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Comparison of cosmogenic radionuclide production and geomagnetic field intensity over the last 200 000 years

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The production rate of cosmogenic radionuclides such as ^{10}Be or ^{14}C is known to vary as a function of the geomagnetic field intensity. It should, therefore, be possible to extract a record of palaeofield intensity from the deposition record of these radionuclides in marine or terrestrial sediments and ice cores. Field intensity variations, however, are not the only factor that has influenced the cosmogenic radionuclide records. In the case of ^{14}C, variations of the global carbon cycle, caused by reorganization of the ocean circulation patterns from the last glacial to the present interglacial, are superimposed. ^{10}Be is not affected by these variations because it is not part of the carbon cycle, but its deposition rates in marine sediments vary as a function of lateral sediment redistribution and boundary scavenging intensity. A global stacked record of ^{10}Be deposition rates, corrected for sediment redistribution by normalizing to ^{230}Th$_{\mathrm{ex}}$, was shown to remove most of the disturbances, and provides a record of ^{10}Be production rate variations over the last 200 000 years, which translates into geomagnetic field intensity variations. This dataset is compared with palaeofield intensities reconstructed from marine sediments by palaeomagnetic methods, from variations in atmospheric ^{14}C/^{12}C derived from independent calibrations of ^{14}C ages, such as U/Th dating and tree ring chronology, and from ^{36}Cl and ^{10}Be fluxes in polar ice cores. Potential influences of the Earth's orbital parameters and insufficient correction for orbitally triggered climate variations on the palaeointensity reconstructions are assessed. It is argued that the palaeointensity records derived from marine sediments are not significantly affected by these factors.

Keywords: cosmogenic radionuclide production rate; geomagnetic field intensity; orbital forcing; palaeoclimatic disturbances

1. Introduction

Cosmogenic radionuclides are produced in the Earth's atmosphere, mostly the stratosphere, by interaction of the incident flux of galactic cosmic ray particles with the particles of the atmosphere. The production rate of cosmogenic radionuclides is, therefore, primarily a function of changes in primary cosmic ray flux, solar activity, and shielding by the Earth's magnetic field. Although there have been suggestions

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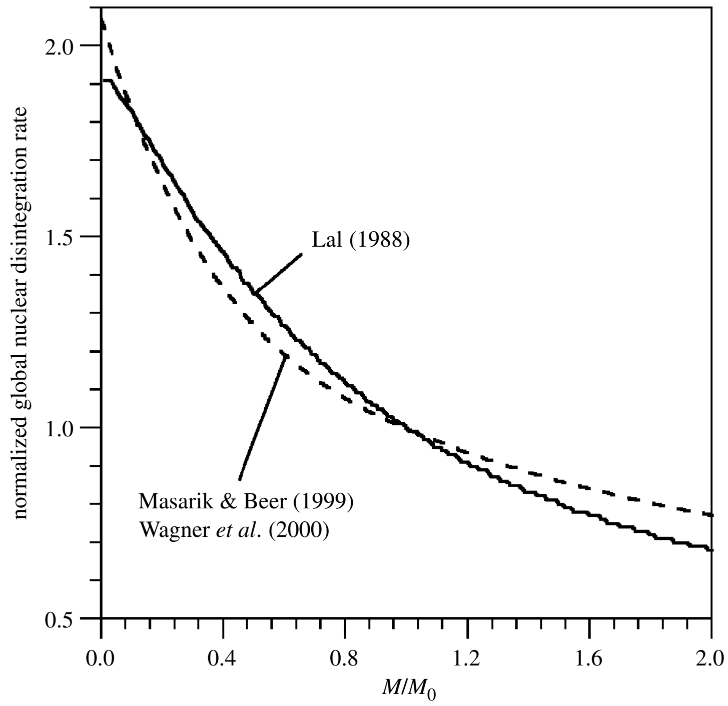

