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Correction of in situ cosmogenic nuclide production rates for geomagnetic field intensity variations during the past 800,000 years

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Abstract—We present integrated relative production rates for cosmogenic nuclides in rock surfaces, which take into account reported variations of the geomagnetic field intensity during the past 800,000 yr. The calculations are based on the model simulating cosmic ray particle interactions with the Earth's atmosphere given by Masarik and Beer ["Simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere," *J. Geophys. Res.* 104(D10), 12099–12111, 1999]. Corrections are nearly independent on altitude between sea level and at least 5000 m. The correction factors are essentially identical for all stable and radioactive cosmogenic nuclides with half-lives longer than a few hundred thousand years. At the equator, integrated production rates for exposure ages between ~40,000 to 800,000 yr are 10 to 12% higher than the present-day values, whereas at latitudes >40°, geomagnetic field intensity variations have hardly influenced in situ cosmogenic nuclide production. Correction factors for in situ ^{14}C production rates differ from those of longer-lived nuclides. They are always smaller than ~2% because the magnetic field intensity remained rather constant during the past ~10 kyr, when the major fraction of the ^{14}C extant today was produced. *Copyright © 2001 Elsevier Science Ltd*

1. INTRODUCTION

Interactions of charged cosmic ray protons and alpha particles with the Earth's atmosphere produce secondary cosmic ray neutrons. A small part of these reach the ground where they produce stable and radioactive nuclides in near-surface rocks. These in situ–produced cosmogenic nuclides have become a very important tool in quantitative geomorphology because they allow determination of the time a sample spent within the uppermost few meters of the Earth's surface. Possibilities and limitations of this surface exposure dating method have recently been reviewed by Lal (2000) and Gosse and Phillips (2001).

For these studies, a precise knowledge of in situ nuclide production rates for the samples under investigation is essential. The neutron flux reaching the Earth's solid surface depends on the atmospheric shielding, and hence production rates are higher at higher altitude. The flux of charged particles in the upper atmosphere and therefore the neutron flux at the surface of the Earth also depend on the intensity of the geomagnetic field. The shielding effect of the geomagnetic field is stronger at low latitudes than near the poles, where the field lines are nearly perpendicular to the Earth's surface such that charged particles of all energies reach the atmosphere nearly unhindered. With the present-day field intensity, in situ cosmogenic nuclide production at sea level is therefore almost twice as high near the poles than at the equator. Pioneering work on cosmogenic nuclide production systematics on the Earth was carried out by Lal and Peters (1967). Today, most workers use the scaling factors describing production rate dependencies as a function of latitude and altitude above sea level presented by Lal (1991) or Dunai (2000).

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When adopting these scaling factors or production rates determined from model calculations (e.g., Masarik and Reedy, 1995) or independently dated samples (e.g., Nishiizumi et al., 1989; Cerling and Craig, 1994a; Niedermann et al., 1994; Kubik et al., 1998), it is usually assumed that the geomagnetic field intensity has remained constant during the time period of interest. There is, however, clear evidence that this has not been the case (cf. Bard et al., 1990; Guyodo and Valet, 1996, 1999; Frank et al., 1997). Hence, commonly adopted production rates may be inaccurate, particularly for low-latitude samples. Attempts to estimate necessary corrections have been made in several studies, mostly for the age range up to 10^5 yr, with significantly different results, however (e.g., Nishiizumi et al., 1989; Kurz et al., 1990; Cerling and Craig, 1994b; Shanahan and Zreda, 2000).

The purpose of this article is to determine a detailed latitude-dependent correction of in situ production rates for geomagnetic field intensity variations for the last 800 kyr on the basis of a purely physical model. This model describes cosmic ray–charged particle interactions with the terrestrial atmosphere and the subsequent production and transport of the secondary particle cascade (Masarik and Beer, 1999) as a function of the intensity of the geomagnetic field. As input for the model, we will use mostly the paleointensity reconstruction by Guyodo and Valet (1999; see also Guyodo and Valet, 1996), who combined a large number of records of variations of the field intensity obtained from marine sediments to provide a continuous record for the past 800,000 yr. The reliability of this paleomagnetic approach to reconstruct geomagnetic field intensity has been validated on different time scales by a number of reconstructions of past atmospheric cosmogenic nuclide production rates (Bard et al., 1990; Frank et al., 1997; Kitagawa and van der Plicht, 1998; Stuiver et al., 1998). These records are generally consistent with each other and show that the field intensity has gradually increased by a factor of ~2.5 from ~40 kyr BP until 10 kyr BP and has stayed rather constant since. Between 40 and 800 kyr BP, the field has mostly been lower than the present-day value by ~30% (Guyodo and Valet, 1999). This means that on average, low- to midlatitude production rates were higher than at present for all exposure ages between ~10 and 800 kyr BP. For the past 10 kyr, we rely on a translation of dendrochronologically derived $\Delta^{14}C$ data (Stuiver et al., 1998) into geomagnetic field intensity. For the past 200 kyr, the results will be compared with those based on the paleointensity reconstruction by Frank et al. (1997). We present our correction factors in a way allowing readers to choose their preferred present-day production rates as well as scalings for latitude and altitude. We will also compare our results with other estimates of the effects of time-variable magnetic field intensity on nuclide production, notably a recent study by Dunai (2001, pers. comm.). This work is based on the same field reconstruction as the one adopted here but takes another approach, one relying on an analytical expression of the cutoff rigidity (see section 3) as a function of the paleomagnetic field intensity.

