ABSTRACT

U–Th–Ra disequilibria, cosmogenic in situ $^{10}Be$ concentrations and major and trace element concentrations have been analyzed in a 2 m-deep weathering profile sampled at the summit of the granitic Strengbach catchment (France). The data have been used to independently estimate both the long-term regolith production and denudation rates and the weathering and erosion rates. Modeling of the $^{238}U$–$^{234}U$–$^{230}Th$–$^{226}Ra$ disequilibrium variations in the lower part of the profile yields a regolith production rate of $12 \pm 4$ mm/kyr ($30 \pm 10$ T/km$^2$/yr), while modeling of the high-resolution $^{10}Be$ concentration profile leads to an exposure age of $19.7 \pm 2.2$ kyr, an inherited concentration of 15,000 $\pm$ 1,000 at/g in quartz and a mean denudation rate of $22 \pm 10$ mm/kyr ($37 \pm 15$ T/km$^2$/yr). The consistency between production and denudation rates suggests that, on a millennial timescale, the regolith mass balance at the summit of the catchment is close to a steady state, even if the watershed may have been impacted by Quaternary climatic changes and by recent anthropogenic perturbations (e.g., 20th century acid rain and recent afforestation efforts). The results also indicate that physical erosion is likely the dominant long-term process of regolith denudation in the catchment. Furthermore, the comparison of the long-term production and denudation rates and of weathering and erosion rates determined from the depth profile analyses with the current weathering and erosion rates estimated at the outlet of the watershed based on monitoring of the water chemistry and sediment fluxes suggests that physical erosion may have varied more than the chemical weathering flux during the last 150 kyr. Although very few other sites with U-series, in situ $^{10}Be$ and stream monitoring data are available for comparison, the current data suggest that (1) the mass balance steady state of regolith might be commonly achieved in soil mantled landscapes, and (2) physical erosion has varied much more than chemical weathering in mid-mountain catchments over the last 10–150 kyr. These results highlight the importance of the combined analysis of U-series nuclides and in situ $^{10}Be$ in the same weathering profile for the determination of key geomorphic parameters, which are important to constraining landscape stability and the responses of landscapes to natural or anthropogenic forcing.



## 1. Introduction

Regolith production and denudation rates, which correspond to the rate at which bedrock is weathered into mobile regolith and removed by chemical and physical processes, are key parameters in the evaluation of landscape stability and the responses of landscapes to natural or anthropogenic forcing (e.g., Brantley et al., 2007; Banwart et al., 2011). The analytical developments made over the last decades for precisely analyzing the U-series nuclides (i.e., $^{238}U$–$^{234}U$–$^{230}Th$) in geological and environmental samples have led to the development of the study of U-series nuclides in soils and weathering profiles and to the definition of a theoretical framework for quantifying regolith production rates from the variations in radioactive disequilibria along a weathering profile (Dequincey et al., 2002; Chabaux et al., 2003, 2013; Dosseto et al., 2008, 2012; Ma et al., 2010). These studies were mainly

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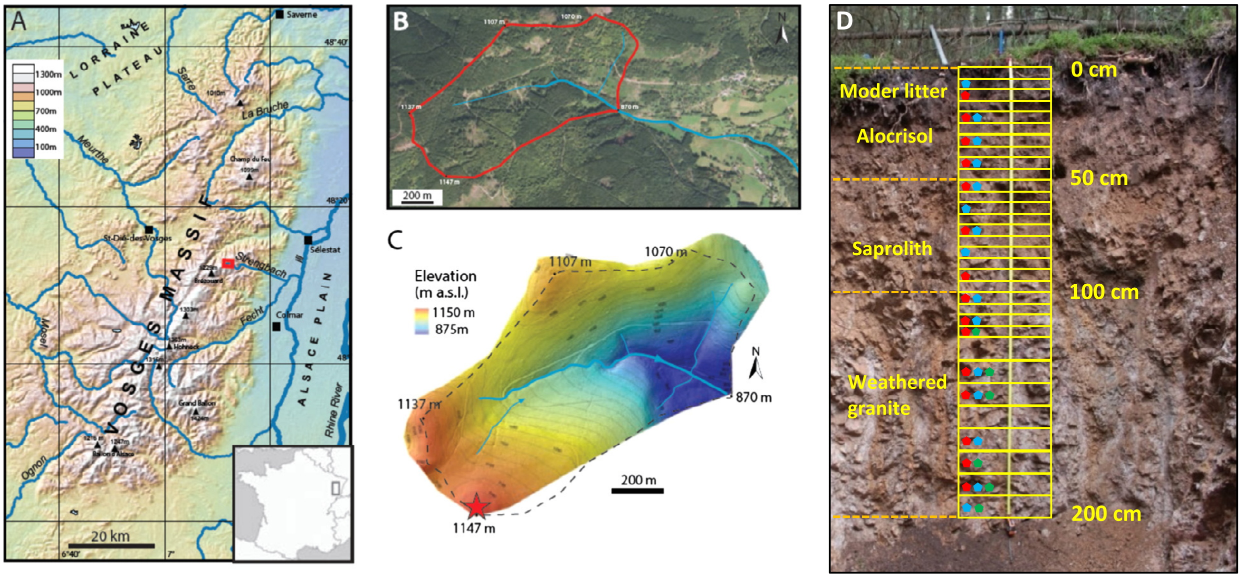