Figure 1. Relationship between normalized global radionuclide production rate and normalized geomagnetic field intensity. The solid curve represents a fit to the data given by Lal (1988), and the dashed curve represents the results for ^{10}Be of the model by Masarik & Beer (1999) and Wagner *et al.* (2000) for a long-term average solar modulation parameter $\phi = 550$ MeV.

that the primary cosmic ray flux has varied as a consequence of supernovae (Sonnett *et al.* 1987), the overall flux on time-scales of millions of years appears to have been constant within *ca.* 20% (Vogt *et al.* 1990). Solar activity has been shown to influence the production rate of cosmogenic radionuclides on time-scales of years to hundreds of years with maxima in cosmogenic radionuclide production rate being related to minima in solar activity, as observed in ^{10}Be records of polar ice cores (Beer *et al.* 1988, 1990) and ^{14}C records of tree rings (Stuiver 1961; Bard *et al.* 1997). Compared with the long-term variations in cosmogenic radionuclide production rate, observed on time-scales of thousands to hundreds of thousands of years, the changes caused by solar activity are small (see Frank *et al.* 1997; Bard 1998).

This leaves variations in strength of the Earth's magnetic field as the most important factor controlling cosmogenic radionuclide production. This was already suggested in the 1950s and a first-order relationship between the relative strength of the magnetic field and cosmogenic radionuclide production rate was determined (Elsaesser *et al.* 1956)

$$Q_M/Q_{M_0} = \text{const.}(M/M_0)^{-0.5},$$

where Q stands for the global nuclear disintegration rate at a certain field strength M and at the reference strength M_0 (present field strength). This relationship, which is not applicable for very small values of M, was later refined by Lal (1988) and is displayed graphically in figure 1. More recently, an alternative physical model for the simulation of cosmic ray particle interactions with the Earth's atmosphere was developed and applied to investigate the relationship between cosmogenic radionuclide production rates and field strength (Masarik & Beer 1999; Wagner *et al*. 2000). In figure 1, the results derived from this model for the production rate of ^{10}Be at an average solar modulation parameter ($\phi = 550$ MeV) are shown for comparison with the former relationship of Lal (1988). Both models are in relatively good agreement but the physical model tends towards slightly higher cosmogenic radionuclide production rates for very low field intensities and indicates a smaller effect for high field intensities. The shielding of the Earth by its magnetic field varies strongly as a function of latitude with highest values at low latitudes *ca.* 0–10° and lowest values at high latitudes between 60° and the poles, where the magnetic field lines are perpendicular to the Earth's surface. Accordingly, the production rates of cosmogenic radionuclides are highest between 60° and 90° latitude and lowest around the Equator. The flux of cosmogenically produced isotopes such as ^{10}Be to the Earth's surface is, however, dominated by mixing between stratosphere and troposphere, which occurs mainly at mid-latitudes. This results in a maximum of deposition on the surface of the Earth at *ca.* 40° latitude (Lal & Peters 1967).

While there are ways of accurately determining the present-day geomagnetic field intensity and radionuclide production rates, the reconstruction of both parameters for the past is difficult and has been the subject of a large number of studies. In particular, radioactive cosmogenic radionuclides such as ^{14}C or ^{10}Be are widely applied for dating and for tracing environmental processes, which requires a precise knowledge of variations in their production rate over time.

(*a*) *Palaeomagnetic reconstruction of field intensity variations*

Absolute reconstructions of the palaeomagnetic field intensity can only be recovered from lavas, which generally provide unequally distributed spot recordings resulting in a low time resolution (see Valet *et al*. 1998). Numerous palaeomagnetic studies have therefore addressed the reconstruction of relative secular field intensity variations from marine (Kent & Opdyke 1977; Meynadier *et al*. 1992; Tric *et al*. 1992; Tauxe 1993; Valet & Meynadier 1993; Tauxe & Shackleton 1994; Yamazaki & Ioka 1995; Weeks *et al*. 1995; Lehman *et al*. 1996; Channell *et al*. 1997) and lacustrine (Thouveny *et al*. 1993; Williams *et al*. 1998) sediments during the Quaternary. Global stacks of marine palaeointensity records have been produced to isolate common features and to achieve a general palaeointensity reconstruction (Guyodo & Valet 1996, 1999). In the stacked 800 kyr marine sediment-derived palaeointensity record (1 kyr = 1000 yr), which has been calibrated to absolute field intensity data of the last 40 kyr, all as-yet independently identified major directional excursions of the magnetic field during the last 800 kyr are reflected by minima in field intensity below a critical value (Guyodo & Valet 1999; Langereis *et al*. 1997).