2. MODEL CALCULATIONS

Our model for the simulation of the interaction of primary and secondary galactic cosmic ray particles with matter is based on the GEANT (Brun et al., 1987) and MCNP (Briesmeister, 1993) codes. This code system is described in detail elsewhere (Masarik and Beer, 1999) and we repeat here only its main features relevant for the present study.

Only primary galactic protons with energies between 10 MeV and 100 GeV are considered. Solar cosmic ray particles are ignored, and galactic alpha particles are only taken into account by multiplying the primary proton flux by a factor of 1.44. Because we are solely interested in production rate changes as a function of the magnetic field, this factor (as well as the value of the primary proton flux) cancels out. We also do not consider nuclide production by muons, but we expect correction factors that would include this contribution to be identical within statistical uncertainties with those reported below because the codes indicate a similar behavior for fast muons and fast neutrons. The Earth's atmosphere is modeled as a spherical shell with an inner radius of 6378 km and a thickness of 100 km and chemical composition (in weight percentage): 75% N, 23.2% O, and 1.3% Ar. The total thickness of the atmosphere is 1033 g cm^{-2}, and its density and temperature structure is in accordance with U.S. standard atmosphere. The elemental composition of the surface is assumed to be the average terrestrial one (in weight percentages: 0.2% H, 47.3% O, 2.5% Na, 4.0% Mg, 6.0% Al, 29% Si, 5% Ca, and 6% Fe). The statistical errors of the calculations are on the level of 4 to 6%.

The solar magnetic field also influences the flux of galactic cosmic rays arriving on Earth. This solar modulation is taken into account in the expression for the differential primary galactic cosmic ray (GCR) proton flux (Masarik and Reedy, 1994) and is assumed to be constant in these simulations. The GCR source flux beyond the heliosphere is assumed to be constant because no firm evidence for a possible temporal variability on time scales relevant here exists.

3. GEOMAGNETIC MODULATION OF THE COSMOGENIC NUCLIDE PRODUCTION

The magnetic field of the Earth deflects incoming cosmic ray particles depending on their magnetic rigidity, R, and angle of incidence. The rigidity of a particle is defined as the momentum per unit charge, $R = pc/Z_e$, where p is the momentum, Z_e is the charge of the particle, and c is the velocity of light. For each angle of incidence, there is a critical rigidity below which the incoming particle cannot reach the Earth's atmosphere. We use the world grid of calculated cosmic ray vertical cutoff rigidities for the year 1980 (Shea and Smart, 1983) to determine the nonvertical cutoffs. In the calculations, we divide the Earth's surface in latitudinal bins of 10° and change the field values according to the adopted paleorecords in steps of 0.25 times the current field to cover the field changes between almost zero and about two times the current intensity during the last 800 kyr (see below).

At present, the terrestrial magnetic field can well be approximated by a pure dipole because nondipole components are minor (Acton et al., 1996). For the present-day field, the nondipole components are taken into account in our calculations via the adopted cutoff rigidities (Masarik and Beer, 1999). However, we suppose that in the past only the absolute values of the field intensity varied, because in our calculations, the shape of the field stays unchanged, and therefore the variations in field intensity correspond just to a multiplication of the adopted cutoff rigidities by an appropriate constant. This assumption will not be correct for times of low field intensity, where mainly the dipole component decreases. Although this cannot be quantitatively modeled with present-day information on paleomagnetic field intensities, this effect probably results in a slight overestimation of our correction factors for low latitudes and a slight underestimation at high latitudes. We also assume that the poles of the magnetic field always coincide with the geographic poles of the earth, which is justified for periods longer than ~10 kyr (Gosse and Phillips, 2001).

The dependence of production rates on the magnetic field varies with altitude because the shape of the energy spectrum of the secondary cosmic ray neutrons is a function of the atmospheric depth. However, this will only be relevant for altitudes >10 km because at depths exceeding ~150 g/cm^2, the shape of the neutron energy spectrum remains constant after having reached an equilibrium state. Our calculations indeed show that all relative production rate changes between 0 and 5000 m agree within the statistical uncertainties of the respective calculations, and therefore this effect is not relevant for in situ production rates. In the figures, we will therefore only show the curves for sea level. The latitudinal dependence of production rates of all investigated nuclides on geomagnetic field intensity can by fitted by a polynomial of fifth degree, whereby the polynomial coefficients depend on the nuclide. However, the calculations revealed again that within statistical uncertainties, production rate ratios for nuclides produced by spallation reactions are independent of solar modulation and geomagnetic field intensity. Therefore, the relative production rate curves we will present are valid for all spallogenic nuclides calculated: ^{3}He, ^{14}C, ^{21}Ne, ^{10}Be, ^{26}Al, and ^{36}Cl.

4. PALEOMAGNETIC FIELD INTENSITY RECORDS

Records of past magnetic field intensity have been obtained from paleomagnetic studies on unconsolidated marine sediments from which the natural remnant magnetization can be reconstructed after normalization for changes in lithogenic parameters (Guyodo and Valet, 1996, 1999). The validity of this approach has recently been confirmed by a reconstruction of paleointensity from sediments with strong, climatically caused variations in lithology and magnetic susceptibility (Haag, 2000). An alternative approach is the reconstruction of production rates of cosmogenic radionuclides in the atmosphere, which can be translated into geomagnetic field intensity variations (Lal, 1988; Masarik and Beer, 1999). Such a record for the past ~45 kyr has, for example, been obtained from the systematic differences between ^{14}C and U/Th datings of the same coral samples (Bard et al., 1990) or discrepancies between ^{14}C and dendrochronological datings (Stuiver et al., 1998; for an overview, see also Frank, 2000). Reconstructions on the basis of $\Delta^{14}C$ are, however, also influenced by changes of the deep water circulation of the ocean, which have to be accounted for (cf. Broecker et al., 1990; Bard, 1998). This is particularly important for comparison of last glacial and Holocene values because it has been shown from circulation models that ~20% of the total ~500‰ increase in $\Delta^{14}C$ during the last glacial maximum (cf. Bard, 1998) has been caused by ocean circulation changes. A record of ^{10}Be production rates for the past 200 kyr avoids this problem due to the insensitivity of ^{10}Be to ocean circulation changes (Frank et al., 1997). Records obtained from these and other sources show consistent results (Bard, 1998; Frank, 2000). Influences on these field intensity reconstructions by other factors such as residual climatic signals (Kok, 1999) are considered insignificant for this study (see Frank, 2000, for discussion).

