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Establishing a Bayesian approach to determining cosmogenic nuclide reference production rates using He-3

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A B S T R A C T

Production rates are a cornerstone of in situ cosmogenic nuclide applications, including surface exposure dating, erosion rate/denudation rate estimates, and burial dating. The most common approach for estimating production rates is to measure cosmogenic nuclide samples from sites with independently well-constrained exposure histories. In addition, while researchers attempt to minimize the effects of erosion through careful site and sample selection, it can be present at some unknown level in certain sites. We present a general Bayesian methodology for combining information from the nuclide concentrations, the exposure history, and the possibility of erosion, to determine the production rate at a given site. Then, we use another Bayesian approach to combine the results from the various sites.

Cosmogenic ^{3}He is an ideal test-bed for our Bayesian approach. It has the most calibration sites of the commonly measured cosmogenic nuclides, and there is evidence for the effect of erosion on some of the sites. Our approach largely reconciles previous discrepancies between sites of widely varying age, even at latitudes where geomagnetic effects are significant. With the canonical Lal/Stone scaling scheme, we derive a global sea level high latitude ^{3}He production rate of 118 ± 2 atoms g^{-1} yr^{-1} when considering olivine and pyroxene together. Using the Lifton–Sato–Dunai scaling scheme yields a similar rate of 121 ± 2 atoms g^{-1} yr^{-1}. Uncertainties associated with these values are improved over previous studies, due to both reduced scatter among the sites and an approach to combining sites which deemphasizes outliers.

1. Introduction

Cosmogenic nuclide production rates are most commonly derived empirically from locations with well-constrained exposure histories. In this context, 'well-constrained' generally refers to good independent age control, but also includes inferences regarding geomorphic history (e.g., surface erosion, uplift, and/or ash and sediment cover). The method by which the independent exposure age is estimated varies; in general, most researchers have taken the well-reasoned and simple approach of choosing an exposure age thought to represent the central tendency of the data constraining the sites exposure age and assumed Gaussian uncertainties on the age (Borchers et al., 2016). Information regarding the geomorphic history of a site tends to be more subjective and more difficult to quantify. For that reason, most cosmogenic nuclide calibration sites tend to be from surfaces impacted by geologically instantaneous events. Quantification of the long-term erosion of a calibration site surface is less-well-understood, but generally is derived from the measurement of differential surface relief or preservation of fine surface features or patinas. However, in many studies erosion is assumed to be small enough in magnitude to be ignored and assumed equal to zero.

Cosmogenic helium-3 (^{3}He) was among the first cosmogenic nuclides to be studied in detail (e.g., Cerling, 1990; Kurz, 1986; Kurz et al., 1990) and as such many production rate calibration sites exist. Published ^{3}He production rate calibration sites span a wide-range of ages (ca. 2–1350 ka), latitudes (ca. 50°S to 66°N), and elevations (ca. 0 to 4000 m). While most studies yield sea level high latitude ^{3}He production rates near 120 atoms g^{-1} yr^{-1}, some yield significantly higher production rates and others anomalously low reference production rates. Following Goehring et al. (2010) a reference ^{3}He production rate refers to the rate of ^{3}He production at sea level and high latitude via scaling of the site production rate to sea level and high latitude. Fig. 1 shows the distribution of reference ^{3}He production rates for the sites used in our analysis relative to scaling of Lifton et al. (2014a) and time-dependent geomagnetic and atmospheric frameworks presented in Lifton (2016). No apparent trends ($r^2 < 0.1$) are observed be-

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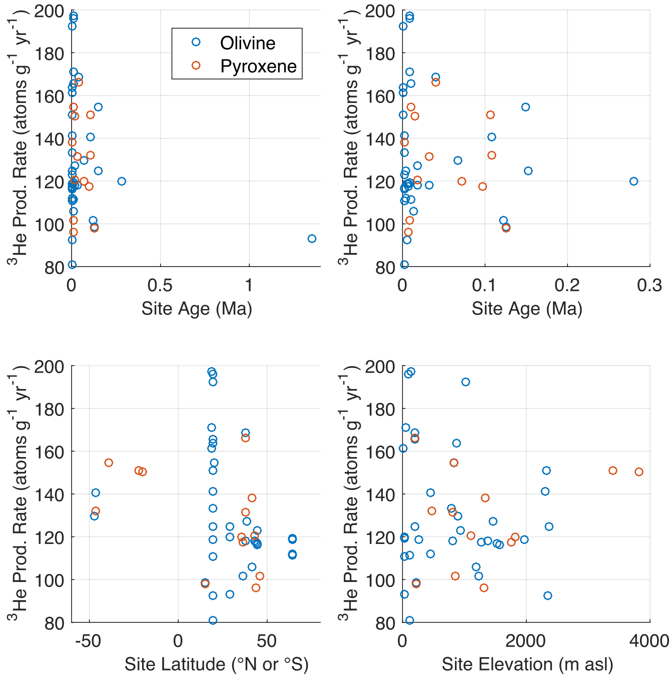

