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A 200 kyr record of cosmogenic radionuclide production rate and geomagnetic field intensity from ^{10}Be in globally stacked deep-sea sediments

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Abstract

The reconstruction of geomagnetic field intensity variations during the last 200 kyr from paleomagnetic data is at present the subject of numerous studies and major debate. There is currently no generally accepted record. Here we present a global stacked record of ($^{230}Th_{ex}$-normalized) ^{10}Be deposition in marine sediments representing relative variations in ^{10}Be production rate which are translated into field intensity variations. The record shows major periods during which the field intensity was between 10% and 40% of the present day value; namely 30–42, 60–75, 85–110 and 180–192 kyr B.P. Our results are compared to independently derived paleomagnetic studies and Th/U calibrations of ^{14}C dates on corals. During most of the observed period the geomagnetic field intensity was weaker than today, resulting in an overall 30% reduced value for the last 200 kyr.

Keywords: geomagnetic field intensity; Be-10 production rate; sediment redistribution; Th-230 normalization; Be-10 boundary scavenging

1. Introduction

The production rate of cosmogenic radioisotopes such as ^{14}C and ^{10}Be in the earth's atmosphere varies with the strength of the geomagnetic field intensity as a function of the incident primary cosmic ray flux, which is also modulated by solar activity [1–3]. At first order, the relation between field strength and cosmogenic radionuclide production rate can be expressed as [1]:

$$Q_M/Q_{Mo} = \text{constant} \cdot (M/Mo)^{-0.5}$$

where Q stands for the global nuclear disintegration rate at a certain field strength M and the reference strength Mo (present field), respectively. This relation is not applicable for very small values of M and was reassessed by Lal [3], resulting in the relation displayed in Fig. 1.

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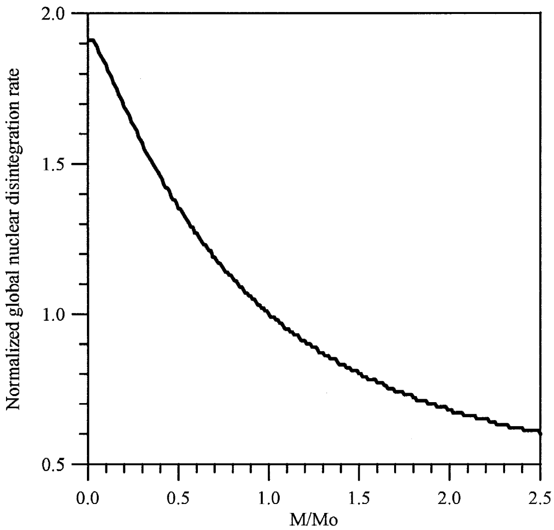

Fig. 1. Relation between normalized global nuclear disintegration rate and strength of the magnetic field normalized to the present day value. The curve was fitted to the data given in [3].

The reconstruction of the variability of the field intensity during the late Quaternary has been the subject of various studies. Bard et al. [4] deduced an up to 40% reduced field intensity during the last glacial by calibrating ^{14}C ages of Barbados corals to mass spectrometric U/Th ages. A similar result was reported by Lao et al. [5], who explained an average 30% increase in ^{10}Be deposition during the last glacial maximum in the Pacific by a reduction in geomagnetic field intensity. Furthermore, peaks of ^{10}Be concentration at about 35 kyr B.P. in ice cores [6–8] and Mediterranean sediments [9] may indicate a major weakening of the geomagnetic field, corresponding approximately to the Laschamp Event [10]. Another significant peak in ^{10}Be concentration, possibly related to field intensity variations, was observed at about 60 kyr B.P. in the Vostok ice core [6]. A comparison between measured ^{10}Be deposition rate and a synthetic deposition rate derived from geomagnetic field intensity variations [11] showed good agreement in the Vostok ice core for the last 140 kyr, which allowed the ^{10}Be deposition rates to be used as a geomagnetic chronometer [12]. The interpretation of changes in the authigenic (adsorbed) $^{10}Be/^{9}Be$ ratio in a single marine deep-sea sediment core in terms of field intensity variations [13] yielded promising results but changes in this ratio caused by advection of different water masses on glacial/interglacial timescales may not be excluded [14].