Major minima in field intensity, and thus maxima in atmospheric and in situ–produced cosmogenic radionuclides, have occurred during periods of geomagnetic excursions such as the Laschamps or the Biwa I events ca. 40 and 190 kyr BP, respectively. Other than these minima, the field went through well-resolved fluctuations on different time scales. One of the most prominent of those is a constant increase of field intensity from the minimum at 40 kyr BP until ~10 kyr BP. In general, the studies above agree in that the field intensity during the past 800 kyr has mostly been lower than today by an overall ~30% (Guyodo and Valet, 1999). This means that on average, low- to midlatitude in situ production rates were higher than at present for exposure ages older than 10 kyr.

As input for the model, we will use mostly the magnetic field reconstruction based on a global stack of paleomagnetic data from marine sediments by Guyodo and Valet (1999). Their data set, which dates back to 800 kyr BP, is currently the most reliable continuous record. It yields only relative paleointensity variations. Guyodo and Valet (1999) calibrated their record with absolute paleointensities obtained from a discontinuous record of lava flows for the past 40 kyr. The mean virtual axis dipole moment (VADM) of the calibrated data of the past 10 kyr, except the one at 2 kyr BP, is very close to the present-day VADM of 8.0×10^{22} Am^2. We normalized the 800-kyr VADM data set to this present-day value of the VADM. This yields a very good correspondence with independent reconstructions of field intensity obtained from other approaches—for example, stacking ^{10}Be deposition rates (Frank et al., 1997), $\Delta^{14}C$ data derived from calibrations of ^{14}C ages in corals by U/Th dating (Bard et al., 1990), or varve counting of lake sediments (Kitagawa and van der Plicht, 1998). The only significant difference to these other reconstructions is a somewhat smaller amplitude of the major variations in the normalized 800-kyr VADM data set. To estimate the effect of this difference on the results of our calculations, we will therefore also show the modeling results by use of the 200-kyr paleointensity reconstruction of Frank et al. (1997) from the global stack of ^{10}Be deposition rates in the marine sediments. For the past ~10 kyr, data derived from marine sediments have to be considered with great caution because the tops of gravity cores become mostly disturbed during coring, which results in the relatively high statistical uncertainties in the paleointensity reconstructions (Guyodo and Valet, 1996, 1999; Frank et al., 1997). For this period, we therefore adopt the dendrochronologically derived $\Delta^{14}C$ record (Stuiver et al., 1998) to reconstruct relative field intensity because for the Holocene, major ocean circulation changes affecting the $\Delta^{14}C$ significantly can be excluded. The high quality of the dendrochronological time scale in conjunction with the $\Delta^{14}C$ data renders this the most precise record of paleointensity for the past 10 kyr. This record clearly excludes the occurrence of any major field intensity excursions relevant for the reconstruction of in situ production rates for the past 10 kyr.

5. RESULTS

The dotted lines in Figures 1 and 2 show the relative magnetic field intensities adopted in this work. The thin solid lines represent the corresponding variation of the instantaneous in situ production rate at the Earth's surface, calculated for 0 to 10° latitude. In this latitude bin, the variations are largest, yet we note that the instantaneous production rate varies considerably less than the magnetic field. For example, at 780 kyr ago, the field intensity was almost an order of magnitude lower than the present-day value, but the production rate was only 40% higher than today, even at the equator. This is substantially less than the increase of almost a factor of two predicted for global atmospheric ^{10}Be or ^{14}C production for such a low field (Masarik and Beer, 1999; see also Frank, 2000). As noted in section 3, the reason for this difference is that the energy spectrum of cosmic ray neutrons in the stratosphere, where most of the atmospheric ^{10}Be and ^{14}C production occurs, differs from the neutron spectrum near ground.

The thick solid lines show the average production rate integrated from present day to the respective time. This is the parameter directly relevant for exposure age calculations. Note that integrated production rates are robust to short-term changes in field intensity, which means that for calibrating exposure ages, it is insignificant whether the surface exposure of a sample started just before or after any of the pronounced field excursions.

