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Express Letter

Chlorine-36 evidence for the Mono Lake event in the Summit GRIP ice core

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Abstract

A distinct peak has been discovered in the ^{36}Cl data from the GRIP ice core between the Dansgaard Oeschger (D–O) events 6 and 7 at approximately 32 kyr BP. This peak can be attributed to a minimum of the geomagnetic dipole field associated with the Mono Lake event. Since the ^{36}Cl peak reflects a higher production rate of all cosmogenic radionuclides, it has an impact on the ^{14}C dating of the last ice age. Furthermore, it provides an additional time marker similar to a peak found earlier corresponding to the Laschamp event at approximately 39 kyr BP.

Keywords: Cl-36; magnetic field; paleomagnetism; cosmogenic elements; radioactive elements

1. Introduction

A new record of the relative geomagnetic field intensity (NAPIS-75) has recently been reported for the time period from 10 to 75 kyr BP [1]. NAPIS-75 was obtained by combining results from six ocean sediment cores in the North Atlantic characterised by a high mean sedimentation rate (15–30 cm/kyr). Precise correlation between cores was obtained by synchronising the Heinrich layers, the ash zone II and bulk magnetic parameters [2]. The data were then synchronised to the GISP2 age model by correlating the planktonic $\delta^{18}0$ record of one of the cores with the $\delta^{18}0$ of the GISP2 ice core [3].

In the NAPIS-75 record a magnetic field intensity minimum at approximately 32 kyr BP is observed beside the known minima at approximately 39 kyr BP (corresponding to the Laschamp event) and at approximately 66 kyr BP according to the GRIP time scale suggested by Johnsen et al. [4]. According to the GISP time scale suggested by

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Grootes and Stuiver [5] these magnetic field intensity minima occur approximately at 34, 41 and 65 kyr BP respectively. The 32 kyr (GRIP time scale) minimum is also marked in one of the cores (PS 2644-5) by an inclination change and coincides in time with an event discovered by Denham and Cox [6] in the sediments of the Mono Lake in California. Hence it will be referred to as the Mono Lake event.

In contrast to the Laschamp event and the minimum at 66 kyr BP (GRIP time scale [4]) the Mono Lake intensity low is not as clearly marked in published oceanic records (Blake Outer Ridge, the Labrador Sea, the Lake Baikal, the Somali Basin, the Mediterranean) as it is in NAPIS-75, with the exception of a very recent record from the Eastern Arctic Ocean [7]. This could indicate that either the time resolution of previous ocean sediment records is insufficient (lower sedimentation rates and/or bioturbation) or that the Mono Lake event is not global.

Cosmogenic radionuclides in ice sheets provide an ideal tool to address this issue for the following reasons:

- Cosmogenic radionuclides are produced by interaction of cosmic ray particles (mainly protons and α-particles) with the atmosphere. Their production rate varies inversely with the Earth's geomagnetic field intensity, which modulates the cosmic ray flux penetrating into the atmosphere [8].
- The production rate of the cosmogenic nuclides is mainly sensitive to the geomagnetic dipole field and not to non-dipolar components [8].
- Cosmogenic nuclides are especially sensitive to low geomagnetic fields because their production rates increase non-linearly for a decreasing geomagnetic field [8].

2. Data presentation

We report here the results of a new, extensive analysis of ^{36}Cl concentrations in the GRIP ice core, which now yields an almost continuous ^{36}Cl record over the last ice age. Our analysis covers the core section from 2100 to 2300 m, which contains the D–O events 6 to 11, corresponding to the time interval 30–43 kyr BP based on the GRIP time scale [4]. The data record consists of 166 individually measured samples with a mean experimental uncertainty of 7%. The depth resolution of the ^{36}Cl record from GRIP is 110 cm corresponding to approximately 60 yr during the Mono Lake event. More details on the experimental procedure can be found in Baumgartner et al. [9].

Fig. 1 shows the ^{36}Cl data (upper panel: ^{36}Cl concentrations; middle panel: ^{36}Cl fluxes). In the lower panel we show a modified NAPIS-75 record obtained by combining the four paleomagnetic records (out of the six used in NAPIS-75) in which the Mono Lake event is most clearly apparent, probably because of a locally very high sedimentation rate at the time of this event. Originally placed on the GISP2 age model, the modified NAPIS-75 record has been transferred to the GRIP age model and therefore also to the GRIP depth by matching the δ^{18}O wiggles from the GISP2 [5] with those of the GRIP [4] record.

The upper panel of Fig. 1 shows that, except for the prominent excursions between 2115 and 2135 m depth and between 2200 and 2250 m depth, there is a good correlation between the ^{36}Cl concentrations and the δ^{18}O values. This correlation is related to a dilution effect due to a changing accumulation rate [9], which is connected to the δ^{18}O values [4]. To eliminate this dilution effect we converted the concentrations into fluxes using the accumulation rate suggested by Johnsen et al. [4]. The ^{36}Cl flux (decay corrected) is shown in the middle panel of Fig. 1. The raw data are smoothed with a running mean filter over 15 data points corresponding to a time interval of approximately 1000 yr. Comparison of the middle and lower panels of Fig. 1 shows that both maxima in the ^{36}Cl flux occur at minima in the paleomagnetic field intensity. Contrary to the Laschamp event peak corresponding to the D–O events 9 and 10, the relatively narrow peak between the D–O events 6 and 7 has not been detected so far using cosmogenic radionuclides due to insufficient time resolution.

