U-series nuclides in weathering profiles: Rates of soil processes

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Abstract
The development of U-series nuclides for investigating weathering processes is quite recent, and was significantly stimulated by the analytical improvement made over the last decades in measuring the ^{238}U series nuclides with intermediate half-lives (i.e., ^{234}U-^{230}Th-^{226}Ra). Here it is proposed to review the recent results obtained with the analysis of U-series nuclides in weathering profiles to determine rates of soils processes as well as the age of minerals or concretions that the weathering profile can contain.

Key Words
U-series nuclides, rates of weathering processes, soil mineral dating

Introduction
The time parameter of processes that control the formation and evolution of soils and weathering profiles is a key information to be determined for many questions of the Earth Surface and Environmental Sciences. Such a determination is especially required for constraining and modelling the future evolution of soils and weathering profiles in response to external factors, including the impact of human activity. Radiochronological methods have a real potential for addressing this general issue (e.g., Vasconcelos, 1999; Chabaux *et al*., 2008; Cornu *et al*., 2009).

Here it is proposed to focus on the U-series nuclides, the potential of which for investigating weathering processes is recognized since the1960s with for instance the works of Rosholt *et al*. (1966) and Hansen and Stout (1968). The development of this area of research is however quite recent, and was significantly stimulated by the analytical improvement made over the last decades in measuring the ^{238}U series nuclides with intermediate half-lives (i.e., ^{234}U-^{230}Th-^{226}Ra) using, first, thermal-ionisation mass spectrometric techniques, and, later, MC ICP-MS techniques. The interest of U-series nuclides as tracers and chronometers of weathering processes results from the dual property of the nuclides to be fractionated during water-rock interactions and to have radioactive periods of the same order of magnitude as the time constants of many weathering processes. Recent reviews of the application of U-series nuclides to the study of weathering and river transport can be found in Chabaux *et al*. (2003b; 2008). Here it is proposed to illustrate the interest of the analysis of U-series nuclides in weathering profiles to determine rates of soils processes as well as the age of minerals or concretion the weathering profile can bear.

Determination of regolith formation rates from analysis of U-series disequilibria in weathering profiles
Following the work by Hansen and Stout (1968) it was anticipated that the depth variation of U-series nuclides within a weathering profile could constitute a simple way to estimate the propagation rate of weathering fronts in regoliths. The subsequent studies in this topic (e.g., Boulad *et al*., 1978; Mathieu *et al*., 1995; Dequincey *et al*., 2002) however demonstrated that U-series nuclides in soils and weathering profiles usually follow complex trends as a function of depth, which suggest the occurrence of complex history for U-Th-Ra fractionation in regoliths. These studies clearly show also that the recovery of time information on weathering processes from the analysis of U-series in soils requires a comprehensive understanding of the main processes leading to U-series fractionations in such weathering systems (Chabaux *et al*., 2003a). As exemplified with the study of an African (Kaya) lateritic toposequence (Dequincey *et al*., 2002; 2006; Chabaux *et al*., 2003a), the combination of the study of U-series nuclides in soils with the study of major and trace element concentrations may constitute a simple method to bring important information on the origin of U-Th fractionation in weathering profiles. Such an approach, applied to the case of the Kaya toposequence, has shown that the main mechanisms that control U-Th distribution in the saprolite of this toposequence, is the breakdown of the upper ferruginous duricrusts that induces a downward vertical migration of U in the underlying pedological units. The comparison of the variations of ^{234}U-^{238}U and ^{234}U-^{230}Th disequilibria in the lateritic system, also suggests that both uranium gains and losses occur in each horizon of the profile. The mobility of U and Th isotopes in this system can be therefore modelled by the following equation:

$$\frac{dN_s^i}{dt} = Fi - kiN_s^i - \lambda_i N_s^i + \lambda_{i-1} N_s^{i-1}$$

where, the subscript s refers to soil, N^i represents the number of nuclides i in the soil phase, λ_i is the decay constant of nuclide i, k_i is a first-order constant describing the loss of nuclide i, and Fi is the input Flux of nuclide i gained by the soil. Using the Kaya data and the above modelling yields time information about chemical redistribution linked to the breakdown of the iron cap in this weathering profile (Chabaux *et al.*, 2003a). Similar approaches have been applied to other weathering profiles developed on different parent bedrocks, in Amazon (Chabaux *et al.*, 2006; Pelt, 2007) (Figure 1) and in Puerto Rico (Blaes *et al.*, 2009).