In numerous paleomagnetic studies in the recent past attempts have been made to reconstruct variations in the geomagnetic field intensity from marine and lacustrine sediments during different periods of the last 200 kyr [11,15–21]. Recently, these results were compiled and a stacked record was calculated [22]. Further major periods of reduced field intensity were determined: the Blake event (about 120–110 kyr B.P.) represents a period of several short-term geomagnetic reversals or a large excursion of the field [23–25]. A similar excursion is the Biwa I event (about 190 kyr B.P.) [24,26]. However, no standard method of calculating field intensity variations derived from paleomagnetic data from deep-sea sediments has yet been established. Thus, there is no generally accepted record of paleointensity at present.

The strength of the pattern of the past ocean circulation has probably changed on glacial/interglacial timescales. Thus, any approach to reconstruct geomagnetic field intensity variations based on ^{14}C is complicated by the corresponding carbon cycle-controlled variations in ^{14}C exchange with the atmospheric reservoir [27,28]. Although it was recently argued that the ocean circulation effect should not be greater than 20% [28], an uncertainty remains because the ^{14}C-based results depend on the accuracy of the applied glacial ocean model. In contrast to ^{14}C, a ^{10}Be-based reconstruction of cosmogenic production rate has the big advantage of being independent of changes in the ocean circulation because ^{10}Be, once introduced into the ocean water column, is not retransferred into the atmosphere. In addition, it is not restricted to at best the last 50 kyr, but can cover the last 200 kyr.

The extensive research on sedimentary ^{10}Be and ^{230}Th in the last few years has provided a unique data base which enables us to suggest an alternative approach to evaluate paleointensity changes in the earth's magnetic field. The idea is: (1) to evaluate relative variations in global average cosmogenic radionuclide production rate from $^{230}Th_{ex}$-normalized ^{10}Be deposition rates in deep-sea sediments and (2) to deduce relative field intensity variations from these production rate changes in ^{10}Be. By normalization to initial $^{230}Th_{ex}$, the flux of which to the sediments is supposed to match its local production rate, the sedimentary deposition rate of ^{10}Be may be corrected for effects of lateral sediment redistribution [5,29–31]. This method renders sedimentary ^{10}Be deposition rates influenced only by boundary scavenging effects and production rate variations. Lao et al. [5] attempted to eliminate the effects of regionally different boundary scavenging by assuming the Pacific to be a closed system with respect to ^{10}Be exchange with other ocean basins, and by averaging the last glacial and Holocene values of 18 sediment cores from different areas within the Pacific. We suggest a similar approach on a global basis, by which relative variations in the global average ^{10}Be deposition rate may be evaluated for the last 200 kyr with a higher time resolution. Because this rate is only controlled by production rate changes, it may be translated into variations in geomagnetic field intensity, assuming that variations in solar activity are negligible, since these are not resolvable at the time resolution of the sedimentary records.

2. Material and methods

In total, ^{10}Be and $^{230}Th_{ex}$ results from 19 long sediment cores, mostly covering at least the last 140 kyr and 18 shorter records [5], covering the Holocene and the last glacial period, were included in the calculations (Table 1; Figs. 2 and 3).

The analytical methods for separation and measurement of both radioisotopes from marine sediments have been described in detail previously and are only briefly summarized here. The radioisotopes ^{230}Th, ^{238}U and ^{234}U were measured via alpha spectrometry after complete dissolution and chemical separation following the procedure described in [32] for the data published by the Heidelberg group and following [29] for the data of the Lamont group. For the calculation of excess ^{230}Th activity originating from the water column, the amount of detrital ^{230}Th which is in radioactive equilibrium with its mother nuclide ^{234}U has to be subtracted from the total supported ^{230}Th activity. Additionally, a possible

Table 1
Locations of the sediment cores, age ranges, water depths and references of publications containing the original data where available

