Nuclear Instruments and Methods in Physics Research B 294 (2013) 484–490

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Determination of muon attenuation lengths in depth profiles from in situ produced cosmogenic nuclides

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ARTICLE INFO

Article history:
Received 6 June 2011
Received in revised form 7 February 2012
Available online 18 May 2012

Keywords:
Cosmogenic nuclides
Muon
Attenuation length
Depth profile

ABSTRACT

Cosmogenic nuclides are important tools to understand and quantify the processes that control the development and evolution of landscapes during the quaternary. Among all published studies, few are related to the accurate and precise determination of the physical parameters governing their production in the Earth's crust surface (in situ produced cosmogenic nuclides) and its evolution as a function of depth below the Earth's surface. Currently, it is nearly impossible to advocate global parameters that could be used worldwide. Indeed, at each sampling site, not only the geometry and the mineralogy will differ but also their evolution as a function of depth. In this paper, a new approach based on the measurement of the evolution of cosmogenic nuclide concentrations along depth profiles to determine the muon attenuation lengths is proposed. Contrarily to previous studies that used to describe both slow and fast muons, only one type of muons will be considered in this paper and nuclide accumulation at depth will be described by a single exponential. The determined attenuation length integrates the potential effect of the chemical composition of the overlying matrix and takes into account the entire energy range of the incident particles. Additionally, when denudational steady state is reached, muon contributions can be determined. When scaled to sea level, these contributions appear to be comparable for a given nuclide whatever the site where they have been determined. The average weighted muon contributions are 0.028 ± 0.004 atoms $g^{-1}\,a^{-1}$ for ^{10}Be, 0.233 ± 0.045 atoms $g^{-1}\,a^{-1}$ for ^{26}Al and 1.063 ± 0.329 atoms $g^{-1}\,a^{-1}$ for ^{36}Cl and are valid within the depth range 0–6500 g cm^{-2}.

1. Introduction

A quick view at the number of publications on cosmogenic nuclides within the last two decades easily reveals their importance in quantifying geomorphological processes such as the timing of deglaciation [1,2], fault activity through the dating of displaced geological features [3] and denudation processes [4]. Most of these studies concern exposure dating or quantification of denudation rates of surface samples only. However, as cosmogenic nuclide concentrations in surface samples are a function of both duration of exposure to cosmic radiation and denudation rate, it is not possible from a single nuclide measurement in a single surface sample to determine simultaneously the exposure duration and the denudation rate. This may be answered with the use of two nuclides assuming a simple exposure history. A more constraining approach to accurately quantify both values (exposure time and denudation rate) is to take advantage of the fact that in situ produced cosmogenic nuclides are formed in the rocks after nuclear reactions induced by two different particles having different physical behavior: the neutrons and the muons. The effective production attenuation length of neutrons is significantly shorter than that of muons. Consequently, the neutron-induced cosmonuclide concentrations reach steady-state with respect to denudational loss much more rapidly than the muon induced ones. Therefore, the near-surface produced cosmogenic nuclides mainly resulting from interactions with neutrons might be used to estimate the denudation rates while nuclides accumulated in samples shielded by several meters depth mainly resulting from interactions with muons might be used to estimate the exposure duration. Thus a unique well-constrained depth profile permits determination of both the exposure time and the denudation rate and, in the case of abandoned material, inheritance due to previous exposition to cosmic rays can be revealed by this depth profile approach. Special attention has to

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http://dx.doi.org/10.1016/j.nimb.2012.05.023

be raised here to the fact that a univocal determination of both denudation rate and exposure age is only possible on a single deposition event or on a surface that has experienced a single exposition. Practically this means, for example, that in case of glaciated landscape even if several meters of material have been removed to efficiently reset the neutron clock, this could not be the case for the muon one at depth and a simple depth profile approach might overestimate the exposure age due to inheritance resulting from deep nuclides production from muons.

The depth profile approach is only valid if all physical parameters that control muon contributions (attenuation length, production, etc.) are well constrained. In the nineties, the contribution of muons has been estimated to be at least 10% of the total surface production rate of ^{10}Be and ^{26}Al in quartz [5] and of ∼6% of ^{36}Cl production rate in calcite [6]. These percentages have been then reduced to 2–3% by [7]. In 2003, Braucher et al. [8] proposed muon contributions to be on the order of $(1.20 \pm 0.60)\%$ and of $(0.65 \pm 0.25)\%$ of total production for slow and fast muons, respectively, for ^{10}Be. These contributions are equivalent to sea level high latitude (SLHL) production rates in the order of (0.022 ± 0.008) atoms $g^{-1}\,a^{-1}$ and of (0.029 ± 0.012) atoms $g^{-1}\,a^{-1}$ for slow and fast muons, respectively, considering a modern spallation production rate of 4.49 ± 0.03 atoms $g^{-1}\,a^{-1}$. All these numbers have been deduced from experimental data from natural rock samples. However, there is currently a growing body of theoretical literature examining production of cosmogenic nuclides induced by muons [9–14]. It has been observed that muon contributions proposed by Heisinger et al. [11–14] might have been overestimated [8,15,16] because physical experiments that yield to these numbers have been conducted at two discrete energies that may not be representative of the natural muon spectrum energy range.