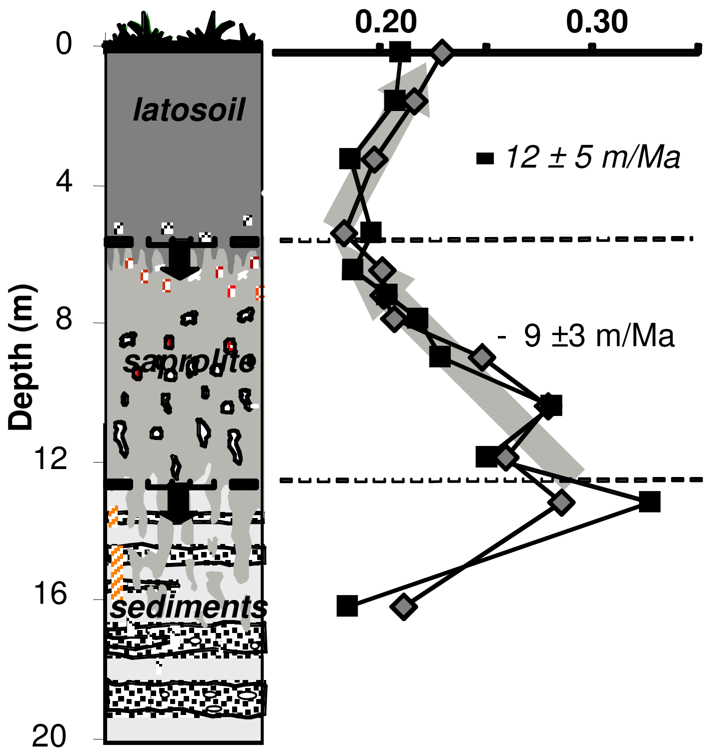

Figure 1 Propagation rate of a weathering front determined by ^{238}U-^{234}U-^{230}Th disequilibrium method in a lateritic profile developed on sediments (Manaus, Brazil) (in. Pelt, PhD Thesis, 2007). Black squares: ($^{230}Th/^{232}Th$) activity ratios; grey diamonds: ($^{238}U/^{232}Th$) activity ratios.

In both cases U-Th data allow to recover the propagation rates of the bedrock weathering front (Figure 1) and to discuss the steady-state situation of these weathering and erosion systems. Recently it was also shown that U-series isotopes can be successfully used to constrain the formation rate of a weathering rind developed on a basaltic clast in a sedimentary Costa Rican terrace (Pelt *et al.*, 2008). All these data clearly demonstrate now that analysis of U-series nuclides in weathering profile constitutes a powerful tool or approach to constrain the regolith production rate in weathering profiles (see also Dosseto *et al.*, 2008). The previous works and results should prompt new research in the field over the coming years.

U-Th Dating of soil minerals

Study of the mineralogical soil fractions can also constitute another means of getting time information on soil processes. U-series nuclides can be indeed used for dating soil minerals or concretions such as pedogenic calcite, pedogenic silica or soil ferruginous concretions and rinds (see review in Chabaux *et al.*, 2008). All these studies more or less rely on the hypothesis that soils and weathering profiles contain minerals and materials that have evolved in closed systems with respect to the U series chain. However the classical dating method used for pure carbonates (Kaufmann and Broecker, 1965) is rarely applicable for soil materials, even for soil carbonates, that usually contain detrital Th. Therefore, U-Th dating of soil minerals requires correction for initial detrital ^{230}Th, following classical methods reviewed for instance in Ludwig (2003). These methods rely on the assumption that soil concretions are mixtures of two isotopically homogeneous end-members, one of which does not contain initial Th. The aim of all the correction methods is to determine the $^{234}U/^{238}U$ and $^{234}U/^{230}Th$ ratios of the Th-free end-member to calculate its age. One approach to recover such ratios is to analyse a suite of coeval sub-samples from the same pedogenic horizon or the same soil samples. This approach has benefited from the analytical performances afforded by TIMS and MC-ICPMS techniques, especially due to the sample size reduction, (and hence sampling resolution), which enable the analysis of sufficiently small size samples to avoid the measurement of composite material with complex history. The more recent development of for *in situ* U and Th isotope analysis methods (e.g., Paces *et al*., 2004; Bernal *et al*., 2005; 2006) certainly constitutes a new and important step in the study and the dating of soil minerals, as already illustrated with accurate in situ U-Th isotope analysis of silicates glasses and iron oxides. These "in situ" studies are only at their initial stages. Their development could nevertheless rapidly renew the study of the weathering profiles and the determination of their formation ages and their history.

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