Core	Location	Age range (kyr B.P.)	Water depth (m)	References
Atlantic				
1533	82°1,9′N, 15°10,7′E	0–130	2030	^{10}Be [38], ^{230}Th: this study
23059	70°18,3′N, 4°1,3′W	0–205	2281	^{10}Be [38], ^{230}Th [39]
GeoB1523-1	3°39,9′N, 41°37,3′W	5–190	3292	^{10}Be: this study, ^{230}Th [40]
M16772	1°21′S, 11°58′W	16–205	3913	[41], δ^{18}O [42]
GeoB1008-3	6°34,9′S, 10°19,1′E	0–173	3124	[43]
V22-108	43°11′S, 3°15′W	6–163	4171	[30]
PS2082-1	43°13,2′S, 11°44,3′E	0–205	4610	[31,35]
RC15-94	42°54′S, 20°51′W	11–93	3762	[30]
RC15-93	46°06′S, 13°13′W	13–86	2714	[30]
PS1754-1	46°46,2′S, 7°36,7′E	0–144	2471	[31,35]
RC13-254	48°43′S, 5°07′E	0–138	3636	[30]
PS1756-5	48°43,9′S, 6°42,8′E	7–147	3787	[31,35]
RC13-271	51°59′S, 4°31′E	0–89	3634	[30]
PS1768-8	52°35,6′S, 4°28,5′E	3–144	3270	[31,35]
RC13-259	53°53′S, 4°56′W	0–188	2677	[30]
PS1772-8	55°27,5′S, 1°10′E	0–205	4135	[31,35]
Pacific				
KLH093	1°30′N, 102°3,8′W	0–94	3259	[32]
RNDB 74P	0°20,5′N, 159°22,5′E	0–205	2547	[44], δ^{18}O [45]
RNDB 75P	1°53,15′N, 160°11,49′E	130–205	3078	[44], δ^{18}O [18]

References for the δ^{18}O stratigraphies are included if not referenced in the corresponding publication of the ^{230}Th or ^{10}Be data.

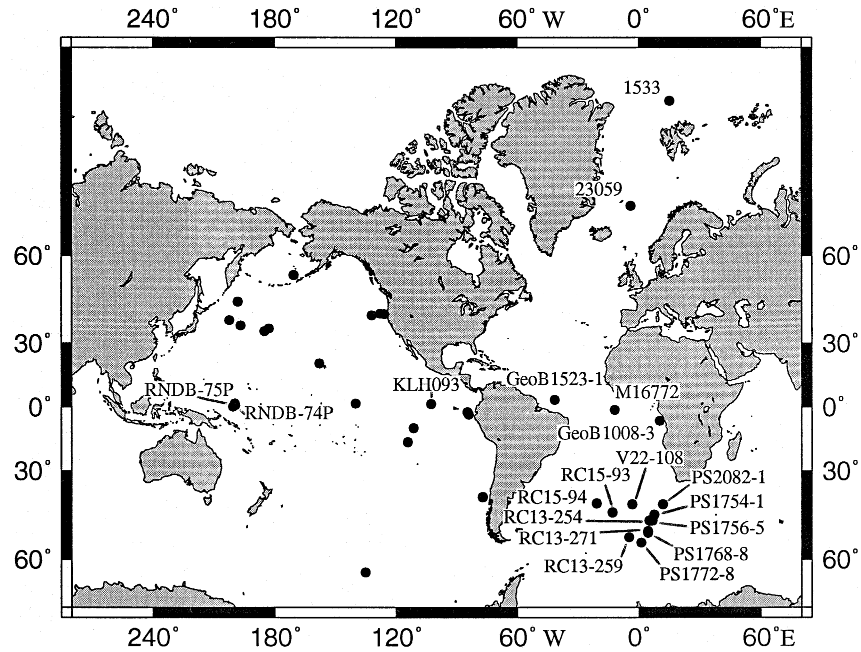

Fig. 2. Locations of the sediment cores included in this study. The symbols in the Pacific without labels correspond to the Holocene and last glacial core sections of Lao et al. [5]. See references therein for exact names and locations of the cores.