Disturbances of the natural remanent magnetization (NRM) signal in sediments can arise from many sources, such as climatically controlled variations of different lithological parameters (see Kent 1982). Despite a lot of effort to screen out lithologic variables, there is an ongoing debate as to which of the procedures is the most suitable, whether there is a generally applicable method, and whether all disturbances are completely corrected for (see Schwartz *et al*. 1996; Valet & Meynadier 1998; Kok 1999; Yamazaki 1999). In this paper, the information provided by reconstructions of cosmogenic radionuclide production rate is evaluated and compared with the results achieved by globally stacking the palaeomagnetic reconstructions of relative field intensity, which appears to be the most reliable current approach based on palaeomagnetic methods.

(*b*) *Variations of cosmogenic radionuclide production rate over time*

A precise record of atmospheric $\Delta\,^{14}$C (^{14}C/^{12}C) variations over the last 30 kyr has been obtained by direct comparison of ^{14}C and U/Th ages in corals from Barbados, Tahiti, Mururoa and New Guinea (Bard *et al*. 1990, 1993, 1996, 1998; Edwards *et al*. 1993). For the last 11.85 kyr, this record is supported by a calibration of ^{14}C ages of fossil wood with very precise absolute ages obtained from tree ring chronology (see Stuiver *et al*. (1986), Kromer & Becker (1993), Kromer & Spurk (1998); and figure 2). These data apparently document a long-term decrease in the production rate and, thus, an increasing strength of the magnetic field from values as low as only 40% of the present-day intensity *ca.* 30 kyr BP (BP denotes 'before present') towards values similar to the present day at *ca.* 5 kyr BP. For approximately the last 30 kyr, these variations have been corroborated by a high-resolution $\Delta\,^{14}$C record obtained from a varved sediment record from Lake Suigetsu in Japan (Kitagawa & van der Plicht 1998). This lake sediment record extends back to *ca.* 45 kyr BP and suggests that the field intensity between 45 and 32 kyr BP was significantly higher than during the minimum following after 32 kyr BP (figure 2). Due to the ages of these samples, which correspond to 5–8 half-lives of ^{14}C, and the additional uncertainties arising from the fact that the varve chronology is more uncertain than the absolute U/Th ages of the corals and can also not exclude missing sections of sediment, these results for the period between 32 and 45 kyr BP have to be considered with some caution.

An alternative approach to evaluate $\Delta\,^{14}$C back to 55 kyr BP was based on calibration of ^{14}C ages of foraminifera in a marine sediment core from the southwestern Iceland Sea in the Atlantic Ocean by correlating its high-resolution stable carbon and oxygen isotope record to the GISP2 ice-core oxygen isotope record and, thus, achieving an independent absolute time-scale (Voelker *et al*. 1998). This approach has relatively large uncertainties caused by an unknown process that renders the ages of the planktonic formainifera up to 2 kyr older than benthic species from the same depth in this core. Additional uncertainty arises from possible bias due to bioturbation, the assumption that the oxygen isotope variations in the planktonic foraminifera were solely caused by meltwater injections rather than changes of sea surface temperature, and uncertainties with the GISP2 time-scale itself. Nevertheless, the results are in relatively good agreement with the other approaches mentioned

