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A geomagnetic chronology for antarctic ice accumulation

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Abstract. The curve of ^{10}Be flux versus age in the Vostok ice core largely covaries with a synthetic curve calculated assuming that a large fraction of ^{10}Be production rate is modulated by changes in the geomagnetic field intensity. With this assumption, it is also possible to derive a precise chronology for the Vostok core. This chronology is in good agreement with a very recent glaciological chronology obtained for Vostok ice core, and improves the correspondence of climate events recorded in Antarctic ice with correlative events recorded in deep sea sediments. Therefore, the idea that changes in the ^{10}Be flux at Vostok may arise from variations in Earth's geomagnetic dipole field has to be seriously considered. This would imply that a large portion of the ^{10}Be deposited there is derived from lower latitudes.

Introduction.

The production rates of cosmogenic isotopes have not been constant in time. For instance, analyses of ^{14}C in tree rings shows that the ^{14}C content of the atmosphere was higher ≈ 10 kyr BP than its present day value [Stuiver et al., 1986]. Also, between 20-30 kyr BP, the ^{14}C content of the atmosphere was about 140% of its preindustrial value [Bard et al., 1990]. It has been argued that ^{14}C changes mainly reflect variations in the global production rate of cosmogenic radionuclides, due to geomagnetic modulation of the flux of cosmic rays bombarding the atmosphere [Barbetti, 1980; Bard et al., 1990; Mazaud et al., 1991; Thouveny et al., 1993]. The idea that cosmogenic nuclide production has been affected by changes in the intensity of the geomagnetic dipole is reinforced by spot determinations of $^{36}\text{Cl}/\text{Cl}$ ratio observed in samples of fossil packrat urine [Phillips et al., 1991], and also by the recent observation that the flux of ^{10}Be in Pacific sediments was higher at the end of the last ice age, when the geomagnetic dipole intensity was low [Lao et al., 1992]. The record of geomagnetic field intensity has recently been extended to 140 kyr [Meynadier et al., 1992; Tric et al., 1992]. We use these new records to examine whether or not changes in the concentration of ^{10}Be in the Vostok ice core over the last 140 kyr reflect changes in global ^{10}Be production, due to changes in the geomagnetic screening of the cosmic ray flux.

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^{10}Be variation in Vostok ice.

An important part of variability in ^{10}Be concentration along the Vostok ice core is controlled by climatic changes which modified the precipitation rates [Raisbeck et al., 1987; McHargue and Damon, 1991]. In addition to climatic effects, two marked peaks, respectively dated at ≈ 35 and 60 ky B.P., have been interpreted as reflecting changes in global production of cosmogenic ^{10}Be [Raisbeck et al., 1987, 1989; Beer et al., 1992]. Maxima in production may arise from external causes such as cosmic ray flux pulses and/or solar modulation of the cosmic ray flux [Raisbeck et al., 1987, 1989]. Alternatively, ^{10}Be production changes, like variations in production of ^{14}C or ^{36}Cl , may arise from changes in the intensity of the Earth's geomagnetic field, which influences the flux of cosmic rays bombarding the atmosphere. One does not expect the geomagnetic field to significantly modulate cosmogenic isotope production in the atmosphere directly above polar regions such as Vostok [Castagnoli and Lal, 1980]. A correlation between ^{10}Be accumulation at Vostok and changes in geomagnetic field intensity would suggest that a fraction of the measured ^{10}Be has been transported by stratospheric aerosols from lower latitude regions, where the geomagnetic screening of cosmic rays is efficient.

A first comparison between the Vostok ^{10}Be profile and the geomagnetic profile.

We have first calculated the global change in cosmogenic ^{10}Be production rate caused by geomagnetic intensity modulation, assuming that the cosmic ray flux has remained unchanged through time. The dipole intensity records [Meynadier et al., 1992; Tric et al., 1992] have been converted into a profile of ^{10}Be global production rate (Figure 1), using the data of Lal [1988], after interpolation. These data are given in Table I of this paper. High values of global ^{10}Be production are calculated for times of low geomagnetic screening, at about 20 kyr, 37-40 kyr and 60 kyr B.P., as well as between 80 and 130 kyr B. P. (Figure 1). Then, following Raisbeck et al. [1987, 1989], a profile of ^{10}Be flux versus age in Antarctic ice was calculated from the ^{10}Be concentrations obtained at Vostok. The values of ^{10}Be concentrations have been transformed into ^{10}Be deposition rates (flux), by multiplying the ^{10}Be concentrations by the ice deposition rates. We have used the most recent ice deposition rates and ice ages calculated by Jouzel et al. [1993] who established the "Extended Glaciological Timescale" (E.G.T.). The curves obtained from geomagnetic intensities and from ice analyses are normalised to present day value (Figure 1).

