Chemical Geology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Chemical Geology

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

Variability of magmatic and cosmogenic ^{3}He in Ethiopian river sands of detrital pyroxenes: Impact on denudation rate determinations

Nicolas Puchol, Pierre-Henri Blard *, Raphaël Pik, Bouchaïb Tibari, Jérôme Lavé

CRPG, CNRS - Université de Lorraine, UMR7358, 15 rue Notre Dame des Pauvres, 54501 Vandoeuvre-lès-Nancy, France

ARTICLE INFO

Article history:
Received 4 February 2016
Received in revised form 16 October 2016
Accepted 26 October 2016
Available online xxxx

Keywords:
Ethiopia
Erosion
River sand
Cosmogenic ^{3}He
Magmatic correction

ABSTRACT

In-situ cosmogenic ^{3}He is a robust tool for determining denudation rates or exposure ages of lavas bearing mafic phenocrysts. However, analyses are often complicated by the presence of several helium sources. In particular, in old magmatic rocks with high radiogenic ^{4}He contents, discriminating cosmogenic ^{3}He from magmatic ^{3}He is not straightforward since these varieties may vary largely between aliquots.

We sampled sands from the Tekeze and Mile rivers, both draining the basaltic Ethiopian highlands, an area where erosion patterns are intimately linked to the development of the Western Afar margin and to heterogeneous monsoon precipitation. From each river we analyzed ~15 aliquots of pyroxenes having variable grain sizes (0.3 mm up to >1 mm). The total ^{3}He is both higher and more scattered in the bigger grains. Crushing of these largest grains and subsequent melting of the powder tends to produce more homogeneous ^{3}He values, suggesting that magmatic ^{3}He hosted in inclusions is responsible for most of the inter-aliquot variability. We also performed a Monte Carlo simulation based on a numerical denudation model of the two watersheds. The simulation confirms that cosmogenic ^{3}He variability cannot be responsible for the observed scatter since the cosmogenic ^{3}He variability is averaged away and unobservable in aliquots of ~200 grains. A compilation of previously published data also indicates that magmatic helium can be significantly variable, even between pre-crushed aliquots. Hence, magmatic helium, unlike cosmogenic ^{3}He, is highly variable, even in the case of aliquots of hundreds of grains. We suggest this is due to a strong nugget effect, possibly due to large fluid (or melt)-inclusions contained in phenocrysts.

In addition, the fact that small and big grains have comparable radiogenic ^{4}He concentrations suggests that grain fragmentation during river transport is responsible for the lower magmatic helium content of the smallest grains. Therefore, one should preferably use small grain (0.2–0.5 mm) granulometry for in-situ cosmogenic ^{3}He analysis in mafic phenocrysts.

Using the measured cosmogenic ^{3}He, we calculate basin-averaged denudation rates of 70 ± 20 and 57 ± 5 mm kyr^{-1}, for the Mile and for the Tekeze river, respectively. These values are coherent with long-term denudation rates previously proposed from low-temperature thermochronology.

1. Introduction

In-situ cosmogenic nuclides are produced by the flux of secondary cosmic particles in the top few meters of the Earth's surface. They represent a useful tool with which to quantify many key Earth-surface processes (Gosse and Phillips, 2001) for history and review. Along with other cosmogenic nuclides (e.g. ^{10}Be, ^{26}Al, ^{36}Cl, ^{21}Ne), ^{3}He has been widely used for the past 25 years to date lava flows (e.g. Ammon et al., 2009; Kurz et al., 1990), to reconstruct continental paleoclimates (e.g. Blard et al., 2007; Licciardi et al., 2001) or to measure in-situ (e.g. Sarda et al., 1993) or basin-averaged (e.g. Gayer et al., 2008) denudation rates. ^{3}He presents several advantages compared to more commonly used isotopes like ^{10}Be or ^{26}Al. It requires neither a complex chemical preparation nor the use of an Accelerator Mass Spectrometer (AMS). Furthermore, many rocks - especially basalts - do not contain significant amounts of quartz, the mineral in which ^{10}Be and ^{26}Al are preferentially analyzed.

