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Constraining Quaternary ice covers and erosion rates using cosmogenic $^{26}Al/^{10}Be$ nuclide concentrations

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A B S T R A C T

Paired cosmogenic nuclides are often used to constrain the exposure/burial history of landforms repeatedly covered by ice during the Quaternary, including tors, high-elevation surfaces, and steep alpine summits in the circum-Arctic regions. The approach generally exploits the different production rates and half-lives of ^{10}Be and ^{26}Al to infer past exposure/burial histories. However, the two-stage minimum-limiting exposure and burial model regularly used to interpret the nuclides ignores the effect of variable erosion rates, which potentially may bias the interpretation. In this study, we use a Monte Carlo model approach to investigate systematically how the exposure/burial and erosion history, including variable erosion and the timing of erosion events, influence concentrations of ^{10}Be and ^{26}Al. The results show that low $^{26}Al/^{10}Be$ ratios are not uniquely associated with prolonged burial under ice, but may as well reflect ice covers that were limited to the coldest part of the late Pleistocene combined with recent exhumation of the sample, e.g. due to glacial plucking during the last glacial period. As an example, we simulate published $^{26}Al/^{10}Be$ data from Svalbard and show that it is possible that the steep alpine summits experienced ice-free conditions during large parts of the late Pleistocene and varying amounts of glacial erosion. This scenario, which contrasts with the original interpretation of more-or-less continuous burial under non-erosive ice over the last ~1 Myr, thus challenge the conventional interpretation of such data. On the other hand, high $^{26}Al/^{10}Be$ ratios do not necessarily reflect limited burial under ice, which is the common interpretation of high ratios. In fact, high $^{26}Al/^{10}Be$ ratios may also reflect extensive burial under ice, combined with a change from burial under erosive ice, which brought the sample close to the surface, to burial under non-erosive ice at some point during the mid-Pleistocene. Importantly, by allowing for variable erosion rates, the model results may reconcile spatially varying $^{26}Al/^{10}Be$ data from bedrock surfaces preserved over multiple glacial cycles, suggesting that samples from the same high-elevation surface or neighbouring alpine summits may have experienced similar long-term burial under ice, but varying amounts of glacial erosion.

1. Introduction

The extent and longevity of past and present ice sheets represent topics of wide interest, because they are key to understand how ice sheets respond to climatic changes, and, in turn, influence global sea level (Lambeck et al., 2014; Clark et al., 2016, Schaefer et al., 2016; Bierman et al., 2016; Blard and Leduc, 2016; Glasser, 2016). They are also important because ice sheets and cold-climate processes have shaped much of the landscape we observe at high latitudes and in mountainous regions today (Sugden, 1974; Sugden and John, 1976; Kessler et al., 2008). It is inherently difficult, however, to study the extent and longevity of past glaciations, as the geological evidence remains fragmentary (Nielsen and Kuijpers, 2013). The terrestrial deposits that bear witness of past glacial-interglacial cycles are often removed by subsequent glacial advances (Gibbons et al., 1984), and it is therefore difficult to establish past ice-sheet variations pre-dating the Last Glacial Maximum (LGM) around 21 kyr ago, except when the ice advanced beyond the LGM limit. In the absence of geological evidence, many studies rely on measurements of paired cosmogenic radionuclides in bedrock samples. This approach exploits the fact that the cosmogenic nuclides ^{10}Be and ^{26}Al are produced at known rates and at a fixed ratio of ~6.75 (Nishiizumi et al., 1989; Balco et al., 2008), although recent studies suggest this production ratio may be higher (Argento et al.,

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2013; Corbett et al., 2017) and vary with latitude and altitude (Argento et al., 2015a, 2015b; Borchers et al., 2016). The ratio in a sample, however, changes over time, both under continuous exposure with steady erosion and when buried under ice or rock, because the two nuclides have different half-lives. Since the mid-1980's, ratios of ^{26}Al/^{10}Be have been used to study the long-term exposure/burial and erosion history of non-glaciated areas, such as the Libyan desert (Klein et al., 1986), and subsequently in glaciated areas such as Antarctica (Nishiizumi et al., 1991). This research initiated the use of the two-stage ^{26}Al/^{10}Be vs. ^{10}Be diagram to either infer mean erosion rates for the limiting case of steady-state surface exposure, or minimum-limiting exposure and burial durations for the limiting case of no erosion (Nishiizumi et al., 1991; Granger, 2006). The minimum-limiting exposure and burial durations represent the simplest and shortest possible exposure/burial history that can explain concentrations of ^{10}Be and ^{26}Al measured in rock samples (Fig. 1). In this model, samples plotting along a burial isochron is interpreted to have experienced equal lengths of burial irrespective of the absolute ^{10}Be concentration.

Paired ^{26}Al/^{10}Be data from bedrock surfaces have been used to study the landscape history and past glacial ice cover in areas that were covered by ice during parts of the Quaternary, including Svalbard (Gjermundsen et al., 2015), Minnesota in the US (Bierman et al., 1999), the Torngat Mountains (Staiger et al., 2005) and Baffin Island in arctic Canada (Briner et al., 2006, 2014; Margreth et al., 2016), as well as several areas in western Greenland (Roberts et al., 2009, 2013; Lane et al., 2014; Corbett et al., 2013; Beel et al., 2016). Low ^{26}Al/^{10}Be ratios have been used to infer prolonged periods of burial under cold-based ice in several of these areas (e.g. Bierman et al., 1999; Briner et al., 2006; Corbett et al., 2013; Gjermundsen et al., 2015), whereas high ^{26}Al/^{10}Be ratios have been used to infer limited burial under ice (e.g. Beel et al., 2016; Strunk et al., 2017). Examples include high-elevation surfaces in western Greenland and the steep alpine summits of Svalbard that were interpreted by the authors as largely buried under cold-based, non-erosive ice throughout the latter half of the Quaternary (Corbett et al., 2013; Gjermundsen et al., 2015). In contrast, other studies of paired ^{26}Al/^{10}Be bedrock data from western Greenland indicate that burial under ice during the Quaternary was very limited, suggesting that some of the high-elevation surfaces