Figures 3A and B present the curves relevant to correct integrated production rates for paleomagnetic field intensity. The integrated production rates are shown for various latitude bins, normalized to the present-day value (the uppermost curve in both figures is the same as the respective thick solid lines in

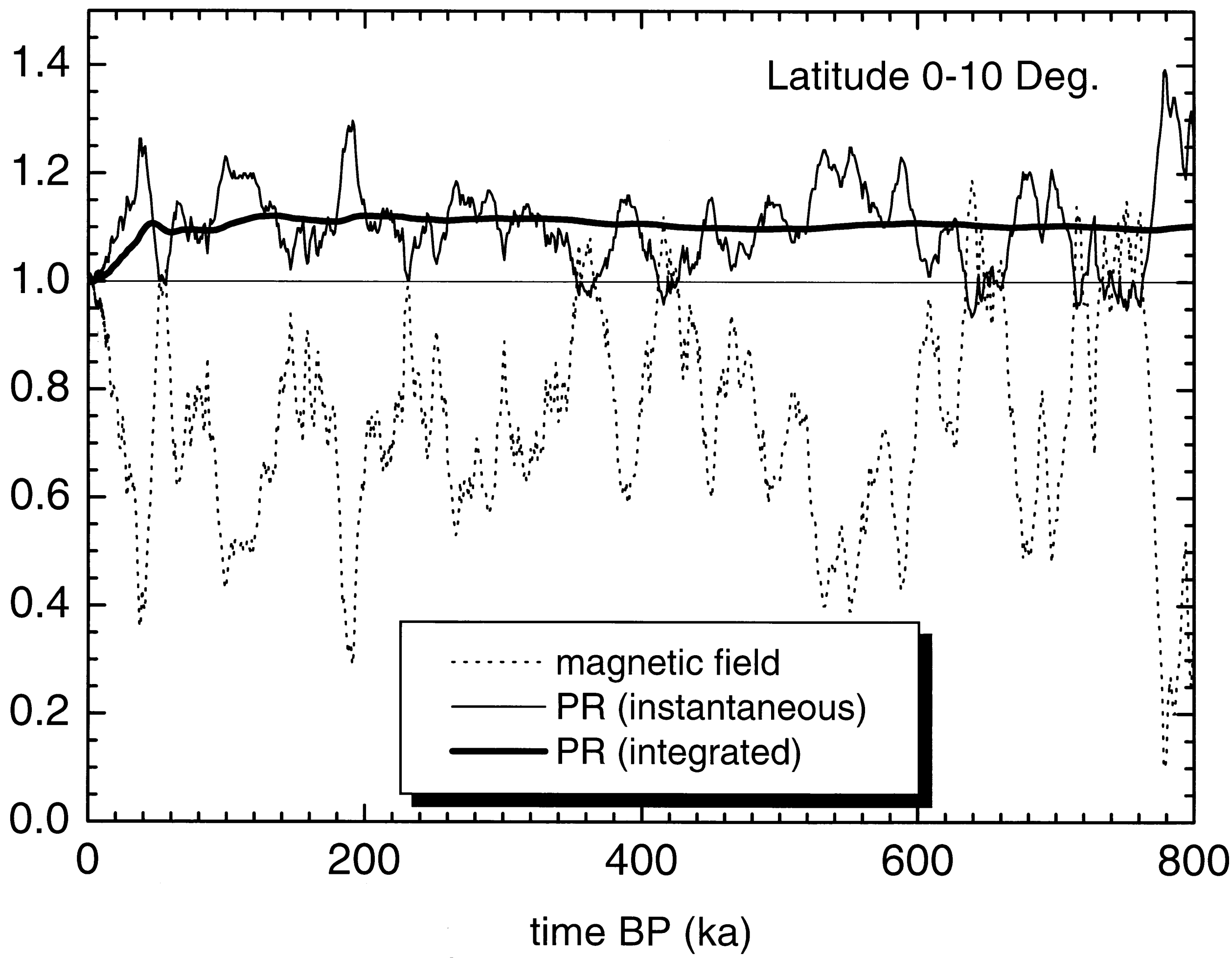

Fig. 1. Relative magnetic field intensity in the past 800 kyr adopted in this work (dotted line). For the past 10 kyr, we used the field reconstruction based on the dendrochronologically derived $\Delta^{14}C$ record (Stuiver et al., 1998). For the period 10 to 800 kyr, we rely on the reconstruction by Guyodo and Valet (1999). The instantaneous production rate (PR) of cosmogenic nuclides in rocks calculated here is shown (thin solid line), normalized to the present-day production rate and for the latitude range 0 to 10°. The resulting mean or integrated relative production rate for samples exposed ever since the time given on the abscissa up to the present is also shown (thick solid line), again for 0 to 10° latitude.

Figs. 1 and 2). At low latitudes, the integrated production rate increases between ~5 and 40 kyr more or less linearly with exposure age to ~10% above the present-day value and remains then ~9 to 12% higher than at present until 800 kyr ago. For higher latitudes, the influence of the magnetic field becomes smaller, as has been noted earlier (e.g., Lal, 1991). Already at 30 to 40°, the integrated production rates do not vary by more than 2%, which is less than several other sources of uncertainty that need to be assigned to production rates. At higher latitudes, the magnetic field variations essentially do not influence cosmogenic nuclide production rates at all. This reflects the fact that at higher latitudes, cutoff rigidities are so low that particles of more or less all energies are allowed to penetrate even at times of high field intensity.

For radionuclides, an excursion in field strength (and instantaneous production rate) that occurred a long time ago will influence the present-day nuclide concentration less than an excursion of same magnitude and duration that happened recently, because a larger fraction of the radioactive atoms from an early event will have decayed already. In contrast, for stable nuclides, both these excursions will lead to the same variations of their present-day concentrations. Therefore, the apparent integrated relative production rates for radionuclides and stable nuclides are not identical. For ^{36}Cl (half-life 300,000 yr), this is illustrated in Figure 3A. The dashed line represents the decay-corrected integrated production rate for this radionuclide in the 0 to 10° latitude bin. Obviously, for the time period up to 800,000 yr BP considered here, the decay of ^{36}Cl can almost be neglected because the dashed line is nearly identical to the uppermost solid line, which is for stable nuclides in the same latitude range. The only difference is a slight flattening of the ^{36}Cl curve at higher ages. For ^{26}Al and ^{10}Be, which have longer half-lives than ^{36}Cl, the differences are even smaller (curves not shown). Hence, for practical purposes, the stable nuclide curves also apply for the radionuclides most commonly used for exposure dating. This is not the case for ^{14}C, which has a half-life of only 5730 yr. Few analyses of in situ–produced ^{14}C in terrestrial samples have been published so far, but the