Fig. 1. Reference ^{3}He production rates for all sites used in our analysis shown versus site age, site latitude, and site elevation. Production rates were calculated assuming zero erosion and are shown by mineral phase analyzed following the methods presented here. Reference production rates are shown for the nuclide specific scaling model of Lifton et al. (2014a) (aka LSDn) and the time dependent geomagnetic framework of Lifton (2016). For simplicity we refer to them both hence forth as LSDn.

tween the production rate and age, site latitude or site elevation. To first order this suggests that there are no systematic temporal or spatial biases contained within the geomorphic and scaling models used to derive reference ^{3}He production rates. Yet, several ^{3}He calibration studies have reference production rates that are lower than canonical values even when all studies are scaled using the same parameters and models (e.g., Dunai and Wijbrans, 2000; Fenton et al., 2013; Foeken et al., 2012). The observation of a handful of anomalously low ^{3}He reference production rates raises three possibilities. First, it is possible that temporal variations in the Earth's geomagnetic field (and hence cosmogenic nuclide production) are not adequately described by geomagnetic field reconstructions used in the current scaling models for the handful of specific sites; however, one would expect the appearance of trends more robust than presently observed if this were the case. Second, factors such as laboratory biases might have an influence (Blard et al., 2014), as measurements of cosmogenic ^{3}He are made in several different laboratories using differing procedures and standardizations, and could lead to anomalously low values. Finally, lower reference production rates can result for young flows due to temporary ash or other sediment cover that was later eroded, or from underestimating surface erosion magnitude at a site (Fig. 2). The former scenario is more important for young flows, where a significant portion of the integrated exposure history may have occurred with ash or sediment cover. Considering the absence of any significant spatial or temporal trends in Fig. 1 when reference production rates are calculated using internally consistent scaling systematics and the coefficient of variation due to laboratory biases is smaller than differences in calibrated production rates, we focus our analysis on erosion below.

Here we formalize a Bayesian approach to cosmogenic nuclide production rate calibration, explicitly accounting for uncertainties associated with calibration site erosion characterization. Additionally, our Bayesian approach also allows for non-Gaussian site age

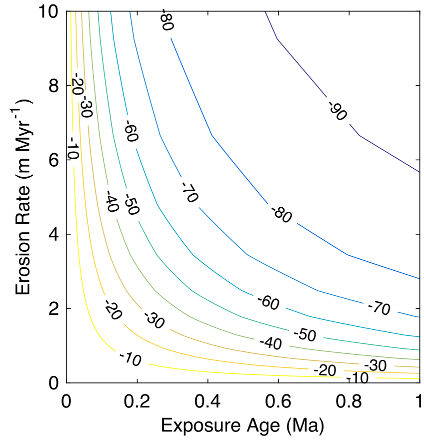

Fig. 2. Plot of the sensitivity of apparent ^{3}He production rate for a range of erosion rates and ages. Contours show the percent underestimation the calculated production rate is relative to the true production rate. Here we assumed a ^{3}He production rate of 120 at g^{-1} yr^{-1} as the true production rate.

probability distributions, much like that of Borchers et al. (2016). The methods presented here can be generalized and applied to the other in situ cosmogenic nuclides. Finally, we present a global reference ^{3}He production rate with lower overall uncertainties than other published compilations because of reduced scatter in the ^{3}He production rate calibration dataset when potential erosion is accounted for. Thus, we are making use of Bayesian thinking in two separate parts of this paper; first, in the development following Equation (1), and second, in the development following Equation (9).

2. Calibration datasets

There are five recent ^{3}He production rate compilations, Goehring et al. (2010), Borchers et al. (2016), Lifton (2016), Delunel et al. (2016), and Martin et al. (2017). The five datasets have many similarities in terms of the sites included in their compilations, with the Borchers et al. (2016), Lifton (2016), Delunel et al. (2016), and Martin et al. (2017) compilations incorporating calibration studies published since 2010, while omitting some of the studies included in Goehring et al. (2010). Exclusion of sites in the Borchers et al. (2016) study followed the criteria outlined by the CRONUS-Earth project for primary and secondary calibration sites, while the Delunel et al. (2016) and Martin et al. (2017) studies were more ad hoc in their exclusions. Since the Borchers et al. (2016) compilation data was finalized for calculation, additional calibration studies have been published from Bolivia (Blard et al., 2013), the island of Fogo (Foeken et al., 2012), Arizona (Fenton and Niedermann, 2014; Fenton et al., 2013), New Zealand (Eaves et al., 2015), and Argentina (Delunel et al., 2016). The complete list of calibration datasets used here is summarized in Table S1. In this study, we take a more inclusive approach and consider each site to have equal weight and therefore do not separate into primary and secondary sites and include all previously published ^{3}He production rate data.

3. Methods

Before proceeding further, we define what we mean by a "site". Some previous compilations have grouped individual calibration sites by geographic proximity and/or age (e.g., Goehring et al., 2010). In this work, a "site" refers to a calibration site as defined first by its age, and second by its geographic location. For example, there may be multiple sites with similar and/or related ages (e.g., Tabernacle Hill and the Lake Bonneville Flood deposits) that are in