Figure 2. (*a*) Difference between conventional ^{14}C ages (obtained by accelerator mass spectrometry (AMS)) and mass spectrometric (TIMS) U/Th ages from corals given as calendar ages in kyr BP for the last 45 kyr (triangles). The thin solid line represents the so-called tree ring calibration of ^{14}C ages, which now extends back 11 850 years. The ^{14}C data of the varved sediment record of Lake Suigetsu in Japan are given as open squares, and the results of the ^{14}C calibration derived from a sediment core in the Iceland Sea are given as open diamonds. The dashed line represents the 1:1 correlation line and all uncertainties are given as 2σ errors of the ^{14}C ages. (*b*) Atmospheric $\Delta\,^{14}$C variations over the last 45 kyr as derived from the differences between the ^{14}C ages and the absolute ages in (*a*). The data of the Lake Suigetsu record are connected by a dashed line. The data for the sediment core form the Iceland Sea are given as a solid grey line with the error marked by the light-grey area. Uncertainties are given at the 2σ level. Note that any errors in the calendar age chronologies of the Lake Suigetsu and Iceland Sea records are not included in the 2σ uncertainties shown in (*a*) and (*b*). Sources of all data are given in the text.

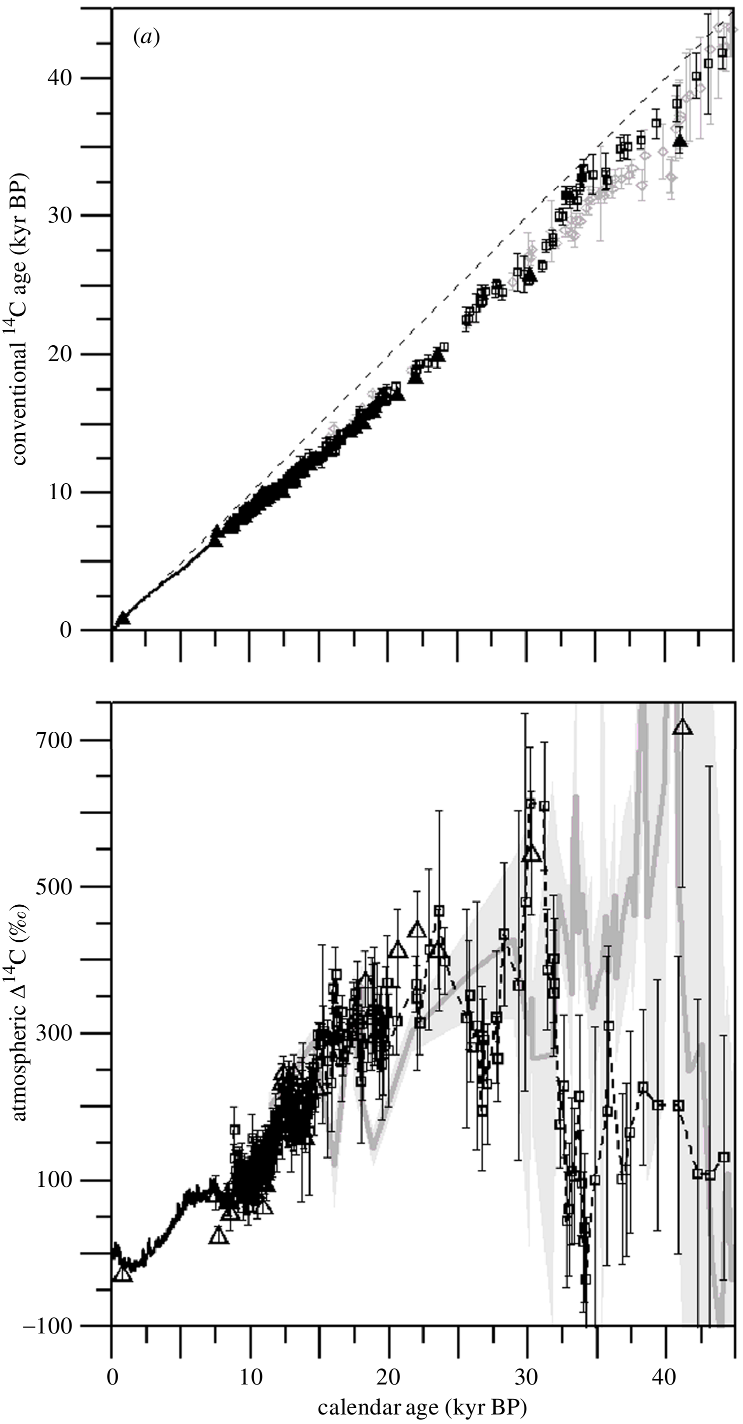

Figure 2. See opposite for description.

above to evaluate atmospheric Δ^{14}C for the period between 11 and 30 kyr BP (figure 2). Beyond 30 kyr BP the statistical uncertainties in the Δ^{14}C record calculated from the data in Voelker *et al.* (1998) are huge, but, in contrast with the results of Kitagawa & van der Plicht (1998), it suggests that field intensity was at minimum values between 32 and 42 kyr BP.

The variations in Δ^{14}C over time are not only influenced by field intensity variations but also by changes of the global carbon cycle because $^{14}CO_2$ is exchanged between the atmosphere and the ocean (see Oeschger *et al.* 1975; Bard *et al.* 1990, 1997; Kitagawa & van der Plicht 1998). There is evidence for significant variability of the global climate system affecting the carbon cycle, such as a more sluggish thermohaline circulation during glacials (Broecker *et al.* 1990), and also other parameters, such as a reduction of the glacial global biosphere reservoir and lowered glacial atmospheric CO_2 levels (see Bard (1998) for a summary). These processes prevent the direct translation of the observed Δ^{14}C variations into palaeointensity variations of the Earth's magnetic field.