Similarities are observed in the first 30 kyr. The maximum at about 20 kyr appears slightly older in the curve of ^{10}Be flux than in the geomagnetic production profile. Then, a large peak is present at ≈ 37 kyr in the curve of ^{10}Be

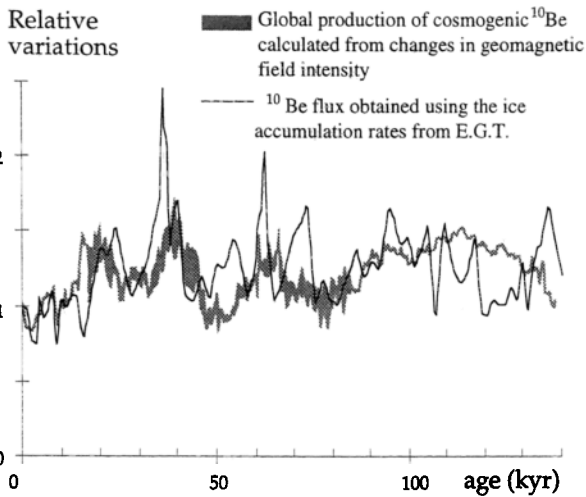


Fig. 1. Variation in the ^{10}Be global production calculated from geomagnetic intensity changes (grey line), and in the flux of ^{10}Be at Vostok (black line) calculated from the ^{10}Be concentrations [Raisbeck et al., 1987] and the ice paleoaccumulation rates of the E.G.T. [Jouzel et al., 1993].

flux, while a less marked peak appears at ≈ 40 kyr in the geomagnetic production profile (Figure 1). Other peaks are present, at approximately 60 kyr and 70 kyr, in the profile of ^{10}Be flux. There is a broad maximum between ≈ 55 -70 kyr in the global production curve (Figure 1). Both curves show a relative low at ≈ 80 kyr. Then, they show similarities up to ≈ 110 kyr, and differ at older ages. The curve of the ^{10}Be flux shows more high frequencies than the global production curve calculated from geomagnetic intensities. Since the two records of field intensity variations [Meynadier et al., 1992; Tric et al., 1992] which were used were obtained from deep sea cores, this may correspond to a smoothing of geomagnetic field intensity changes by sediments. The sharp peaks at ≈ 35 and ≈ 60 kyr exceed the limit of a zero field intensity (1.88). Nevertheless, there is an overall correlation between ^{10}Be flux profile at Vostok and the global production profile during the past 110 kyr, which suggests that at least part of changes in ^{10}Be flux at Vostok are due to changes in the screening of cosmic ray flux by the geomagnetic field. We show that the problem of the nul field limit can be solved by adjusting the age-depth model of the Vostok ice.

A geomagnetic chronology.

A more direct approach consists in determining a model of absolute ice accumulation rate which transforms the ^{10}Be concentrations versus depth measured at Vostok into a profile of ^{10}Be flux versus age that matches a synthetic profile derived from the geomagnetic production profile of Figure 1.

TABLE 1. Global nuclear-disintegration rates as a function of geomagnetic dipole strength; $M_0 = 1$ for present day field (values from Lal [1988]). See also Castagnoli and Lal [1980].

M/M_0	0	0.1	0.25	0.5	1	2	4	10	30	100
rates	3.35	3.2	2.88	2.33	1.78	1.18	0.83	0.52	0.28	0.14

This synthetic profile was calculated assuming that ^{10}Be deposition at Vostok is in part geomagnetically modulated. We assume that today $X\%$ of the ^{10}Be deposition is modulated by geomagnetic intensity changes, and $Y = 1-X\%$ is not modulated. Going back through time, the accumulation rate of the fraction not modulated is assumed to be constant (essentially ^{10}Be produced at high latitudes). We are well aware that this simple model ignores possible changes in ^{10}Be deposition due to modifications in atmospheric circulation. The accumulation of the distal, modulated, component is assumed to be proportional to relative global production. Quantitatively, the rate of ^{10}Be deposition at a certain past time equals $(X/100) \cdot \text{PR}(t) + (Y/100)$. $\text{PR}(t)$ is the normalized rate of global ^{10}Be production calculated from the geomagnetic intensity changes.

