Earth and Planetary Science Letters 433 (2016) 257–268

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Implications of two Holocene time-dependent geomagnetic models for cosmogenic nuclide production rate scaling

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ARTICLE INFO

Article history:
Received 17 June 2015
Received in revised form 29 October 2015
Accepted 6 November 2015
Available online 18 November 2015
Editor: A. Yin

Keywords:
geomagnetic field
spherical harmonic
cutoff rigidity
scaling factor
dipole

ABSTRACT

The geomagnetic field is a major influence on in situ cosmogenic nuclide production rates at a given location (in addition to atmospheric pressure and, to a lesser extent, solar modulation effects). A better understanding of how past fluctuations in these influences affected production rates should allow more accurate application of cosmogenic nuclides. As such, this work explores the cosmogenic nuclide production rate scaling implications of two recent time-dependent spherical harmonic geomagnetic models spanning the Holocene. Korte and Constable (2011, *Phys. Earth Planet. Inter.* **188**, 247–259) and Korte et al. (2011, *Earth Planet. Sci. Lett.* **312**, 497–505) recently updated earlier spherical harmonic paleomagnetic models with new paleomagnetic data from sediment cores in addition to new archeomagnetic and volcanic data. These updated models offer improved resolution and accuracy over the previous versions, in part due to increased temporal and spatial data coverage. In addition, Pavón-Carrasco et al. (2014, *Earth Planet. Sci. Lett.* **388**, 98–109) developed another time-dependent spherical harmonic model of the Holocene geomagnetic field, based solely on archeomagnetic and volcanic paleomagnetic data from the same underlying paleomagnetic database as the Korte et al. models, but extending to 14 ka.

With the new models as input, trajectory-traced estimates of effective vertical cutoff rigidity (R_C – the standard method for ordering cosmic ray data) yield significantly different time-integrated scaling predictions when compared to each other and to results using the earlier models. In addition, predictions of each new model using R_C are tested empirically using recently published production rate calibration data for both ^{10}Be and ^{3}He, and compared to predictions using corresponding time-varying geocentric dipolar R_C formulations and a static geocentric axial dipole (GAD) model. Results for the few calibration sites from geomagnetically sensitive regions suggest that the Pavón-Carrasco et al. (2014) time-varying dipolar model tends to predict sea level, high latitude production rates more in line with those from calibration sites not affected by geomagnetic variations. This suggests that uncertainties arising from hemispheric and temporal sampling biases in the Holocene spherical harmonic models considered here, combined with the currently limited spatial and temporal distribution of production rate calibration sites as empirical tests, limit the robustness of the non-dipole aspects of these models for production rate scaling. These analyses should be revisited as such models improve and additional calibration sites become available.

1. Introduction

The geomagnetic field is a key influence on the distribution of charged primary cosmic ray particles incident on the Earth's atmosphere. This spatial variation is reflected in the resulting atmospheric cascade of secondary cosmic rays, some of which interact with terrestrial materials to yield in situ cosmogenic nuclides. Models of how the production rates of these nuclides vary in time and space therefore must account for both geographic variability associated with position within the geomagnetic field and variability arising from time-dependent changes in field strength.

Early representations of the geomagnetic field in cosmic ray and cosmogenic nuclide research relied on static dipolar approximations to the field (e.g., Lal, 1958, 1991; Lal and Peters, 1967; Rose et al., 1956; Simpson, 1951), since the dipole component comprises ca. 90% of the modern field (Butler, 1992). Nishiizumi et al. (1989) recognized the need to account for time-dependent geomagnetic effects on estimating in situ cosmogenic ^{10}Be and

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http://dx.doi.org/10.1016/j.epsl.2015.11.006

^{26}Al production rates from their measured concentrations, but assumed simple dipolar intensity changes. Subsequent models accounted for time-dependent geomagnetic variation using various geocentric dipolar models driven by separate records of paleointensity and paleomagnetic pole position (e.g., Ohno and Hamano, 1992). Dunai (2000) presented a model for scaling in situ cosmogenic nuclide production rates with altitude and latitude that attempted to include non-dipole field effects by adapting a dipolar field approximation incorporating modern geomagnetic inclination measurements. Dunai (2001) expanded on that with a time-varying model adapted to use paleo-inclination records (to approximate non-dipole field effects) and virtual axial dipole moment (VADM) reconstructions (e.g., Guyodo and Valet, 1999; Yang et al., 2000).

Desilets and Zreda (2003) and Lifton et al. (2005) subsequently published in situ cosmogenic nuclide production rate scaling models that accommodated both dipole and non-dipole field effects on cosmic rays using numerically derived effective vertical cutoff rigidities (R_C), a measure of the energy required for primary cosmic rays to penetrate the geomagnetic field to interact with the atmosphere at a given location (see discussion in Lifton et al., 2008). R_C values are computed by numerically tracing the paths of vertically incident antiprotons outward from the Earth's surface to infinity using high-order, static spherical harmonic representations of the modern geomagnetic field, to identify plausible trajectories vs. physically impossible trajectories that arise due to the presence of the solid Earth – a process known as trajectory tracing (e.g., Cooke et al., 1991; Shea et al., 1968). R_C is widely accepted as one of the most accurate means of ordering cosmic-ray measurements (e.g., Grieder, 2001). Still, these scaling models relied on dipolar representations to model time-dependent fluctuations in the paleo-geomagnetic field – in large part because millennial-scale, time-dependent, high-order spherical harmonic models were lacking.