However, ^{3}He is not retained in many minerals (Trull et al., 1995). Most studies using ^{3}He have hence been carried out on mafic phenocrysts such as olivine and pyroxene (e.g. Kurz, 1986b), which are known to have a high helium retentivity (Blard and Pik, 2008; Shuster et al., 2004; Trull et al., 1991). In these minerals, the helium budget is a four-component system (Blard and Farley, 2008; Farley et al., 2006) consisting of:

- Cosmogenic ^{3}He (^{3}He$_c$), matrix-sited.
- Magmatic inherited ^{3}He and ^{4}He (He$_{mag}$), fluid (or melt) inclusion

---

* Corresponding author.
E-mail address: blard@crpg.cnrs-nancy.fr (P.-H. Blard).

http://dx.doi.org/10.1016/j.chemgeo.2016.10.033

Please cite this article as: Puchol, N., et al., Variability of magmatic and cosmogenic 3He in Ethiopian river sands of detrital pyroxenes: Impact on denudation rate determination..., Chem. Geol. (2016), http://dx.doi.org/10.1016/j.chemgeo.2016.10.033

and (a small fraction) matrix-sited.
- Radiogenic ^{4}He (^{4}He$_r$), produced by the decay of ^{238}U, ^{235}U and ^{232}Th, matrix-sited.
- Nucleogenic ^{3}He (^{3}He$_{nuc}$), produced by neutron capture on Li nuclei and subsequent disintegration, matrix-sited.

For most young (≪1 Ma) mafic rocks with low U, Th and Li contents (<10 ppm), the radiogenic and nucleogenic components can be neglected or corrected for (Blard and Farley, 2008). In this case, the cosmogenic component can be determined by a standard two-step procedure (Kurz, 1986a):

1. In vacuo mineral crushing to preferentially release and analyze inclusion-sited magmatic helium, allowing the magmatic ^{3}He/^{4}He ratio to be measured and also reducing the He$_{mag}$ concentration of the residue.
2. Fusion of the same aliquot as for the crush analysis or a different aliquot of the same sample, in order to measure the bulk (^{3}He/^{4}He)$_{melt}$ ratio and the total ^{4}He.

Then, assuming ^{4}He$_r$ ~ 0 at g^{-1}:

$$^3\mathrm{He_c} = {}^4\mathrm{He_{melt}} \times \left[\left({}^3\mathrm{He}/{}^4\mathrm{He}\right)_{melt} - \left({}^3\mathrm{He}/{}^4\mathrm{He}\right)_{mag}\right] \tag{1}$$

Under certain conditions, one can also construct isochrons in ^{3}He/^{4}He vs 1/[^{4}He] space (Blard and Pik, 2008; Cerling and Craig, 1994b), thereby avoiding the first crushing step, which may trigger possible loss of matrix sited helium (Blard et al., 2006; Hilton et al., 1993; Scarsi, 2000; Yokochi et al., 2005), or, more probably, contamination by atmospheric helium (Protin et al., 2016).

However, given the concentrations of U and Th in olivine, pyroxene and in the lava matrix, the radiogenic ^{4}He component can rarely be neglected (Blard and Farley, 2008). Consequently, in several situations, the amount of ^{4}He extracted by melting the samples cannot be used to correct for the magmatic ^{3}He. In such cases, ^{3}He$_c$ determinations thus require a crushing step that is sufficiently long to release and purge most of the trapped magmatic helium. If the matrix-sited magmatic helium is negligible, there is thus no more need for a magmatic helium correction. This crushing should however not be too intense in order to avoid releasing the matrix sited cosmogenic ^{3}He (Blard et al., 2006, 2008; Scarsi, 2000; Yokochi et al., 2005), nor contaminate the sample with atmospheric helium (Protin et al., 2016). Alternatively, a previous study (Williams et al., 2005) conducted on pyroxene microphenocrysts of Pliocene basalts of Gran Canaria (Canary Islands) has shown that the magmatic component may be negligible in the smallest grains (i.e. 125–250 μm). In the case of moderate to high (>0.5 mm yr^{-1}) erosion rates, the cosmogenic ^{3}He concentration in river sands is low (<10^{-18} mol g^{-1} for watersheds with average elevation lower than 2000 m), implying that the resulting magmatic ^{3}He correction could represent a significant source of uncertainty. Consequently, it is important to overcome this methodological limitation, particularly for old phenocrysts that may also have significant amounts of radiogenic ^{4}He.

In the present study, we test the possibility of obtaining reliable cosmogenic ^{3}He-based denudation rates in basins dominated by old lavas. We observe that coarse-grained aliquots display very variable ^{3}He concentrations. However, fine-grained aliquots exhibit ^{3}He concentrations homogeneous enough to allow correction of the magmatic component with reasonable precision and confidence. We then examine the main cause of the variability of the coarse aliquots.