^{10}Be flux values were calculated by multiplying the ^{10}Be concentrations by the adjusted ice accumulation rates. Ice ages were obtained by combining the adjusted ice accumulation rates with the thinning model of Ritz [in press]. Consequently, changing the ice accumulation rates modifies both ^{10}Be flux and ice ages. For instance, when ice paleoaccumulation rates are low, ^{10}Be flux values are reduced. Simultaneously, ice ages become older. We were able to derive a very good match throughout the last 140 kyr between the ^{10}Be flux and the synthetic profile calculated with X equal to 75, and Y equal to 25 (Figure 2). This fractionation corresponds to extensive geomagnetic modulation of ^{10}Be accumulation at Vostok. We call the ice chronology obtained by combining the adjusted ice accumulation rates with the thinning model of Ritz [in press] the geomagnetic chronology. None of the peaks in the obtained ^{10}Be flux exceed the upper limit (1.66) of normalized ^{10}Be flux calculated for a zero geomagnetic field intensity with the above fractionation ($X=75$; $Y=25$). It was not possible to exactly match the age of the first ^{10}Be accumulation rate maximum with the age of the corresponding minimum in magnetic intensity (Figure 2). This time lag, which is mostly confined to the stage 3 of the oxygen isotope record, is however consistent with the uncertainties of the dating of both the marine cores and of the Antarctic ice layers.

Discussion

We consider now the profile versus depth of adjusted ice accumulation rates, and the corresponding geomagnetic

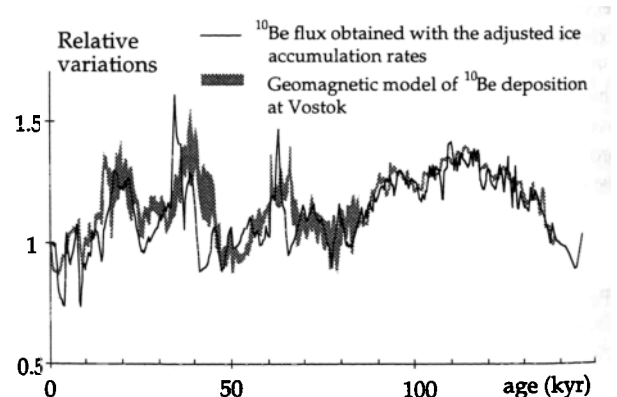


Fig. 2. The match between the ^{10}Be flux profile obtained after adjusting the ice paleoaccumulation rates (black line), and a synthetic profile for ^{10}Be deposition calculated assuming that 75% of the ^{10}Be deposited at Vostok is modulated by global geomagnetic intensity changes (grey line).

chronology. If the hypothesis of a large geomagnetic modulation for ^{10}Be flux at Vostok is irrelevant, then the adjusted ice accumulation rates, and the geomagnetic chronology, should not agree with ice accumulation rates and ice chronologies derived from other investigations.

The present day value of adjusted ice accumulation (Figure 3) is found to be $2.33 \text{ g cm}^{-2}\text{yr}^{-1}$. Determinations of ice accumulation rate at present time at Vostok lies between 2.0 and $2.4 \text{ g cm}^{-2}\text{yr}^{-1}$ [Jouzel et al., 1993, and references therein]. For the first 300 m, the magnetic ice accumulation rates are slightly higher than glaciological values of E.G.T. [about $2 \text{ g cm}^{-2}\text{yr}^{-1}$; Jouzel et al., 1993]. As noted by these authors, a value of $2 \text{ g cm}^{-2}\text{yr}^{-1}$ falls at the lower end of the estimated range of present day ice accumulation rate at Vostok. In the next interval, from 300 to 1500 m, there are impressive similarities with glaciological ice paleoaccumulations, despite the fact that at $\approx 600 \text{ m}$, i.e. for the first peak in ^{10}Be concentration observed by Raisbeck et al. [1987], the adjusted value for the paleoaccumulation is 74% of the value obtained by Jouzel et al. [1993]. Between ≈ 1650 and 1800 m, magnetic ice paleoaccumulations, calculated from the record of geomagnetic field intensity from the Somali basin [Meynadier et al., 1992], are $\approx 40\%$ higher than those obtained for present time. This is also the case for the values determined from glaciologic studies (Figure 3). Thus, the hypothesis of a geomagnetic modulation for the ^{10}Be flux at Vostok gives overall quite acceptable values for ice paleoaccumulation rate.

It should be noticed that this is not the case if one assumes that ^{10}Be flux at Vostok reflect two pulses of rapid accumulation at ≈ 35 and 60 kyr B.P. , superimposed on a constant ^{10}Be flux [Raisbeck et al., 1987 and 1989; Jouzel et al., 1989]. This hypothesis, in which there is no modulation by the geomagnetic field, allows the relative variations of ice accumulation rate to be readily calculated [Jouzel et al., 1989]. With this profile, however, one needs to fix the value of the present ice accumulation rate at $\approx 2.8 \text{ g cm}^{-2}\text{yr}^{-1}$ to obtain an age of 110 kyr at a 1534 m, generally accepted [Lorius et al., 1985; Jouzel et al., 1993]. This value of $2.8 \text{ g cm}^{-2}\text{yr}^{-1}$ does not range within accepted values for present time ice accumulation rate at Vostok.