In a recent study, [16], these discrepancies have been confirmed when working on a natural depth profile along which ^{10}Be, ^{26}Al and ^{36}Cl analysis have been performed. Despite agreeing with Heisinger et al. [11–14] for slow muons contribution for ^{26}Al, this study reveals large discrepancies for slow muons regarding ^{10}Be and for fast muons contributions regarding both ^{10}Be and ^{26}Al. Simply oppose laboratory experiments conducted by Heisinger et al. [11–14] at concentrations of cosmogenic nuclides measured in natural samples collected along depth profiles is not completely satisfactory to explain the differences in the contributions of muons. In this paper, a solution to reconcile both approaches will be proposed by reviewing most of the depth profiles already published in the literature.

It has to be mentioned that the clear distinction between slow and fast muons presented in the studies cited above appears to be artificial. Muons are the most numerous charged particles at sea level [17]. They lose energy by ionization and by radiative processes: Bremsstrahlung, direct production of e^+e^-pairs, and photonuclear interactions. The terms *"slow"* and *"fast"* muons thus correspond to different energy levels, as mentioned by Lal and Peters [18]. The slow component ($27\ \text{MeV} < E\mu < 220\ \text{MeV}$) is inducing muon capture, while the fast muon component ($E\mu > 220\ \text{MeV}$) produces high-energy gamma-radiations (Bremsstrahlung reactions) that produce neutrons as well as photonuclear reactions. Slow and fast muons thus correspond to different energy states but refer to only one type of particle.

2. Sites description

Sampling a deep depth profile is not an easy task and few papers are dealing with great depth profiles of sufficiently well-known geomorphology to allow determining muon contribution. The reader should go to the original publication to have a precise site description as well as the original experimental data. However, the Cuiaba data, originally measured using a SRM 4325 NIST standard value of $(2.68 \pm 0.029).10^{-11}$ have been updated with an assigned value of value of $(2.79 \pm 0.03).10^{-11}$ that corresponds to 4.1% change.

2.1. Cuiaba quarry [8]

This depth profile (0–15 m) is located near the city of Cuiaba (15°21'S; 56°03'W) (Mato groso, Brazil) at an altitude of 240 m. It is a composite of two quartz veins embedded in metasediments and granitoids rocks. Original model yields to steady state equilibrium and to a denudation rate of (2.2 ± 0.3) m Ma^{-1}.

2.2. La Ciotat core [16]

The samples come from a core drilled near La Ciotat City (South Provence Basin, France) in a marine sedimentary system that developed during the upper Cretaceous. This core consists of alternations of autochthonous and allochthonous marine deposits. Autochthonous deposits are mainly quartzosecalcarenites or marls. Allochthonous deposits comprise Turonian carbonate lithoclasts supplied from the northern carbonate platform and terrigenous material (older than Permian) derived from the South Provence crystalline continent. The core was drilled at an altitude of 310 m near a coastal cliff formed by Cretaceous marine sediments. The topographic surface, from which the core was taken, is cutting through the Cretaceous strata and has been interpreted as a Miocene wave-cut platform extending throughout the entire region. Based on ^{26}Al and ^{10}Be models, this site is at steady state with a denudation rate of (39 ± 3) m Ma^{-1}.

2.3. Macraes quarry [19]

Data presented in Kim et al. [19] originated from a surface tectonically stable since several millions years in the East Otago, southeast South Island, New Zealand. The sampling site, Macraes Flat, is located at 45.8°S and 170.4°E at an altitude of 535 m above sea level. This is a composite depth profile going down to 49 300 g cm^{-2} (∼183 m) with an average rock density of 2.7 gcm^{-3}. The data allow determining a denudation rate of 12 m Ma^{-1} and an exposure duration of (25.0 ± 3.3) ka.

2.4. Leymon Quarry site

The Leymon quarry site is located near the locality of A Gudiña (42.07 N, 7.01 W, ∼1275 m; north west of Spain, Fig. 1). All data (^{10}Be and ^{26}Al) concerning this site are original and have never been published elsewhere; more details regarding the site as well as the sample preparation will thus be given in the following.

Two depth profiles have been drilled in the quartz dyke of Vilavella in the Leymon quarry. This dyke is part of the materials mobilized by the Chandoiro Fault, the local name of one of the most notorious macro features of Variscan origin in north west Iberia. This fault is separating the Asturoccidental–Leonese area from the Central Iberian area of the Peninsular Hesperian Massif. In the area where the Vilavella quartz dyke is located, the Chandoiro fault affects different types of rocks with different ages as the granite of La Canda, the Gudiña granite, the Armorican quartzite and the epiclastic tuffs of the Ollo de Sapo formation which are the oldest Ordovician rocks (472–488 Ma).

Based on the work of [20], the Chandoiro fault activity, and thus that of the Vilavella quartz dyke, is dated at (286 ± 6) Ma (the Carboniferous–Permian Boundary). The shear band associated to the fault is approximately 3 km wide and 50 km long. During the development of the Chandoiro fault the quartz behaved like a ductile material leading to the formation of sigmoidal ribbons that reach macroscopic dimensions in the area of Leymon Quarry.