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Toward the feldspar alternative for cosmogenic ^{10}Be applications

Swann Zerathe [a, d, *], Pierre-Henri Blard [b], Régis Braucher [c], Didier Bourlès [c], Laurence Audin [a], Julien Carcaillet [a], Fabrizio Delgado [d], Carlos Benavente [d], ASTER Team[1]

[a] Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, 38000 Grenoble, France
[b] CRPG, UMR7358, CNRS, Université de Lorraine, 54501 Vandoeuvre-lès-Nancy, France
[c] Aix-Marseille Univ., CNRS, IRD, Coll. France, UM 34 CEREGE, Technopôle de l'Environnement Arbois-Méditerranée, BP80, 13545 Aix-en-Provence, France
[d] Instituto Geológico, Minero y Metalúrgico INGEMMET, Av. Canadá 1470, Lima, Peru

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ABSTRACT

The possibility of quantifying surface processes in mafic or volcanic environment using the potentialities offered by the *in situ*-produced cosmogenic nuclides, and more specifically by the *in situ*-produced ^{10}Be, is often hampered by the rarity of quartz minerals in the available lithologies. As an alternative to overcome this difficulty, we explore in this work the possibility of relying on feldspar minerals rather that on quartz to perform *in situ*-produced ^{10}Be measurements in such environments. Our strategy was to cross-calibrate the total production rate of ^{10}Be in feldspar (P_{10fsp}) against the total production rate of ^{3}He in pyroxene (P_{3px}) by measuring ^{3}He and ^{10}Be in cogenetic pyroxene ($^{3}He_{px}$) and feldspar ($^{10}Be_{fsp}$). The samples were collected from eight ignimbritic boulders, exposed from ca 120 to 600 ka at elevations ranging from 800 to 2500 m, along the preserved rock-avalanche deposits of the giant Caquilluco landslide (18°S, 70°W), Southern Peru. Along with data recently published by Blard et al. (2013a) at a close latitude (22°S) but higher elevation (ca. 4000 m), the samples yield a remarkably tight cluster of $^{3}He_{px}$ - $^{10}Be_{fsp}$ total production ratios whose weighted-mean is 35.6 ± 0.5 (1σ). The obtained weighted-mean $^{3}He_{px}$ - $^{10}Be_{fsp}$ total production ratio combined with the local $^{3}He_{py}$ total production rate in the high tropical Andes published by Martin et al. (2017) allows to establish a total SLHL ^{10}Be *in situ*-production rate in feldspar mineral (P_{10fsp}) of 3.57 ± 0.21 at.g^{-1}.yr^{-1} (scaled for the LSD scaling scheme, the ERA40 atm model and the VDM of Lifton, 2016).

Despite the large elevation range covered by the whole dataset (800–4300 m), no significant variation of the $^{3}He_{px}$ - $^{10}Be_{fsp}$ total production ratios in pyroxene and feldspar was evidenced. As an attempt to investigate the effect of the chemical composition of feldspar on the total ^{10}Be production rate, major and trace element concentrations of the studied feldspar samples were analyzed. Unfortunately, giving the low compositional variability of our dataset, this issue is still pending.

1. Introduction

Terrestrial Cosmogenic Nuclides (TCN) are produced through nuclear interactions between minerals of the upper Earth's crust surface and the energetic cosmic rays secondary particles. Offering the possibility to determine surface exposure durations to the cosmic ray derived secondary particles, they are useful to quantify the evolution of many geomorphological features (e.g. landslides, moraines, fault-scarps, terraces) (e.g. Gosse and Phillips, 2001). They may also provide quantitative constraints on denudation rates at a single location or at watershed scales (e.g. Brown et al., 1995; von Blanckenburg, 2005). Over the last decades, significant efforts and progress have been made not only to improve the analytical procedures (e.g. Schimmelpfennig et al., 2009; Bromley et al., 2014; Corbett et al., 2016), but also the accuracy and precision of *in situ*-production rates (e.g. Braucher et al., 2011, 2013; Fenton et al., 2011; Blard et al., 2013b; Lifton et al., 2014; Kelly et al., 2015; Martin et al., 2015; Borchers et al., 2016; Delunel et al., 2016).