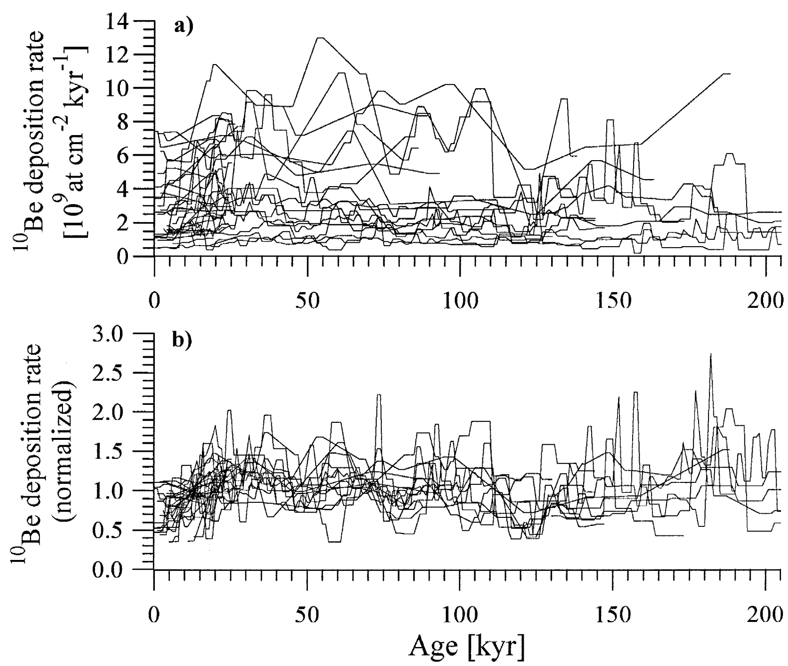

Fig. 3. (a) Compilation of the ^{10}Be deposition rates of all cores. The deposition rates (^{10}Be accumulation rates normalized to $^{230}Th_{ex}$) of ^{10}Be for each core were calculated with an age resolution of 1 kyr from 0 to a maximum of 205 kyr B.P. Although ^{10}Be and $^{230}Th_{ex}$ records for the period older than 205 kyr are available, the statistical uncertainties of the $^{230}Th_{ex}$ measurements become too high for reliable calculations. (b) ^{10}Be deposition rates of each core normalized to their corresponding average values.

diffusive addition of authigenic uranium during deposition of the sediment, which also generates ^{230}Th, has to be taken into account. Peaks of ^{234}U above the lithological background are ascribed to such an authigenic origin and thus the $^{230}Th_{ex}$ activity is calculated as:

$$^{230}Th_{ex} = {}^{230}Th_{(supported)} - {}^{234}U_{(background)} - \left(\left({}^{234}U_{(total)} - {}^{234}U_{(background)}\right) \cdot \left(1 - e^{-\lambda(Th)t}\right)\right)$$

For the ^{10}Be measurement the sediment samples were chemically leached, closely following the method described in [33] for the data published by the Heidelberg group and the one described in [29] for the data of the Lamont group. The ^{10}Be concentrations were measured at the AMS facility of the ETH Zürich and all calibrated to an internal standard (S555) with a nominal $^{10}Be/^{9}Be$ ratio of $95.5 \cdot 10^{-12}$.

The initial concentrations of $^{230}Th_{ex}$ and ^{10}Be at the time of deposition were calculated as:

$$^{230}Th^{0}_{ex}\left({}^{10}Be^{0}\right) = {}^{230}Th_{ex}\left({}^{10}Be\right)(\text{measured}) \cdot e^{\lambda t}$$

with λ being the decay constant ($^{230}Th = 9.24 \cdot 10^{-6}$ 1/y; $^{10}Be = 4.56 \cdot 10^{-7}$ 1/y) and the age t being derived from the application of the $^{230}Th_{ex}$-based dating method described in [31]. The deposition rate of ^{10}Be was calculated using the following equation [34]:

$$DR_{Be} = \beta \cdot z \cdot f_{Be} \cdot {}^{230}Th^{0-1}_{ex}$$

where β is the production rate of ^{230}Th in the water column, z is the water depth, f_{Be} is the ^{10}Be, and $^{230}Th^{0}_{ex}$ is the initial concentration of $^{230}Th_{ex}$.

The sediment cores for the present study were chosen depending on a number of criteria: ^{10}Be and $^{230}Th_{ex}$ must have been determined on aliquot samples, preferably continuous slit samples, allowing the calculation of a constant flux model for $^{230}Th_{ex}$. The application of this model results in high resolution dating for each sample and thus gives detailed age information, especially within individual $\delta^{18}O$ stages [31]. An additional requirement was an independent stratigraphy for each core, either based on $\delta^{18}O$ and/or ^{14}C chronology or other reliable stratigraphic approaches (i.e. diatom biofluctuation stratigraphy and lithostratigraphy combined with $^{230}Th_{ex}$ dating in the Southern Ocean [31]). Knowing the timing for each sediment interval, the values were transferred into 1000 year increments. Included were also cores which were only sampled at distinct points if the age constraint was regarded reliable [5,30]. The clustering of cores in the southern Atlantic does not affect the global nature of the stacked signal because in this area huge paleoenvironmental contrasts have existed within short distances that also changed on glacial/interglacial time scales [30,35].