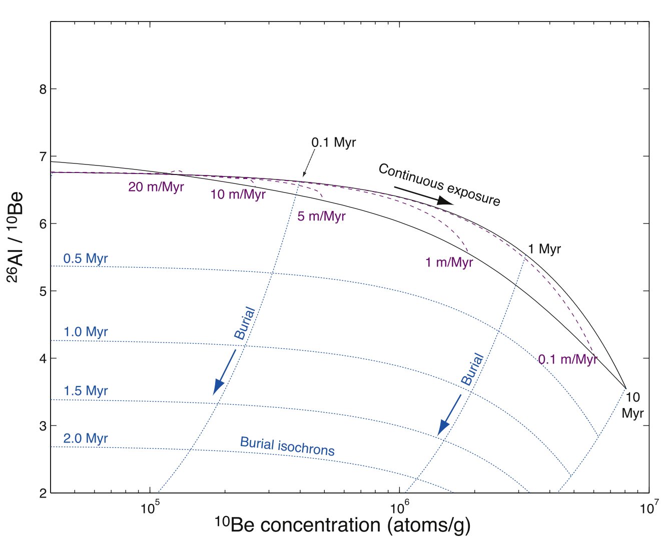

Fig. 1. Standard ^{26}Al/^{10}Be vs. ^{10}Be diagram used to interpret paired ^{26}Al/^{10}Be data from bedrock surfaces with the minimum-limiting exposure and burial model. Lines in the ^{26}Al/^{10}Be vs. ^{10}Be diagram, including burial isochrons, are calculated using the production rates, half-lives, and attenuations lengths reported in Margreth et al. (2016).

around Uummannaq may have remained as nunataks during the most recent glacial maxima (Beel et al., 2016). The ice-cover history inferred for the Ummannaq area is thus very different than the history inferred for other areas in western Greenland. In general, it may be difficult to reconcile ice-cover histories based on spatially varying ^{26}Al/^{10}Be ratios, because it requires regionally, and in some cases locally, varying long-term ice-covers. Such discrepancies are highlighted by the fact that samples from the same area, or even the same sample site (e.g. Gjermundsen et al., 2015), frequently show significantly different ^{26}Al/^{10}Be ratios.

The discrepancies highlighted above reveal some fundamental difficulties concerning the use of the two-isotope ^{26}Al/^{10}Be vs. diagram to constrain complex burial histories. First of all, the ^{26}Al/^{10}Be vs. ^{10}Be burial concept generally assumes constant erosion rates (Nishiizumi et al., 1991). For example, exhumation of a rock sample at a steady pace of 1 m/Myr under ice-free conditions (from a depth of 2.6 m–0 m during the Quaternary) leads to ^{10}Be and ^{26}Al concentrations that correctly indicates zero ice cover in the ^{26}Al/^{10}Be vs. ^{10}Be burial plot (black line in Fig. 2). However, as pointed out by Gosse & Phillips (2001) and discussed by others (e.g. Small et al., 1997; Bierman et al., 1999), the resulting point is shifted significantly within the ^{26}Al/^{10}Be vs. ^{10}Be diagram if the same amount of erosion (2.6 m) is episodic, or occurs at accelerating/decelerating erosion rates (blue and green lines in Fig. 2). An accelerating rate of erosion may thus falsely indicate long-term burial under ice, even when the erosion occurs under fully ice-free conditions (blue lines in Fig. 2). Secondly, the nuclide inventory at the onset of the Quaternary may be non-negligible if the pre-Quaternary erosion rate and the total erosion during the Quaternary was low, which further complicates the use of the ^{26}Al/^{10}Be vs. ^{10}Be diagram.

In this study, we introduce a novel Monte Carlo model that fully integrates the effects of both constant and variable erosion as well as pre-Quaternary inheritance in a systematic effort to map how different exposure/burial and erosion histories influence the resulting ^{10}Be and ^{26}Al concentrations. We show that variable erosion rates, including the timing of the erosion, may critically influence the concentrations of ^{10}Be and ^{26}Al that we measure in rock samples. These effects challenge the conventional interpretation of paired ^{26}Al/^{10}Be data from areas covered by ice during the Quaternary.

2. Simulating ^{10}Be-^{26}Al concentrations using a Monte Carlo approach

The model framework used in this study to simulate the evolution of terrestrial cosmogenic nuclide (TCN) concentrations over multiple glacial-interglacial cycles during the Quaternary combines key aspects of the approaches by Knudsen et al. (2015) and Margreth et al. (2016), although with some important differences. Similar to Knudsen et al. (2015), we use a Lagrangian approach that tracks the depth of a sample as it moves towards the surface due to erosion. The exposure/burial history associated with climatic changes and advancing/retreating ice sheets during the Quaternary is determined by applying a threshold value (Kleman et al., 2008; Fabel et al., 2002; Knudsen et al., 2015) to the global benthic marine δ^{18}O record (Lisiecki and Raymo, 2005), which is a proxy for past global land-ice volume. The δ^{18}O-threshold value is randomly selected from a linear interval (3.25–4.85‰) with uniform probability. With this approach, we assume that the exposure/burial history can be divided into two distinct regimes: i) glacial periods with negligible or no exposure due to overlying ice, and ii) interglacial periods characterized by full exposure (Fig. 3), hereby assuming that shielding due to snow, till, or vegetation is negligible. Interglacial periods are furthermore characterized by a constant