This changed when Korte and Constable (2003) first developed such a model (CALS3k.1) spanning the last 3000 yr, based on a global paleomagnetic dataset comprising lake sediment and archeomagnetic time series. The model combined a spatial spherical harmonic inversion with a temporal cubic B-spline fit. Using a newer and larger global data compilation (Korte et al., 2005), Korte and Constable (2005a) subsequently extended their original model to cover 0–7 ka (CALS7k.2). Lifton et al. (2008) used this model to generate global trajectory-traced R_C grids at 500-yr intervals over that period. Contrary to the common assumption in cosmogenic nuclide studies that non-dipole effects are transient and average out relatively rapidly (e.g., Gosse and Phillips, 2001), that study indicated that time-integrated non-dipole effects could persist for millennia – a significant finding since a prominent application for in situ cosmogenic nuclides is surface exposure dating over the past ca. 20 ka. This work builds on that study and compares the implications for cosmogenic nuclide scaling of two new spherical harmonic paleomagnetic models that span the Holocene, along with corresponding time-dependent dipolar implementations derived from those models as well as a static dipolar model.

1.1. *Geomagnetic records commonly in use*

The CRONUS online calculator (Balco et al., 2008) is one of the most commonly used tools to calculate surface exposure ages and/or steady-state erosion rates from in situ cosmogenic nuclide measurements. The geomagnetic framework in that calculator utilizes the CALS7k.2 R_C grids from Lifton et al. (2008) from 0–7 ka, coupled with global geocentric axial dipolar (GAD) R_C models for older ages (Balco et al., 2008; Elsasser et al., 1956). From 7–12 ka, the Virtual Dipole Moment (VDM) model of Yang et al. (2000), based on volcanic and archeomagnetic paleointensity and directional data, is used to drive a GAD R_C model. From 12 ka–800 ka, on the other hand, the calculator drives a GAD R_C model using the SINT-800 global Virtual Axial Dipole Moment (VADM) model (Guyodo and Valet, 1999). VADMs differ from VDMs in that VADMs are derived only from paleointensity data, while VDMs include directional information as well. SINT-800 is based on 33 stacked paleointensity records from broadly distributed oceanic sediment cores, providing global coverage.

Lifton et al. (2014) updated this framework to include a newer continuous geomagnetic model with significantly higher temporal and spatial resolution, covering the last 3 ka (CALS3k.3) (Korte et al., 2009). They generated global grids of R_C values at 100-yr intervals from CALS3k.3 from 0–3 ka, as well as from CALS7k.2 from 3–7 ka, in contrast to the 500-yr intervals utilized by Lifton et al. (2008) and Balco et al. (2008) (Fig. 1). While the geomagnetic records are referenced to the 0 ka of radiocarbon dating ("present" being 1950 CE), Lifton et al. (2014) expanded that time series to allow for recent in situ cosmogenic sampling by adding R_C grids generated from decadal Definitive Geomagnetic Reference Fields (DGRFs) covering 1950–2010 (Finlay et al., 2010).

Rather than use a simple dipolar R_C model beyond 7 ka (e.g., Elsasser et al., 1956), Lifton et al. (2014) generated trajectory-traced R_C values using a GAD field with variable dipole moment, fit by a 6th-order polynomial of latitudinal cosines – an approach similar to that of Desilets and Zreda (2003). This formulation was then driven by a hybrid paleointensity reconstruction based on GLOPIS-75 (Laj et al., 2004) and PADM2M (Ziegler et al., 2011). GLOPIS-75 is a high-resolution global VADM model from 0–75 ka that is calibrated with the Yang et al. (2000) data and other volcanic paleointensities $<$20 ka. Lifton et al. (2014) used GLOPIS-75 from 7–18 ka, at which point the long-term dipole moment record was switched to PADM2M since both records exhibited similar values and trends at 18 ka. PADM2M was selected over long-term VADM models such as SINT-800 (Guyodo and Valet, 1999) or SINT-2000 (Valet et al., 2005) because it was designed to address bias in recovering geomagnetic variability from VADM datasets.

This geomagnetic framework drives the new CRONUScalc online calculator (Marrero et al., 2015, http://web1.ittc.ku.edu:8888/1.0/). Differences between time-integrated scaling factors generated using the LSD flux-based scaling model of Lifton et al. (2014) and this framework, relative to those predicted with LSD using a static trajectory-traced modern GAD model (Lifton et al., 2014), are presented in Fig. 1 for comparison, assuming time-integrated exposures at sea level of 2, 5, 8, and 12 ka. Common to the Lifton et al. (2014) framework and the GAD are atmospheric conditions based on the ERA-40 re-analysis of mean sea level pressure and 1000-mb temperature (Uppala et al., 2005), and solar modulation effects modeled following Lifton et al. (2014).

The resulting framework predicts a couple of notable persistent features relative to the GAD model (Fig. 1). First, sea level scaling factors in the Northern Hemisphere mid- and low latitudes are typically lower than those predicted by the GAD. This effect is particularly pronounced in the Northern Hemisphere in the north Pacific Ocean, Middle East, and north Atlantic Ocean, and is strongest in times of a strong dipolar field (Fig. 2), when scaling factor differences of greater than 15% are predicted relative to a GAD. This trough-like pattern is generally stable throughout the 12 ka modeled period, but decreases in magnitude as the time-integrated effects of a lower dipole moment in the early to middle Holocene are factored in. The weaker dipole moment in the early to middle Holocene also leads to prediction of a corresponding ridge-like pattern at Southern Hemisphere low to mid-latitudes – for 8 ka exposures the Lifton et al. (2014) scaling factors in those regions exceed those of a GAD by $>$5–10%, whereas for a strong