Radiochemical studies of many sediment cores from high northern and southern latitudes have shown that the $^{230}Th_{ex}$ normalization of the ^{10}Be fluxes is often not applicable there, either due to variable contributions of old, rapidly resedimented particles [36] or very strong dilution with ice transported material [37]. Therefore, we were only able to include two cores from the high northern latitudes where these effects were not found. The sediments were taken from a wide variety of marine environments reaching from the low particle flux areas of the central ocean gyres to the high biological productivity zones at the upwelling areas in the eastern Atlantic and Pacific and the Southern Ocean. Thus, latitudinal effects on the production rate of cosmogenic isotopes [2] should be averaged out by the differences in geographical position and atmospheric and oceanic mixing and deposition processes. In order to eliminate local effects of enrichment or depletion by local influences such as boundary scavenging (i.e. locations at ocean margins on average receive a higher ^{10}Be supply than locations in the central ocean gyres), the ^{10}Be deposition rates of each core were normalized to their average values (Fig. 3b). Thus the resulting variations in normalized ^{10}Be rain rates, if not due to changes in production rate, can only result from changes in boundary scavenging at the particular location, which we average out by calculating a stack of as many cores as possible. We want to note here that, in the sedimentary record of $^{230}Th_{ex}$-normalized ^{10}Be deposition at remote locations far from areas of high particle fluxes, such as, for example, the Ontong Java Plateau [44], the influences of geomagnetic modulation on the ^{10}Be deposition are clearly visible, but still too uncertain for any quantitative statements.

3. Results and discussion

The global stack of ^{10}Be deposition (Fig. 4a), representing variations in cosmogenic production rate, was calculated as the arithmetic mean of every 1 kyr increment of the data from Fig. 3b). The average of the youngest 5 normalized values was 0.82, so that all other values were divided by 0.82 in order to start the record with a present day value of 1. A standard error of the mean was calculated for each 1 kyr increment. Propagation of internal errors of the individual measurements confirms that statistical uncertainties of the ^{10}Be deposition rates of individual core sections were lower than the (external) standard error of the mean and therefore do not have to be taken into account.

The reconstruction of the ^{10}Be production rate shows several prominent features. Integration of the 200 kyr record yields an average production rate increased by 20% over the present day value. Our record suggests that the global ^{10}Be production rate has remained almost constant during the last about 10 kyr, followed by a steep increase to a maximum about 60% excess over present day values from 30 to 42 kyr B.P. (approximately the time of the Laschamps Event [10]). The results of the ^{10}Be production rate record coincide with U/Th based ^{14}C calibrations during the last glacial period, from which a maximum of 40% excess over present day production around 20 kyr B.P. was deduced [4]. Furthermore, the ^{10}Be record suggests, as well as the records of Guyodo and Valet [22] and Laj et al. [28], that the increase in cosmogenic radionuclide production rate, and thus the deviations between U/Th and ^{14}C ages, reach a maximum at 30–42 kyr B.P. which is even more pronounced than deduced in [4]. A short period

