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TEMPORAL ^{10}BE AND ^{14}C VARIATIONS: A TOOL FOR PALEOMAGNETIC RESEARCH

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ABSTRACT. Temporal variations of cosmogenic radionuclide atmospheric concentrations can be caused by such global phenomena as solar activity and geomagnetic field changes as well as atmospheric circulation processes. These causes can be distinguished by the comparison of several isotope records corresponding to the same time period. We discuss a possibility for reconstructing the geomagnetic moment during the last 30,000 years from the comparison of ^{10}Be and ^{14}C concentrations in terrestrial archives. The results agree with conventional paleomagnetic data and promise to enrich our knowledge of geomagnetic field variations and reversals.

INTRODUCTION

Cosmogenic isotopes such as ^{10}Be and ^{14}C are produced in the atmosphere mainly by galactic cosmic ray (GCR) particles. Their production rate is directly related to the primary GCR flux. Three main causes of the production rate variations are known:

1) *Primary GCR variations.* As discussed earlier (Konstantinov & Kocharov, 1984; Sonett, Morfill & Jokipii, 1987), they can result from a supernova explosion, though such an event is very rare.

2) *Solar activity modulation.* This complex process is manifested in the periodic depression of a low-energy part of a GCR spectrum which results in decreased atmospheric cosmic ray flux.

3) *Geomagnetic shielding.* The geomagnetic field prevents the low-energy GCR particles from penetrating into the atmosphere. The geomagnetic cut-off energy strongly depends on the moment of the near-dipole geomagnetic field.

Concentrations of the cosmogenic isotope in the specific archive depend on atmospheric transport and sample formation conditions. Basically, cosmogenic isotope production provides information on all the phenomena mentioned above. The main aim of this paper is to determine the geomagnetic moment in the past. A more detailed description of the cosmogenic isotope production model was published previously (Kocharov *et al*, 1985).

THE PRIMARY PRINCIPLES

Our paleomagnetic research is based on two ideas: the influence of the geomagnetic field on the abundance of cosmogenic nuclei in several archives and some specific features of isotope atmospheric transport. As recently shown (Siegenthaler & Beer, 1988) ^{10}Be and ^{14}C records demonstrate similar long-term variations that can be attributed to a variable sun. ^{10}Be and ^{14}C are similarly dependent on the GCR flux at the top of the atmosphere, which is confirmed by model calculations (Konstantinov & Kocharov, 1984).

What are the reasons for their different sensitivity to the geomagnetic field? Investigations of the transport of radionuclides from nuclear tests through the atmosphere show that the precipitation of the aerosol-bound nuclides has a strong latitude dependence on the altitude of their injection (Lal & Peters, 1967). Isotopes injected into the troposphere are removed not far from the site of injection (the tropospheric residence time is about one month) but the stratospheric fallout mainly occurs in mid-latitudes. Thus, precipitation mainly contains the isotope component of tropospheric origin in polar regions. This type of latitude-fallout-dependence holds also for cosmogenic isotopes, which is confirmed by experimental research on ^{7}Be and ^{10}Be atmospheric transport (Raisbeck *et al,* 1981b). Latitude fallout distribution calculated on the basis of ^{10}Be concentrations measured in polar glaciers agrees with the fallout curve by Lal and Peters (1967). Thus, we used this curve for ^{10}Be atmospheric production rate reconstruction.

As the earth's magnetic field is basically a dipole, the geomagnetic cutoff energy (rigidity) is strongly latitude-dependent. The dependence of cutoff rigidity on the geomagnetic latitude, f, is given by

$$R(f) = R_o * M/M_o * \cos^4 (f) \qquad (1)$$

where R_o is the modern cutoff rigidity on the geomagnetic equator and M/M_o is the ratio of the current geomagnetic dipole moment to its modern value. Near the geomagnetic pole is an area where the magnetic field has no influence on the cosmogenic isotope production rate as the geomagnetic cutoff energy becomes less than the threshold energy of the corresponding nuclear reactions. For the modern geomagnetic field, this region for ^{10}Be production is located on geomagnetic latitudes higher than 68°, whereas, for varying M/M_o from 0.5–1.5, the boundary is moved from 64°–70°, respectively. Thus, there are areas near both poles where precipitation contains almost only isotope components of tropospheric origin insensitive to geomagnetic field variations. The tropospheric production rate in such an area is given by

$$Q_{tr} = \pi \int_{E_t}^{\infty} dN/dE * W_{tr}(E) * dE \qquad (2)$$

where dN/dE is the GCR differential energy spectrum, W_{tr} is the isotope production rate in the troposphere per primary proton with energy E, and E_t is the threshold energy of the nuclear reaction. The isotopes that are mixed in the atmosphere (eg, ^{14}C or stratospheric ^{10}Be) and thus lose their production-rate latitude dependence are sensitive to magnetic field variations. The mean global ^{10}Be stratospheric production rate is described by

$$\langle Q_{str} \rangle = \tfrac{1}{4} * \pi \iint df * dl * \sin (f) \int_{E(f)}^{\infty} dN/dE * W_{str}(E) * dE \qquad (3)$$

where W_{str} is the stratospheric isotope production rate per primary proton with energy E, E(f) is the energy corresponding to the cutoff rigidity R(f) in equation (1), and l is the longitude.