Our experiments were carried out on detrital pyroxenes from two Ethiopian rivers draining two different watersheds of the Ethiopian plateau. This work represents an important step for the study of the geomorphologic processes involved in this region, and, more generally, for estimating erosion rates in old volcanic provinces.

2. Geomorphological setting of the Ethiopian plateau and sampling

The Northwestern Ethiopian plateau is a major feature of the Ethiopian traps, a 1.5 km-thick continental flood basalt (CFB) sequence (Fig. 1) (Mohr, 1983). This imposing volcanic pile erupted 30 Ma ago, and the entire volume of basalt was emplaced in <2 Myr (Hofmann et al., 1997; Rochette et al., 1998). On its eastern margin, along the major Afar escarpment, most of this volcanic sequence consists of ankaramitic porphyritic basalts, with local presence of ignimbrites at the top of the eruptive sequence (Ayalew et al., 2002; Pik et al., 1998, 1999). These geological characteristics are particularly well suited for ^{3}He analyses because rivers draining the Ethiopian plateau bear large amounts of pyroxene and olivine phenocrysts.

Determining the spatial variability of denudation rates is of great interest for understanding climate-tectonic-erosion interactions. First, erosion has a major long term influence on the global atmospheric CO_2 budget (Berner et al., 1983; Galy et al., 2007), even erosion of spatially and temporally discrete large volcanic provinces emplaced on continents (Dessert et al., 2001). Second, the development of the radial drainage network on the Ethiopian plateau is critically linked to the uplift and tectonic evolution of the plateau and its margins (Cox, 1989; McDougall et al., 1975; Pik, 2011; Pik et al., 2003; Stab et al., 2016). In this study, we focused on the comparison of two river catchments, located on both sides of the main plateau drainage divide (Fig. 1).

On the eastern side of the divide, the topographic scarp undergoes both an active morphological evolution linked to the development of its marginal graben system (Stab et al., 2016) and moderate monsoonal precipitations (700–1000 mm yr^{-1}) (Conway, 2000). The Mile river, whose watershed covers ~1600 km^2 with a mean slope of 13°, flows toward the Afar depression through this major topographic feature (Fig. 1). A ~2 kg sample of Mile river sand was collected on the 25th of February 2009, at the outlet of the basin catchment (11.62696°N; 39.97236°E) where it reaches the Afar plain.

By contrast, the northern part of the plateau is generally lower in elevation because most of the original highland morphology has already been eroded by propagation of the Tekeze river (Fig. 1B). The upper part of the actively propagating Tekeze river catchment has a total surface of ~750 km^2 and a mean slope of 16°. As for the Mile river sand sample, a ~2 kg sample of Tekeze river sand was collected at (11.91338°N; 38.97681°E) in February 2009. In each river, the sampled stream-bed sands are mainly composed of gravels resulting from the erosion of lavas (essentially basalts, with minor occurrence of rhyolite clasts) up to ~2 cm in size, single mineral grains (pyroxene, olivine and quartz), and organic debris.

It must be noted that, despite their similar mean slopes, these two watersheds display very different morphologies. While the upper part of the Tekeze river is mainly a high plateau incised by deep valleys, the Mile river hillslopes range from steep at its headwater to gentle slopes along several large North-South oriented valleys (Fig. 1B).

Cosmogenic nuclide measurement in river sands has proven to be a particularly robust method to constrain basin-averaged denudation rates at timescales of several hundreds to thousands of years (e.g. Brown et al., 1995; von Blanckenburg, 2005), while thermochronological methods quantify denudation over million year timescales (e.g. Pik et al., 2003). The two watersheds presented here are particularly well suited for cosmogenic nuclide studies because they are characterized by a homogenous lithology, sparse vegetal cover, no ice or snow cover, limited influence of catastrophic erosive events and no significant storage of sediments (Pik et al., 1998).

3. Methods

3.1. Mineral separation

Bulk sands were sieved under flowing water into two granulometric fractions: 0.3–0.5 mm and >0.5 mm.

Please cite this article as: Puchol, N., et al., Variability of magmatic and cosmogenic 3He in Ethiopian river sands of detrital pyroxenes: Impact on denudation rate determination..., Chem. Geol. (2016), http://dx.doi.org/10.1016/j.chemgeo.2016.10.033