Unlike ^{14}C, ^{10}Be and ^{36}Cl do not exchange with the atmosphere once introduced into the ocean. A large peak of ^{10}Be concentration and flux found in polar ice cores (Raisbeck *et al.* 1987, 1992; Beer *et al.* 1992) and Mediterranean (Cini Castagnoli *et al.* 1995) and Caribbean (Aldahan & Possnert 1998) sediments *ca.* 35 kyr BP has, therefore, been ascribed to a major reduction of the geomagnetic field intensity, roughly coinciding with the Laschamp event (Levi *et al.* 1990). This increase in cosmogenic radionuclide deposition was recently confirmed by high-resolution records of the ^{36}Cl and ^{10}Be flux in the GRIP ice core (Yiou *et al.* 1997; Baumgartner *et al.* 1998; Wagner *et al.* 2000). The good correspondence between geomagnetic field intensity variations derived from Mediterranean marine sediments by palaeomagnetic methods (Tric *et al.* 1992) and the ^{10}Be flux into the Vostok ice core was even suggested to serve as a geomagnetic chronometer in ice cores for the last 140 kyr (Mazaud *et al.* 1994). The pattern of a 96–25 kyr BP record of ^{36}Cl flux obtained from the GRIP ice core is also in good agreement with the variations expected from palaeointensity records, and supports the view that the cosmogenic radionuclide flux into ice cores may serve to reconstruct the Earth's magnetic field intensity provided that the chronology of the ice cores can be reliably established (Baumgartner *et al.* 1998). It should be noted, however, that neither the ^{10}Be nor the ^{36}Cl GRIP records indicate a decrease between 30 and 5 kyr BP, where data are available, which may arise from an atmospheric transport problem (Wagner *et al.* 2000). Another reconstruction of ^{36}Cl production rate from fossil rat urine is in rough agreement with the patterns of the other Δ^{14}C records but with a relatively large scatter and the occurrence of very high ^{36}Cl values for the period between 20 and 11 kyr BP, suggesting that the ^{36}Cl record from this source may have been influenced by local climatic effects (Plummer *et al.* 1997).