Baumgartner et al. [10] concluded that the in-

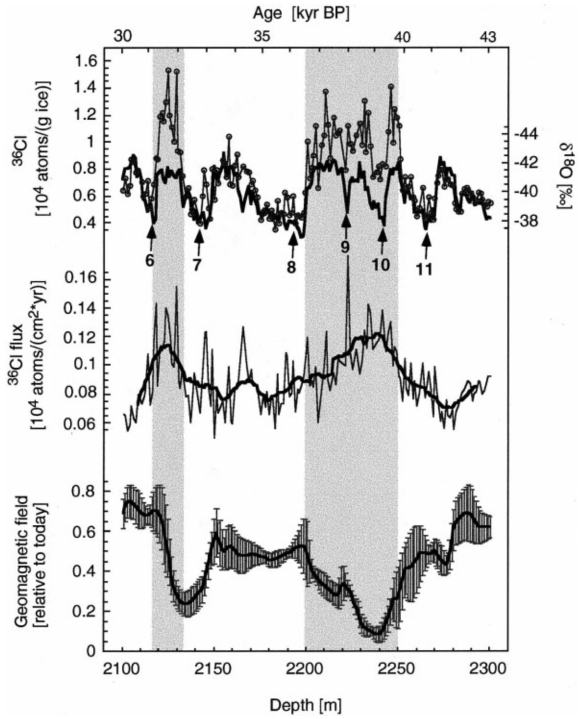

Fig. 1. Upper panel: ^{36}Cl concentrations (line with circles) as a function of depth of the GRIP ice core (lower *x*-axis) and of time (upper *x*-axis) using the time scale suggested by Johnsen et al. [4]. In the same panel the δ^{18}O data are shown. Note that the δ^{18}O data are inversely plotted. The usual numbering scheme was employed for the D–O events [5]. Middle panel: ^{36}Cl flux (decay corrected) derived from ^{36}Cl concentrations and accumulation rates suggested by Johnsen et al. [4]. The thick solid line is the running mean over 15 data points corresponding to approximately 1000 yr. Lower panel: Paleomagnetic field data (modified NAPIS-75) synchronised to the GRIP depth. It is based on remanence measurements of four North Atlantic sediment cores [1]. The shaded area corresponds to the $\pm 2\sigma$ uncertainties.

crease of the ^{36}Cl flux at Summit by a factor of about two at approximately 39 kyr BP is caused by the Laschamp event when the geomagnetic field was reduced to about 10% of its present value. Similar ^{10}Be peaks, that can be associated to the Laschamp event, have been found in the GRIP [11], the Vostok [12] and other ice cores [13] and in ocean sediment cores [14–16]. The coincidence of the ^{36}Cl peak between the D–O events 6 and 7 with the minimum in geomagnetic field intensity related to the Mono Lake event also suggests a causal connection.

3. Quantitative analysis

For a quantitative comparison we have calculated the mean global ^{36}Cl production rate from the paleointensity data. For this calculation we have used the modified NAPIS-75 record, calibrated to absolute values via its correlation [1] to the Mediterranean record, which in turn has been calibrated by the authors using volcanic data [17]. The dashed line in Fig. 2 shows the mean global ^{36}Cl production rate relative to today on time scales larger than 2000 yr. To obtain these data the following assumptions have been made. Firstly, on time scales larger than 2000 yr, the production rate of ^{36}Cl is controlled only by the geomagnetic field. Secondly, the mean solar activity during the period 30–43 kyr was equal to its long-term average. The solar activity can be parameterised by the solar modulation parameter M ($M=0$ MeV corresponds to a quiet and $M \geq 1000$ MeV to a very active sun). The mean

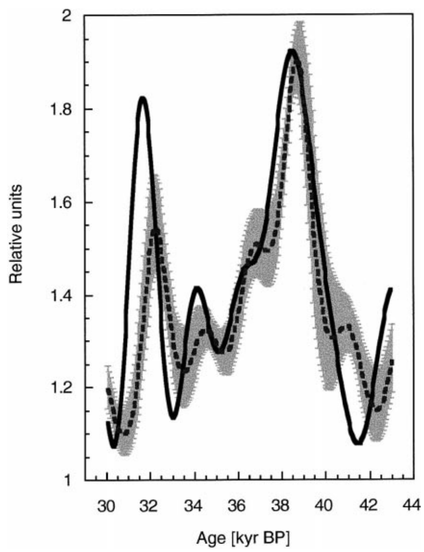

Fig. 2. Comparison of the ^{36}Cl production rate (dashed line) calculated from paleomagnetic field data (modified NAPIS-75) and the decay corrected ^{36}Cl flux (solid line) of the GRIP ice core. The shaded area corresponds to the $\pm 2\sigma$ uncertainties of the ^{36}Cl production rate due to the uncertainties in the geomagnetic field data. Both records are low-pass filtered (cut off frequency 1/2000 yr^{-1}) and are normalised on the present value. Note that they are completely independent and given on the same scale.