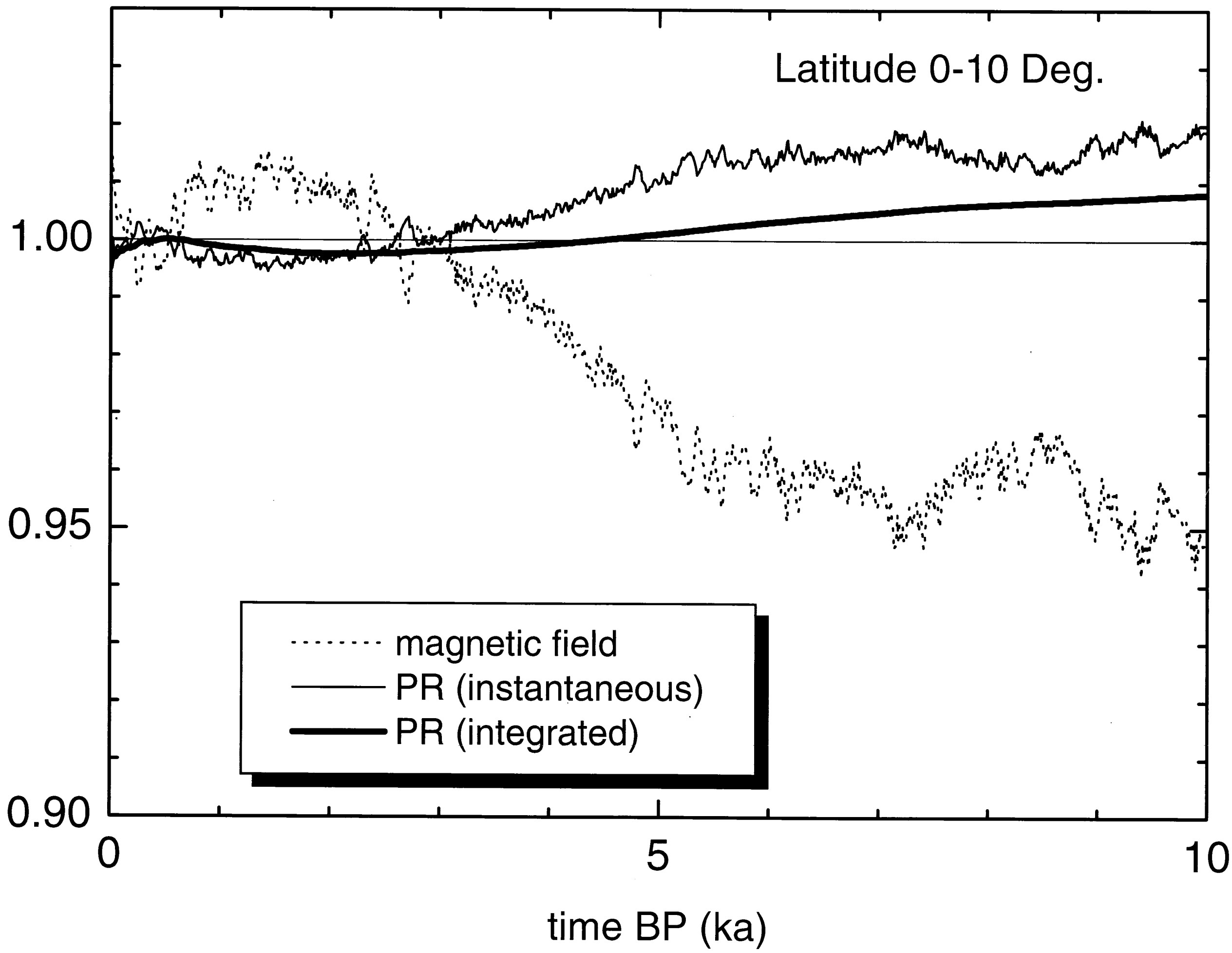

Fig. 2. Same as Figure 1, but for the interval 0 to 10 kyr BP only, the age range for which we adopted the $\Delta^{14}C$-derived paleointensity record (dotted line, Stuiver et al., 1998). PR, production rate.

method has potential for the age range below 10 or 20 kyr, in particular to determine erosion rates in conjunction with other nuclides (Lifton et al., 2001). The inset of Figure 3B shows the decay-corrected integrated ^{14}C calibration curves for 0 to 10° and 20 to 30°, respectively. Accordingly, magnetic field intensity variations can almost be neglected for ^{14}C. The maximum correction of ~2% is considerably less than the respective value for stable nuclides in the same latitude bin and age range. This may seem astonishing, given that the instantaneous global atmospheric ^{14}C production rate varied by ~10% during the past ~2 half-lives of ^{14}C, the period during which most of the now extant ^{14}C was produced. However, as noted above, integrated production rates are smoothed compared to instantaneous production rates, and furthermore, production rates in the stratosphere where most of the atmospheric ^{14}C is produced depend more on the magnetic field intensity than at lower altitudes (cf. Masarik and Beer, 1999).