We next compare in Figure 4 the geomagnetic chronology and the glaciologic time scales. We consider the initial ice chronology of Lorius et al. [1985], and the recent E.G.T.. Geomagnetic and E.G.T. agree much better with each other

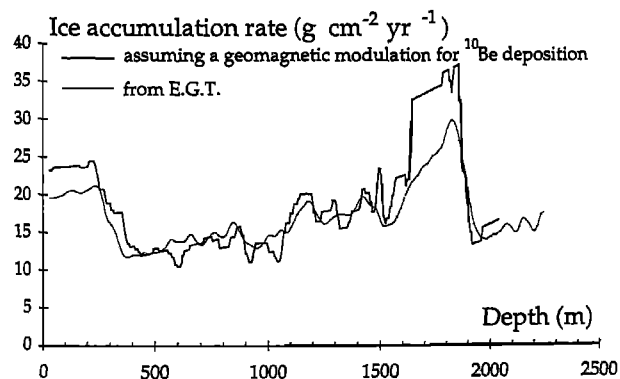


Fig. 3. The profile of adjusted ice deposition rate versus depth which gives the match shown in Fig. 2 (thick line), together with the ice accumulation rates determined from E.G.T. (thin line).

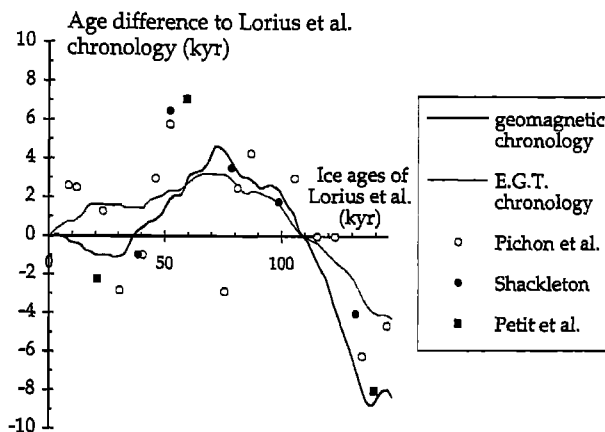


Fig. 4. Comparison of geomagnetic and E.G.T. ice chronologies with the initial chronology of Lorius et al.. The geomagnetic and E.G.T. chronologies agree much better with each other than either agree with the earlier chronologies. Both chronologies globally agree with results obtained from comparisons between marine and ice chronologies.

than either agrees with the earlier chronology of Lorius et al.. However, for ages younger than $\approx 30 \text{ kyr}$, the geomagnetic chronology gives ages younger than those of the E.G.T.. This reflects the different values obtained for recent ice accumulation rates (see Figure 3, and discussion above). For ages older than $\approx 120 \text{ kyr}$, the magnetic age is slightly younger than the E.G.T. glaciological age [Jouzel et al., 1993], in consistency with higher values for adjusted ice deposition rate (Figure 3).

The geomagnetic chronology was determined by correlation with the synthetic deposition curve. This curve was in turn dated by the SPECMAP chronology [Martinson et al., 1987] used to date the variations in the Earth's geomagnetic field. Consequently, if its underlying assumptions are correct, the magnetic chronology should also coincide with earlier chronologies derived by matching proxy records from Vostok with those from SPECMAP dated deep sea sediments cores. In the 0-110 kyr interval, the geomagnetic chronology agrees well with ice ages derived from the glaciologic time scales, as well as with ice ages obtained from intercalibrations between signals from marine deposits and ice [Pichon et al., 1992; Petit et al., 1990; Shackleton et al., 1992] (Figure 4). For older ages, it agrees well with ice ages determined from correlations between signals recorded in marine sediments and in the Vostok ice (Figure 4).

Conclusions

Additional comparisons at older ages between ^{10}Be profiles and new geomagnetic intensity profiles are clearly desirable. However, similarities between the global ^{10}Be production profile calculated from Earth field intensity changes and ^{10}Be flux profiles calculated at the Vostok site strongly suggest that variations of geomagnetic screening of cosmic ray flux are recorded in Antarctic ice. Also, the ice chronology obtained assuming that ^{10}Be deposition at Vostok is geomagnetically modulated, improves the correspondence of climatic events recorded in Vostok ice and marine sediments, in particular during stage 5e (≈ 110 -130 kyr). An extraterrestrial origin has been proposed for the two peaks at

≈ 35 and 60 kyr [Raisbeck et al., 1987]. The results discussed here show however that geomagnetic modulation can also explain a large fraction of the two peaks, with the additional attraction that it also yields a realistic value for the ice paleoaccumulation rates. Since large modulation of cosmogenic isotope production by geomagnetic field is not expected above polar regions where the field is vertical, our interpretation implies an efficient transport of cosmogenic ^{10}Be aerosols in the upper atmosphere, from lower latitude to the Antarctic plateau, before falling out.

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