long time average solar modulation parameter is estimated to be $M = 550$ MeV [18]. The shaded area in Fig. 2 shows the $\pm 2\sigma$ error of the calculated ^{36}Cl production rate due to the uncertainties in the geomagnetic field data. The ^{36}Cl production rate was obtained by low pass filtering (cut off frequency 1/2000 yr^{-1}) the paleomagnetic field data and applying the following polynomial to fit the modelled relationship between the ^{36}Cl production rate and geomagnetic field intensity [8]:

$$P(^{36}\mathrm{Cl}) = 2.11 - 2.81(B) + 3.17(B)^2 - 2.09(B)^3 + 0.73(B)^4 - 0.1(B)^5$$

$P(^{36}\mathrm{Cl})$ = production rate of ^{36}Cl relative to today and B = paleomagnetic field relative to today.

The solid line shows the low-pass filtered (cut off frequency 1/2000 yr^{-1}), decay corrected ^{36}Cl flux at Summit, which is normalised to the mean value (45 data points) during the time period 1984–1991 AD. As a consequence of the increasing solar activity during the 20th century the solar modulation parameter M rose to approximately 750 MeV for the time period 1984–1991 AD. Assuming that M was equal to the long-term average of 550 MeV [18] during the last glaciation a corresponding correction of about 10% has to be made.

4. Discussion

Fig. 2 indicates that there is a generally high quantitative agreement between the completely independent data of the mean global ^{36}Cl production rate calculated from geomagnetic field data (modified NAPIS-75) and the ^{36}Cl flux at Summit. Both records are normalised to their values of today and are therefore quantitatively comparable. The small differences encountered during the Mono Lake event can be explained in the following way: The slight time shift of approximately 500 yr is within the uncertainties of the synchronisation of the involved records. The discrepancy of the amplitudes could be due to at least three possibilities:

1. The magnetic dipole field was lower than suggested by the modified NAPIS-75 record.
2. The ^{36}Cl flux observed at Summit does not exactly reflect the mean global ^{36}Cl production rate due to changes in the atmospheric transport of ^{36}Cl.
3. The solar activity during the Mono Lake event was lower than assumed, leading to a higher ^{36}Cl production rate.

Although at present we have no compelling evidence in favour of one or other of the three possibilities, we prefer the first one for the following reason: The modified NAPIS-75 record is compiled from the geomagnetic signal of four different ocean sediment cores [1] causing some smoothing. Comparing these four geomagnetic field reconstructions in detail, it is evident that the amplitude of the Mono Lake event varies between cores. The geomagnetic field reconstruction of the ocean sediment core PS 2644-5 [3], for example, shows a low which has virtually the same amplitude as the Laschamp event. In addition to the smoothing effect, non-dipolar moments play an increasing role when the dipole moment vanishes. The second and the third possible explanations seem less likely for the following reasons: The ^{36}Cl flux shows no correlation with climate parameters such as δ^{18}O that could be associated with transport effects. There is also no obvious reason why the solar activity should be reduced during the Mono Lake event.

It has recently been suggested [19] that geomagnetic field events occur when the field reverses in the outer fluid core, which has a typical overturn time of 500 yr, but not in the inner solid core, where diffusion of the field occurs on a typical time scale of 3000 yr. It is therefore interesting to evaluate the durations of the maxima in the ^{36}Cl flux record associated with the Mono Lake and the Laschamp events. Assuming that the duration of a maximum corresponds to the full width at the half maximum in the low-pass filtered ^{36}Cl flux data, we obtain values of about 1200 yr for the Mono Lake and 2500 yr for the Laschamp event. Although this last figure is slightly higher than the duration of the event estimated from the intensity minimum in ocean sediments [1], both results provide evidence in favour of the hypothesis that excursions correspond to short-duration processes in the outer core.

5. Conclusion

The fact that the Mono Lake event can be detected in the ^{36}Cl data of the GRIP ice core, led us to the conclusion that the Mono Lake event is a global phenomenon of the geomagnetic dipole field, because the ^{36}Cl production is mostly sensitive to the geomagnetic dipole field and not to non-dipolar components. The fact that the amplitude of the ^{36}Cl peak at 32 kyr BP (GRIP time scale [4]) is comparable with the one at 39 kyr BP is a strong hint that the intensity of the geomagnetic dipole field during the Mono Lake event was similar to that during the Laschamp event and close to zero. However, its duration appears to be shorter. Furthermore, the ^{36}Cl peak at 32 kyr BP has several important implications. The ^{14}C dating of the last ice age has to be discussed in terms of this newly discovered ^{36}Cl peak, because the ^{36}Cl data are a measure for the ^{14}C production rate [8]. Finally, the usefulness of cosmogenic time markers in order to synchronise time scales from different ice cores and sediments has been demonstrated several times [13,20]. The Mono Lake event, visible in geomagnetic field intensity and ^{36}Cl records, provides an additional time marker to synchronise different climate archives such as ice and sediment cores.

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