Uncertainties of the relative integrated production rates shown in Figure 3 are difficult to assess. The statistical uncertainties introduced by the particle flux calculations are ~4 to 6% only, and uncertainties of cross sections cancel out. Guyodo and Valet (1999) and Frank et al. (1997) report standard errors on the order of 15 to 20% for their stacked paleofield records, but short-term variations of such amplitudes around the adopted smoothed field intensity curves have no significant influence on the integrated nuclide production rates, as we noted above. Therefore, systematic errors in the paleomagnetic records are the main potential source of uncertainty of the nuclide production rate corrections proposed here. Figure 4 is an attempt to evaluate the magnitude of such systematic errors. The figure compares the relative integrated production rates calculated on the basis of two different reconstructions of field intensity (Frank et al., 1997; Guyodo and Valet, 1999). The two curves mostly agree within better than 30% of the proposed correction, a number we consider as a reasonable estimate for their uncertainty. However, in the interval ~50 to 90 kyr, the correction factors deduced with the Frank et al. (1997) record are roughly 50% higher than those based on Guyodo and Valet (1999). Hence, for this age interval, this higher uncertainty seems appropriate. Note that part of the discrepancy between the two records may be caused by the normalization of the ^{10}Be-based field reconstruction, which cannot be related to an absolute present-day value (Frank et al., 1997).

The results presented here are similar to those given by

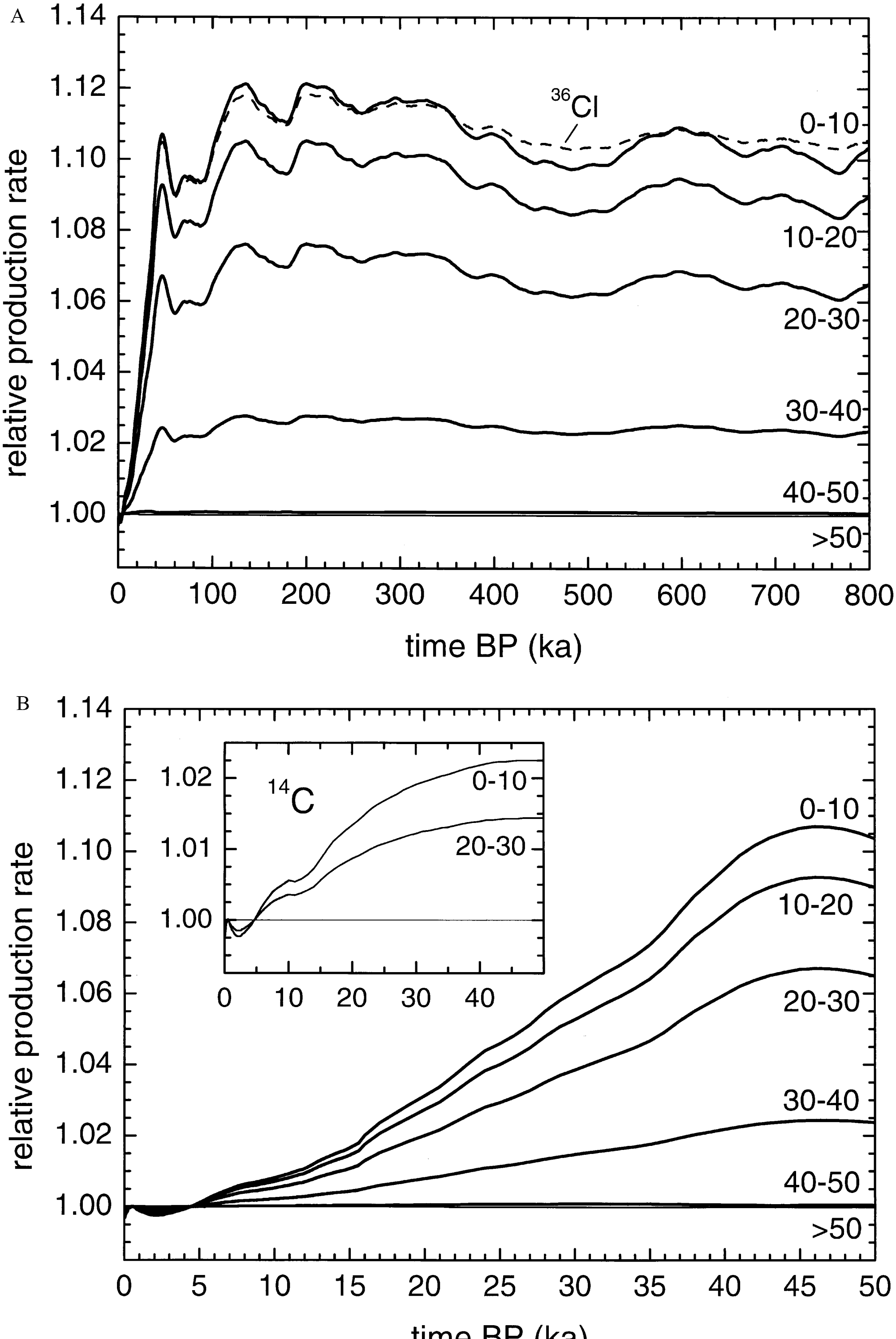

Fig. 3. (A) Figure to be used to correct production rates for paleomagnetic field variations. Shown are relative mean production rates of cosmogenic nuclides in samples exposed between the time given on the abscissa and the present day. The curves are based on the paleofield reconstructions shown in Figures 1 and 2. The different lines are for various latitude bins (in degrees); the uppermost solid line is the same as the thick line in Figure 1. Solid lines, stable nuclides; dashed line, apparent mean production rate for ^{36}Cl (half-life 300 kyr) at 0 to 10°. The latter line takes into account the decay of this nuclide—that is, the fact that an early excursion of the magnetic field affects the present-day ^{36}Cl concentration less than a more recent field excursion of the same magnitude and duration. For practical purposes, this effect is negligible for all radionuclides commonly used for in situ exposure dating, except ^{14}C (Fig. 3B). (B, main panel) Blow-up of A for the age range 0 to 50 kyr BP. (B, inset) Decay-corrected curves for ^{14}C for two latitude bins. For this nuclide, corrections are considerably less than for stable or longer-lived radioactive nuclides.