In situ-produced ^{10}Be is one of the most commonly used TCN in quantitative geomorphology due to the fact that its production rate is relatively well constrained in the ubiquitous quartz mineral whose integrity minimizes the possibility of contamination by

* Corresponding author. Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, 38000 Grenoble, France.
E-mail address: swann.zerathe@ird.fr (S. Zerathe).
[1] ASTER Team: George Aumaître and Karim Keddadouche.

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meteoric ^{10}Be. Easily decontaminated from meteoric ^{10}Be, it is in addition reliably measured using the Accelerator Mass Spectrometry technique for which its detection limit is lower than 10^4 at.g^{-1} (e.g. Arnold et al., 2010). However, volcanic or mafic areas are generally quartz free, which hamper the routine use of ^{10}Be. In these geological settings, other nuclide-mineral couples are used in routine, such as ^{3}He in olivine-pyroxene (e.g. Kurz, 1986), or ^{36}Cl in Ca or K rich feldspars (e.g. Schimmelpfennig et al., 2009). Nevertheless, in some cases, the applicability of these TCNs may be complicated by several limitations such as pre-exposure inheritance in the case of stable TCN (i.e. a cosmogenic component produced in an earlier exposure period) and/or large corrections for non-cosmogenic components in the case of ^{3}He (e.g. Gosse and Phillips, 2001; Blard and Farley, 2008; Amidon et al., 2009; Athanassas et al., 2016). Additionally, when production pathways are multiple such as for the ^{36}Cl, a precise knowledge of the chemical mineral composition is necessary (Phillips et al., 2001; Dunai et al., 2007) which requires measuring specific major and trace elements. Especially in the case of ^{36}Cl, despite recent important progress (Marrero et al., 2016) the problem of the scattering of the different elemental production rates in the literature (e.g. spallation from Ca and from K) is still not completely understood (see discussion in Marrero et al., 2016) and it remains a possible source of significant uncertainties.

In the case of a quartz poor lithology, an alternative possibility is to rely on ^{10}Be - feldspars. Two preliminary studies (Kober et al., 2005; Blard et al., 2013a) already provided promising results, demonstrating that the decontamination protocol classically applied to quartz (Brown et al., 1991) efficiently removes all the meteoric ^{10}Be contamination from the feldspar grains. These studies also suggest that the total production rate of ^{10}Be in feldspar is 8–10% lower than that in quartz. However, only two samples were analyzed in both studies. In order to better constrain the ^{10}Be *in situ*-production rate within feldspars, the number of samples analyzed needs to be increased. Moreover, it is important to further investigate to what extent the ^{10}Be *in situ*-production rate within feldspar depends on the chemical composition of the analyzed minerals.

In this study, we explore and demonstrate the potential of feldspar to accurately determine the concentration of in situ-produced cosmogenic ^{10}Be, thus substituting quartz in mafic areas. For this, we developed a new chemical protocol for the ^{10}Be extraction from these matrices, and to cross-calibrate the total ^{10}Be *in situ*-production rate in feldspar (P_{10fsp}) against the total ^{3}He production rate in pyroxene (P_{3px}). The cosmogenic ^{3}He and ^{10}Be concentrations were measured, respectively, in pyroxene and feldspar extracted from eight samples of ignimbrite boulders from a giant landslide located between 800 and 2500 m in the high central Andes of Southern Peru. This area is ideally located, since two studies have already determined the local total ^{3}He production rate in pyroxene on the nearby Altiplano, above 3000 m (Blard et al., 2013b; Delunel et al., 2016). Starting from the chemical protocol classically used for the extraction of the *in situ*-produced ^{10}Be from quartz, we propose a slightly updated procedure to extract the *in situ*-produced ^{10}Be from feldspar. This adapted chemical procedure allows overcoming difficulties specific to feldspars, such as the precipitation of fluorite salts during HF substitution, and also prevents from the saturation of the resin columns during cation and anion exchange chromatography.