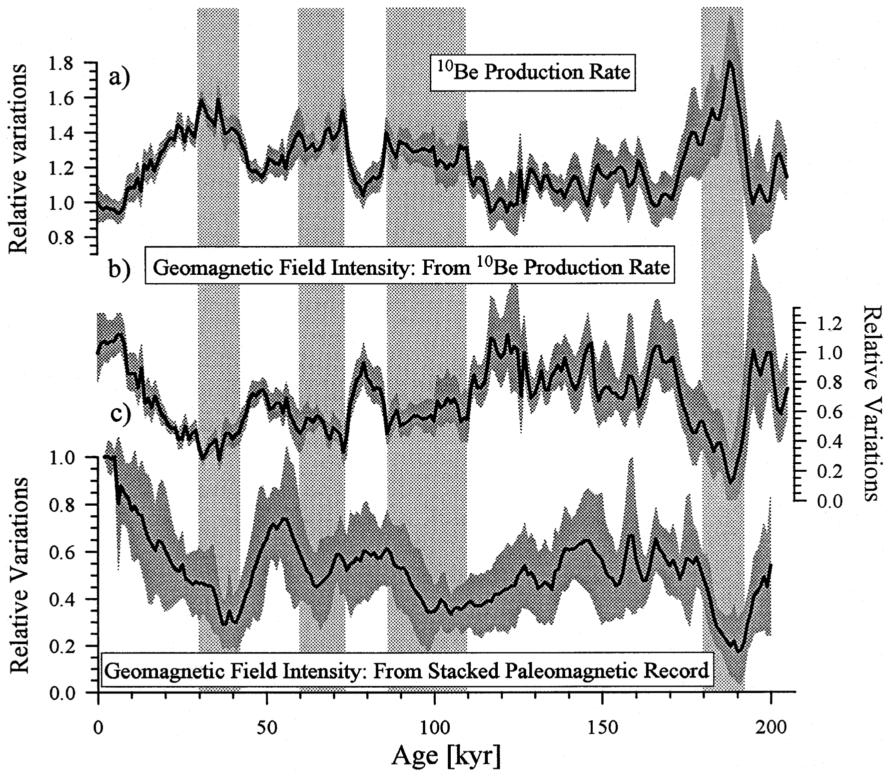

Fig. 4. (a) Global stacked ^{10}Be deposition rate which renders relative ^{10}Be production rate variations as function of age. The dark grey areas in (a) and (b) mark the standard error of the mean. The light grey bars mark periods in which the data show that the production rate of ^{10}Be was increased and the field intensity was reduced. (b) Relative geomagnetic field intensity variations derived from ^{10}Be production rate changes following Lal [3] as function of age. The values between 140 and 205 kyr represent 3-point running means. (c) Global stacked record of field intensity variations based on a stacked paleomagnetic record [22]. The dark grey area marks 1 standard deviation.

of decreased production rate (45–55 kyr B.P.) is followed by another, less pronounced peak (40% excess) between 60 and 75 kyr B.P. From about 85 to 110 kyr B.P. (after the Blake event) the present day production was exceeded by about 30%, while during the period between 110 and 175 kyr B.P. the production rate was equal to or slightly higher than at present without any significant excursions. Finally, a large peak in the production rate occurred from 180 to 192 kyr B.P. (Biwa 1 event [24,26]) where the maximum of the record (1.8 fold increase compared to the present) is reached. This is almost the maximum increase in production rate predicted for zero field intensity [3].

The record of relative ^{10}Be production rate changes is translated into relative field intensity variations following Lal [3] (Figs. 1 and 3b). It is compared to the recent stacked record of geomagnetic field intensity deduced from paleomagnetic studies of marine sediments [22] (Fig. 4c). The relative field intensity was calculated under the assumption that 100% of the variation in our stacked record of ^{10}Be production rate is caused by variations in geomagnetic field intensity (solar activity variations were considered negligible for our approach).

In general, there is a good agreement between the patterns of the two reconstructions (e.g. correlation coefficient r^2 for the last 100 kyr is 0.6 without any adjustments of both time scales). Both records yield an overall field intensity that has been reduced relative to the present day value during the last 200 kyr. Integration of the ^{10}Be-based stack yields an overall value reduced by 30%. Furthermore, the present day field intensity is shown to represent a very strong maximum. In both reconstructions the major events described above are found.

The only significant inconsistency between the paleomagnetic record and the ^{10}Be-based data occurs from about 115 to 125 kyr B.P. During this period the ^{10}Be-based reconstruction of the field intensity shows a pronounced maximum, about comparable to the present, which is not represented by an increase in the paleomagnetic record. This maximum is followed by a pronounced weakening of the field at about 115 kyr B.P. We can only speculate on the reasons for the discrepancy between the records from 115 to 125 kyr B.P. One explanation may be that, by coincidence, we have sampled cores that had uniformly reduced local ^{10}Be rain rates. This explanation, however, seems rather unlikely.

4. Conclusions

The results of the global ^{10}Be stack provide a record of cosmogenic radionuclide production rate for the last 200 kyr and an alternative approach for reconstructing paleomagnetic field intensity variations. For the reconstruction of variations in the global ^{10}Be production rate disturbing effects of sediment redistribution processes were eliminated by normalization of the ^{10}Be fluxes to $^{230}Th_{ex}$. Local effects of boundary scavenging were removed by normalizing the ^{10}Be deposition rates of each core to their corresponding average value and changes in boundary scavenging intensity with time were eliminated by stacking together many cores from different regions.

Instability events or excursions of the geomagnetic field intensity during the last 200 kyr which were found by paleomagnetic studies, such as the Laschamps Event and the Biwa I Event, are mirrored by significant increases in the production rate of ^{10}Be. Integration of the ^{10}Be-based field intensity over the last 200 kyr shows that the field was overall about 30% weaker than today and suggests that the present day field intensity represents a strong maximum. The good agreement between the ^{10}Be-based and paleomagnetic records validates the applicability of sedimentary paleomagnetic investigations for reconstructing geomagnetic field intensity variations.

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of all unpublished cores are available on request or as an **EPSL Online background data set** [1]. *[RV]*

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