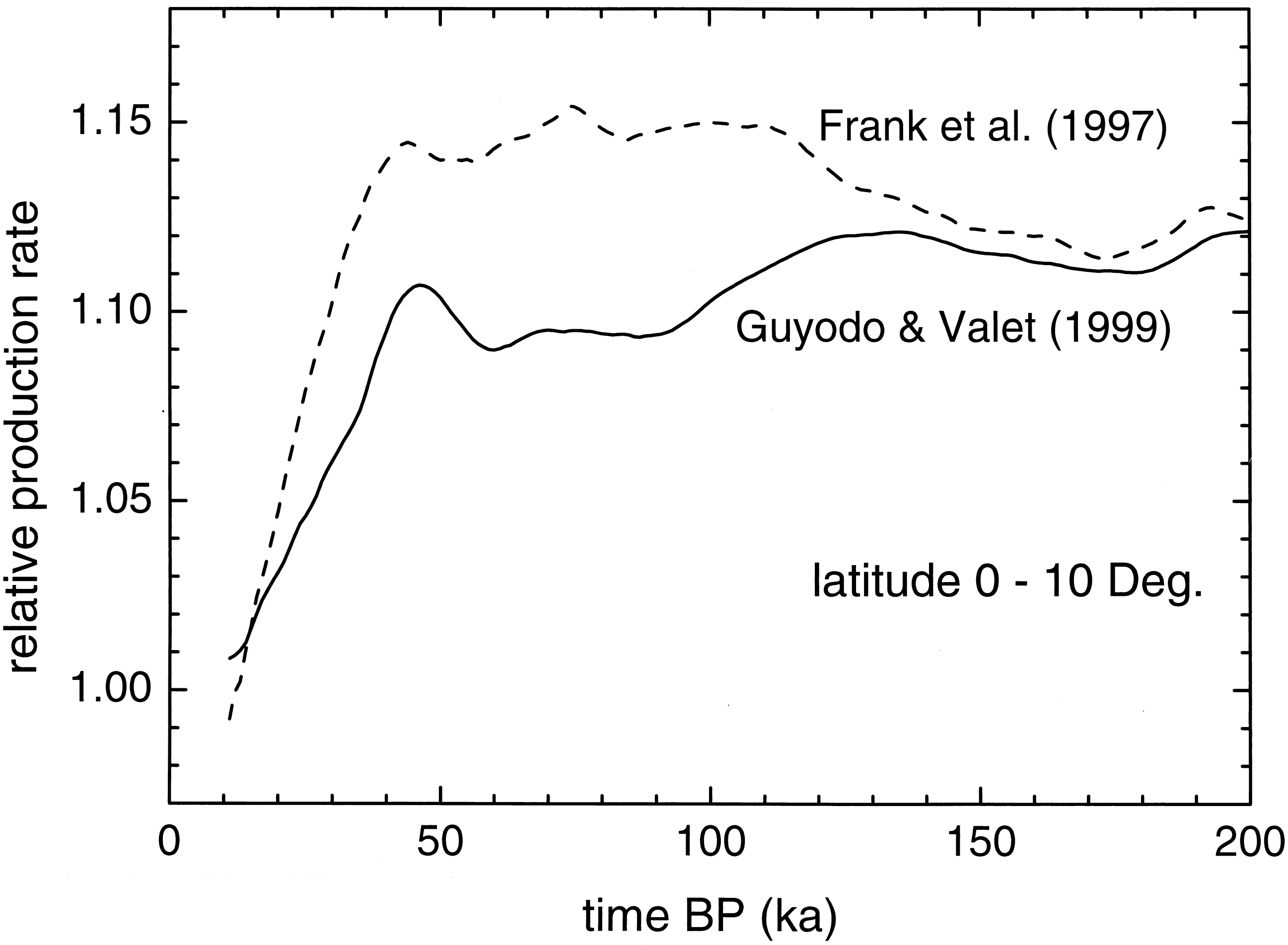

Fig. 4. Comparison of the calculated corrections of production rates for the 0 to 10° latitude bin according to two different magnetic field intensity reconstructions by Guyodo and Valet (1999) and Frank et al. (1997) for the age range 10 to 200 kyr ago.

Dunai (pers. comm.), although his corrections are substantially higher than ours. For example, the integrated production rate for 130 kyr samples at 0 to 10° is higher than the present-day value by ~19% according to Dunai and by 12% according to our work. At midlatitudes, the differences become even more significant. For 130-kyr samples, we calculate in the 30 to 40° bin only a ~2.5% effect, in contrast to 15% (30°) and 6.5% (40°), respectively, obtained by Dunai. Furthermore, we do not observe the ~10% dip in the integrated production rate for ~2 kyr samples reported by Dunai, which is explained by the fact that we adopt the more reliable $\Delta^{14}C$-based field reconstruction for the first 10 kyr.