2. Material: geomorphological and geological settings of the sampling site

The giant Caquilluco landslide is located in southern Peru (Fig. 1A), in the northern part of the Atacama Desert, about forty kilometers north of the city of Tacna (Fig. 1B). The instability has developed along the western flank of the Peruvian Andes, an area characterized by steep slopes and extremely dry climate for the last million years (Placzek et al., 2010). A preliminary geomorphological description of this exceptional site can be found in Audin and Bechir (2006) and Crosta et al. (2015). The Caquilluco landslide is a large complex of imbricated paleo deep-seated landslides and paleo rock-avalanches. It affects the western flank of a large anticline trending NW-SE, which developed during compressive deformation propagation along west-verging blind reverse faults (e.g. the Calientes fault, Hall et al., 2012). The total volume of rock material that has been mobilized is about 15 km^3 (Crosta et al., 2015). From the head scarp (~3800 m a.s.l.) to the most distal rock-avalanche lobe (600 m a.s.l.), avalanche deposits are covering more than 40 km in distance along-strike and about 15 km in width (Fig. 1B). In the upper part of the landslide area (Fig. 1C), several rock avalanche lobes are superimposed. The relative dispositions and relationships of these lobes indicate that several successive gravitational landslides occurred and have then been preserved because of limited erosion and chemical alteration of the Atacama Desert area (e.g. Nishiizumi et al., 2005).

The Caquilluco landslide mainly remobilized Miocene ignimbrites and volcanic tuffs of the Huaylillas formation (Acosta et al., 2010). These materials, poor in quartz, are rich in feldspars and pyroxene, making these rocks suitable for cross-calibration between ^{3}He in pyroxene ($^3He_{px}$) and ^{10}Be in feldspar ($^{10}Be_{fsp}$). The sampling strategy was to collect samples in various landslide lobe deposits in order to cover the largest range of potential exposure durations and sampling elevations. Special care was taken to select well-preserved boulders, as large as possible (>1 m), without any apparent trace of posterior transport, significant denudation, rock fall nor desquamation (Fig. 1). A total of eight boulder samples were collected: seven (CQ1, CQ3, CQ6, CQ8, CQ10, CQ12 and CQ18; Fig. 1C) in the upper landslide zone (>2000 m a.s.l.) and one sample (TM6) on the most distal deposition area (~800 m a.s.l.; Fig. 1B). Field data and all sample characteristics are synthetized in Table 1.

In synthesis, the Caquilluco site is a good candidate for cross-calibration purpose because: (i) the landslide shows several lobes of deposits that are superimposed, which is an opportunity to span different time frames for of exposure, (ii) the area is characterized by low denudation rate and the preservation of landslide morphologies are also indicative of a good landscape preservation, and (iii) this site is the opportunity to conduct a double project: the calibration of the total ^{10}Be production rate in feldspar as well as the reconstruction of the landslide chronology to understand its failure mechanisms.

3. Methods

3.1. Sample treatment - pyroxene and feldspar separation

Thin sections were realized in each rock sample in order to ensure that enough pyroxene and feldspars were available and also to check the crystal sizes (>200 μm). Samples were then crushed, washed and sieved to select the 200–800 μm fractions. Successive magnetic separations were performed using a Frantz© magnetic separator to separate the magnetic from the non-magnetic fraction bearing pyroxene and feldspars, respectively. For efficiency, and because the magnetic fraction dominates in the ignimbrite (≥70%), the first run was done at a low magnet current (0.5–1 A) and by feeding the chute (slope of 25° and tilt 15°) with a rapid sample flow rate (≥5 g/min). This allowed a first rough separation. Then, re-running of the non-magnetic fraction was necessary to reach pure feldspars. This was done with the same chute configuration but under a slower sample flow rate (≤1 g/