**Fig. 1.** a) Regional map of the Vosges massif and location of the Strengbach catchment. b) Contour of the Strengbach watershed. c) Topographic map of the Strengbach watershed and location of the studied weathering profile (map from OHGE). d) Sampling of the weathering profile. The pedological observation led to division of the weathering profile into 3 zones: the soil from 0 to 50 cm, the saprolite from 50 to 100 cm and the granitic weathered bedrock from 100 to 200 cm. Each box in the column represents a collected sample. Red and blue dots indicate samples for which isotopic U–Th–Ra and in situ $^{10}$Be analyses have been performed, respectively. Green dots indicate samples for which thin sections have been performed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

based on the analysis of $^{238}$U–$^{234}$U–$^{230}$Th nuclides and the use of the activity ratios ($^{234}$U/$^{238}$U)–($^{230}$Th/$^{234}$U) (activity ratios will be noted hereafter with parentheses). More recently, some studies have also included the analysis of the $^{226}$Ra nuclide and hence the use of the ($^{226}$Ra/$^{230}$Th) ratio (Chabaux et al., 2013; Gontier et al., 2015). Similarly, the in situ $^{10}$Be depth profile methodology has enabled the estimation of both exposure age and mean denudation rate from cosmogenic isotope inventories (e.g., Brown et al., 1995; Braucher et al., 2009). This approach has been widely used to constrain the ages of alluvial terraces and fans (Anderson et al., 1996; Schaller et al., 2002; Brocard et al., 2003), as well as the long-term denudation rates of regolith (Small et al., 1999; Heimsath et al., 2000; Ferrier and Kirchner, 2008; Cui et al., 2016). However, very few studies have combined a detailed analysis of U–Th–Ra isotopes with cosmogenic in situ $^{10}$Be in a single weathering profile extending from the topsoil to the bedrock. It is the aim of this work to highlight the potential of combining these two approaches to independently constrain both production and denudation rates of regolith and to show that information associated with geochemical mobility can be used to discuss the long-term evolution of the regolith.

## 2. Site presentation and sampling strategy

The study is performed on the Strengbach catchment, which constitutes the "Observatoire Hydrogéochimique de l'Environnement" (OHGE), one of the French critical zone observatories (http://rnbv.ipgp.fr). It is a small watershed of 0.8 km$^2$ located in the Vosges massif (northeastern France; Fig. 1A). With altitudes ranging from 883 to 1147 m (Figs. 1B and 1C), the current climate is mountainous-oceanic, with a mean annual rainfall and temperature of 1400 mm and 6 °C, respectively (Viville et al., 2012). The Vosges massif experienced Pleistocene glaciations in a similar way to other central European mountains, such as the Black Forest and the Bavarian Forest (Heyman et al., 2013). In accordance with regional climatic studies (e.g., Leroy et al., 2000), cold conditions probably persisted at the altitude of the Strengbach catchment well after the Late Glacial Maximum (LGM), and the Vosges forest cover likely developed only at the onset of the Holocene. The Strengbach site has been affected by anthropogenic deforestation associated with pastoralism, likely beginning in the Bronze Age and lasting until the end of the 19th century (Etienne et al., 2013). In the 20th century, the lower grazing pressure led to natural and artificial afforestation in several places in the Vosges massif. In the Strengbach catchment, the return to a densely forested cover is due to the planting of spruce stands at the beginning of the 20th century. The catchment is currently covered with a mixed spruce and beech forest interspersed with small clearings. The bedrock is a base-poor late Hercynian granite and is covered by a 50 to 100 cm-thick brown acidic soil (Hyperdystric Cambisol; WRB, 2006). The granitic bedrock was hydrothermally overprinted, with the degree of hydrothermal alteration decreasing from the northern to the southern part of the watershed (Fichter et al., 1998).

To investigate the recent Quaternary weathering of the granitic bedrock and the denudation rate of the soil, a sampling profile has been collected on the summit of the less hydrothermally altered part of the watershed. This location avoids the presence of colluvial deposition and corresponds to the best strategy ensuring that saprolite and soil are genetically linked to the underlying bedrock and likely formed along the main vertical weathering direction. A 2 m-deep and 3 m-wide pit was dug, and the samples were collected in the middle part of the pit front (Fig. 1D). Thirty-two bulk samples of ≈5 kg each were collected along the profile with a sample every 5 cm within the soil and the saprolite and every 10 cm within the fractured bedrock. The large mass collected per sample is necessary to ensure a representative analysis of the weathering profile developed on the coarse-grained granite (Gy, 1992). For each sample in the upper part of the profile (0–100 cm), the fine fraction density was obtained by weighing a known volume of soil sampled with a steel cylinder. The proportion of blocks, defined here as coarse fragments (>10 cm), was estimated via macroscopic description and photos. The bulk density of each sample was then calculated by combining the fine fraction density and the density of blocks with respect to the proportion of blocks in the horizon. For the blocks, a constant density of 2700 kg/m$^3$ is used, on the basis of granitic bedrock density measurements. A sequential crushing and rigorous quartering process was then performed to obtain representative subsamples for min-