Thus, there is an opportunity for paleomagnetic investigations based on comparative analysis of cosmogenic isotope data independent of the magnetic field influence, which include ^{10}Be in polar ice and those containing a geomagnetic record, eg, ^{14}C and ^{10}Be from areas of significant stratospheric aerosol precipitation. We developed a method for calculating hadronic cascades in the atmosphere, through which we obtained the quantity W(E) (Levchenko & Blinov, 1984) and ^{10}Be production rates for the stratosphere and troposphere. The method enables us to account for the influence of solar modulation and obtain numeric data on the paleomagnetic field. We reconstruct magnetic-field intensity of the past in the following manner: we find the level of solar activity from the high-latitude ^{10}Be record, and with ^{14}C or ^{10}Be records from the lower latitude archives and the determined level of solar modulation, we reconstruct the magnetic field variations (M/M_o). This method differs from that of Beer, Siegenthaler and Blinov (1988).

THE GEOMAGNETIC FIELD OVER THE LAST 30,000 YEARS

In search of verification of this proposed method, we reconstructed the geomagnetic field variations for the 14th–18th centuries AD. We used ^{10}Be abundance data from the Milcent and Camp Century ice cores (Beer *et al,* 1984). According to Raisbeck and Yiou (1987), we suggested that ^{10}Be in the Camp Century core was "not sensitive" to the magnetic field. The geographical position of Milcent ice core is not the best for our purposes but it was the most detailed ^{10}Be record available for the last ca 500 years. The results of the calculations are shown in Figure 1. We compare them with the most detailed uniform series of archeomagnetic data for Moscow (Archeomagnetic determinations, 1977). Agreement with our results is satisfactory, eg, for the 16–17th centuries. It should be noted that this increase is also pronounced in other archeomagnetic series. Some discrepancies may be caused by local geophysical conditions, such as ice deposition rate variations, that were not taken into account. We suggest only general agreement in the data time profile.

Using the data of the ^{10}Be abundance in Greenland: Dye-3 (Beer *et al,* 1983), Milcent and Camp Century (Beer *et al,* 1984); Antarctic glaciers: Dome C (Raisbeck *et al,* 1981) and Vostok (Raisbeck *et al,* 1987); ^{14}C con-

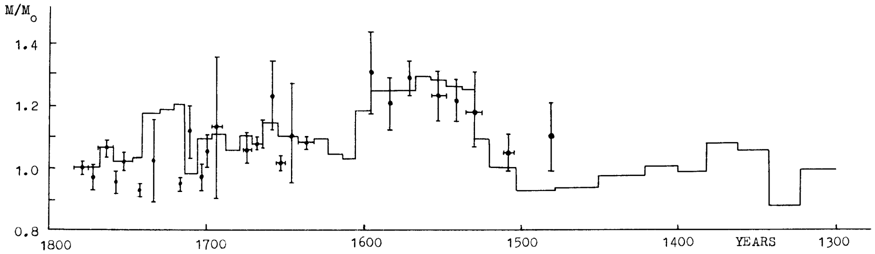

Fig 1. Temporal geomagnetic field variations during the 14th–18th centuries AD. ɸ = uniform series of archeomagnetic data (Archeomagnetic determinations, 1977); — = our geomagnetic field reconstruction.

centrations in tree rings (Suess, 1970) and stalactites (Vogel, 1983), we reconstructed the temporal variations of the geomagnetic dipole moment value over the last 30,000 years. The data from Camp Century, Dome C and Vostok stations were considered free from geomagnetic influence. Ice accumulation rate variations were determined using ^{18}O data and accounted for in the ^{10}Be production rate calculations. The results are plotted in Figure 2. The discrepancies in our results and the paleomagnetic data (Fig 2) and also in the results plotted in Figures 1 and 2 could be caused by: 1) the location of the sampling sites. Apparently, the stratospheric fallout contribution occurs at Camp Century station. It would be better to use the pair, Vostok-Dye 3, for paleomagnetism; 2) the difference in averaging and time scales between Figures 1 and 2; 3) different approaches to calculating ice accumulation rates.

Unfortunately, the paleomagnetic data for the period, 16–30,000 years ago bear such large uncertainties (up to 50%), that there is no reason to compare them with our results.