We do not agree with corrections proposed by Cerling and Craig (1994b) and Shanahan and Zreda (2000), respectively. The latter workers report corrections on the order of +20% for exposure ages in the 8- to 12-kyr range for samples from equatorial Africa (2°S) and Bolivia (19°S), respectively, whereas according to our calculations, these ages need to be corrected by no more than ~1%, and the correction has the reverse sign. Furthermore, all low-latitude samples older than a few ten thousand years need a substantial correction according to our work, which seems to contradict the statement by Shanahan and Zreda that “variations in the geomagnetic field strength should average out over times longer than about 50 kyr.” Cerling and Craig (1994b) present integrated production rates for ages up to 80 kyr. The maximum correction occurs at ~45 kyr BP and amounts to ~38 and ~10% above the present-day value at the equator and at 40°, respectively. These correction factors are also much higher than the respective values proposed here.

6. DISCUSSION

Temporal variations of the geomagnetic field have had a considerable influence on in situ production rates of cosmogenic nuclides at tropical sites. Near the equator, the integrated production rate is 10 to 12% higher than the present-day value for samples with exposure ages between ~40 and 800 kyr. At 20 to 30° latitude, the respective increase is still 6 to 7%. Such corrections are significant compared to other sources of error and have therefore to be taken into account. Once the underlying paleomagnetic field reconstructions become more precise, the accuracy of the corrections will be improved. Before 800 kyr BP, the intensity of the geomagnetic field is not very well constrained. Juarez and Tauxe (2000) conclude that the present-day field is probably stronger that the long-term mean value. They deduce a mean VADM of $\sim 5.5 \times 10^{22}$ Am^2 for the past 5 Myr and note that this is comparable to the average value of 4.2×10^{22} Am^2 for the period 5 to 160 Myr. Their mean value for the past 5 Myr is almost identical to the mean of the Guyodo and Valet (1999) record between 40 and 800 kyr. Until better data become available, we therefore suggest to use for exposure ages above 800 kyr the same correction factors as for 800-kyr-old samples (Fig. 3A). However, integrated production rates for such older samples are clearly less well constrained than for younger samples.

Exposure ages are corrected for the temporal variability of the geomagnetic field by dividing the uncorrected age with the appropriate relative production rate coefficient to be read off Figure 3. For example, if a sample at 15° latitude has an uncorrected age of 400 kyr, the paleofield-corrected age will be ~9% lower, or ~365 kyr, because the production rate during this time has mostly been higher than today. Note that the correct abscissa value in Figure 3 to deduce the correction factor is actually the true (field corrected) age and should thus be determined iteratively, although in practice this iteration will hardly be necessary.

Before the above correction can be applied, it has to be ascertained whether a production rate from the literature used to calculate first the "uncorrected" exposure age might itself have to be renormalized to present-day field intensity. This may be necessary for production rates obtained from natural samples that were independently dated. An example is the ^{3}He production rate determined by Dunai and Wijbrans (2000) that uses lava flows from the Canary Islands at 29°N dated to ~150 to 1350 kyr by the ^{39}Ar-^{40}Ar method. According to Figure 3, the reported value of 118 ± 11 atoms/(g $\times$ a) (for sea level and high latitude) needs to be corrected downward by 4 to 5% to take into account the paleomagnetic field correction. Note, however, that in practice such a correction is rarely required because most production rates in use today were derived from mid- to high-latitude sites, and, moreover, often with samples considerably younger than 40 kyr, for which corrections are minor at all latitudes anyway (e.g., Nishiizumi et al., 1989; Cerling and Craig, 1994a; Niedermann et al., 1994; Kubik et al., 1998; Licciardi et al., 1999). Also, production rates calculated with physical models (e.g., Masarik and Reedy, 1994) assume present-day field intensity. Hence, most reported production rates essentially represent present-day values. Our calculations also reveal that the notable consistency of empirically derived production rates for samples exposed throughout the late Pleistocene and the Holocene reflects the fact that most of the respective sample sites are from >30° latitude.

We do not discuss here corrections of nuclide production rates due to any parameter other than the long-term temporal variability of the Earth's magnetic dipole field. Figure 3 therefore allows the readers to choose their preferred production rate (for present-day field), their preferred latitude and altitude scalings (e.g., Lal, 1991; Dunai, 2000), and possibly to take into account other factors—for example, a site-dependent mean atmospheric sea level pressure (Stone 2000).

7. CONCLUSIONS

Changes in the paleomagnetic field intensity have a sizable effect on the production rates of cosmogenic nuclides in near-surface rock samples at low-latitude sites and for exposure ages higher than some 10 to 40 kyr. The required corrections of up to 12% are comparable to, or higher than, reported uncertainties of production rates determined with independently dated surface samples, as well as reported uncertainties of altitude and latitude scaling factors (e.g., Dunai, 2000). So far, few surface exposure dating studies have concentrated on tropical sites (e.g., Brown et al., 1992, 1994, 1998; Shanahan and Zreda, 2000) and are thus directly affected by the results of this study, but this will certainly change soon. For example, an exact timing of Quaternary glacial events in the tropics will be needed to study whether or not tropical and high-latitude climate excursions were synchronous (cf. Severinghaus et al., 1998; Thompson et al., 1998).

However, as has been realized early on, changes in the geomagnetic field intensity influence in situ production rates at mid- to high latitudes considerably less than at low latitudes (see Gosse and Phillips, 2001, for a review). Our work shows that required corrections are less than a few percent for all latitudes above ~35°. Because most cosmogenic nuclide studies so far have concentrated on such locations, there is little need to revise currently used production rates or published exposure ages due to paleomagnetic field changes. Finally, we also show that magnetic field intensity changes are much less critical for in situ ^{14}C work than for classical ^{14}C dating.

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