THE GEOMAGNETIC FIELD REVERSALS

The ^{10}Be concentrations in deep-sea sediments corresponding to the Brunhes-Matujama reversal (~730,000 yr BC) were measured by Raisbeck *et al* (1985), who determined the increased ^{10}Be concentration in the layers of the reversal. Using the method developed in accord with the geomagnetic nature of this phenomenon, we have reconstructed the temporal variation of the geomagnetic moment during this period (Fig 3). We cannot say anything about the minimum magnetic moment value because the ^{10}Be production rate is not sensitive to the M changes near zero. It is interesting that the magnetic moment decreases to its minimum 3–4000 yr after the

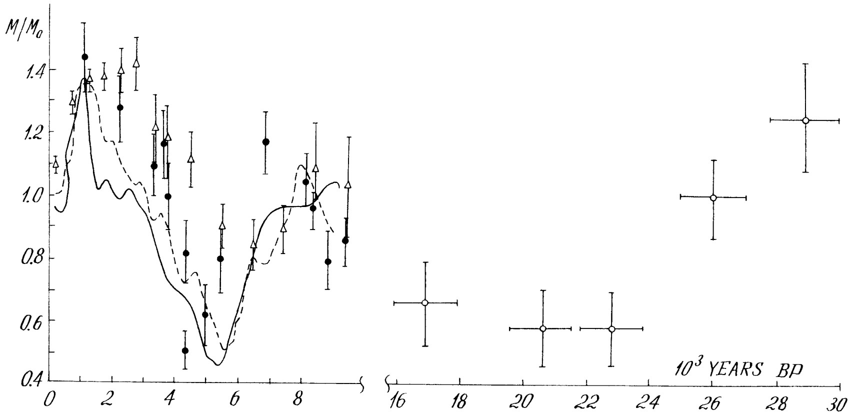

Fig 2. Temporal geomagnetic field variations over the last 30,000 yr. —— = comparison of the ^{14}C record (Suess, 1970) with ^{10}Be (Camp Century) data; ● = result of combined analysis of mixed ^{10}Be data; ○ = comparison of ^{14}C abundances in stalactites (Vogel, 1983) with ^{10}Be Vostok data; - - - = generalized archaeomagnetic data (Archeomagnetic determinations, 1977); △ = compilation of data from Merrill and McElhinny (1983). The error bars are shown for the 95% confidence level.

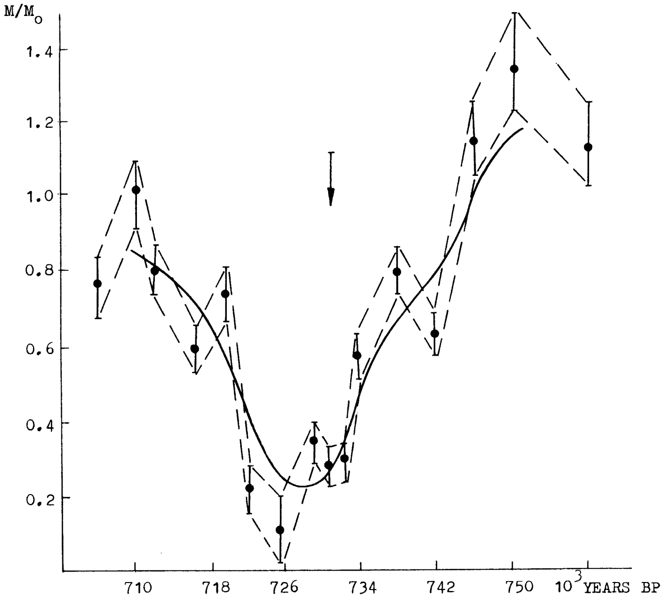

Fig 3. The time profile of the Brunhes—Matuyama magnetic reversal reconstructed from ^{10}Be concentrations in deep-sea sediments measured by Raisbeck *et al* (1985). The arrow marks the reversal position.
--- = uncertainties in M/M$_o$ ratio value; — = result of smoothing.

reversal. This shift can be real (related to the magnetic field behavior) or it can be due to the ^{10}Be transport through the ocean and/or bioturbation in the upper layer of deep-sea sediments (Raisbeck *et al,* 1985). Besides the comparatively slow geomagnetic field variations, we can see, in Figure 3, the quasiperiodic variations in the 10,000-yr period and an amplitude ca (0.1–0.2) M$_o$. A conclusion about the nature of the variations is premature as similar variations were also found for the concentration of the stable isotope, ^{9}Be.

CONCLUSIONS

We have presented evidence that variations in the geomagnetic field moment, reconstructed from isotope data values, agree with conventional archeomagnetic and paleomagnetic results on a time scale of ca 10,000 yr. The methods we use extend the period of investigations up to 10^6 yr. Our calculations also offer a value of mean global geomagnetic moment instead of local values strongly influenced by the nondipole component. Further improvement in understanding cosmogenic isotope production and transport can result in more detailed knowledge not only of paleomagnetic intensities, but also the movement of magnetic pole positions.

We consider these results a demonstration of the promising method that needs not only theoretical improvement but also special experimental support, eg, measurements on ice samples from sites with specific time resolution and accuracy.

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