2. Reconstruction of the relative geomagnetic field intensity of the last 200 kyr from a global stacked record of ^{10}Be deposition in marine sediments

Other approaches involving cosmogenic radionuclides to reconstruct the strength of the Earth's magnetic field have been based on ^{10}Be in sediments. ^{10}Be deposition rates in marine sediments can, however, only be interpreted in terms of relative palaeointensity variations if two major disturbing effects have been accounted for. These are sediment redistribution caused by bottom current activity and boundary scavenging, i.e. the transport of dissolved ^{10}Be within the water column of the ocean and its preferential deposition in areas of high particle fluxes (Anderson *et al*. 1990). One way to correct for these effects is the extraction of the authigenic (adsorbed onto particles from the water column) ^{10}Be/^{9}Be ratio from the sediments (Henken-Mellies *et al*. 1990; Robinson *et al*. 1995). However, even if the authigenic ^{10}Be/^{9}Be signal is correctly measured, which is not trivial, the record may still be influenced by circulation changes and advection of different water masses with different ^{10}Be/^{9}Be ratios on glacial/interglacial time-scales (Robinson *et al*. 1995). A combination of these factors, in addition to a relatively poor age control, may have prevented the detection of a clear signal of cosmogenic radionuclide production increase in the ^{10}Be records across two magnetic reversals in the study of Henken-Mellies *et al*. (1990). Another method of deriving a correct reconstruction of ^{10}Be accumulation in marine sediments applies a normalization to the highly particle-reactive U-series radioisotope ^{230}Th to correct for sediment redistribution effects (Bacon & Rosholt 1982; Bacon 1984). In order to achieve a reconstruction of the global ^{10}Be production rate for the last glacial maximum (18–20 kyr BP) and the Holocene, the ^{230}Th-normalized ^{10}Be deposition rates from the Pacific for the Holocene and the last glacial maximum were averaged to account for variations in boundary scavenging intensity (Lao *et al*. 1992). These authors came up with an estimate of an increase of *ca*. 30% in the radionuclide production rate during the last glacial maximum, which is in good agreement with the estimate derived from U/Th-calibrated ^{14}C ages (Bard *et al*. 1990).

Recently, a method for reconstruction of palaeofield intensity from marine sediments at a higher resolution has been proposed on the basis of a global stacking of ^{10}Be deposition records (Frank *et al*. 1997). This approach also applied normalization of the ^{10}Be fluxes to ^{230}Th in order to correct for sediment redistribution effects. In addition, a ^{230}Th constant flux model was calculated for each core (Frank *et al*. 1996). This provides more-detailed information on variations of sedimentation rate, and, thus, additional age information, between the major climatic transitions, as identified by correlating the oxygen isotope record of each individual core with a globally stacked oxygen-isotope stratigraphy (Martinson *et al*. 1987). Due to boundary scavenging, locations at high particle flux areas, such as ocean margins, will always receive a higher ^{10}Be flux than regions of low particle fluxes, such as central ocean gyres. To account for this effect, the ^{230}Th-normalized ^{10}Be deposition rates were normalized to their average values in each core. These relative variations were then globally averaged in 1000-year increments to account for changes in boundary scavenging over time resulting from climatically induced changes in particle flux and composition at particular locations. The results of this approach are compared in figure 3 with the results of the 200 kyr stacked palaeomagnetic record of Guyodo & Valet (1996). The reconstruction of ^{36}Cl production rate from the GRIP ice core for the period 25–96 kyr BP is also shown for comparison (Baumgartner *et al*. 1998).

It is obvious that the basic patterns in all these records are very similar. Major maxima in the cosmogenic radionuclide production rate occurred in the 30–42 kyr BP and 180–192 kyr BP ranges, corresponding to the Laschamp (Levi *et al*. 1990) and Biwa I (Champion *et al*. 1988) geomagnetic excursions, respectively. Minor maxima in production rate, which are mirrored by minima in the field intensity, are observed between 60 and 75 kyr BP and between 85 and 110 kyr BP. The only obvi-

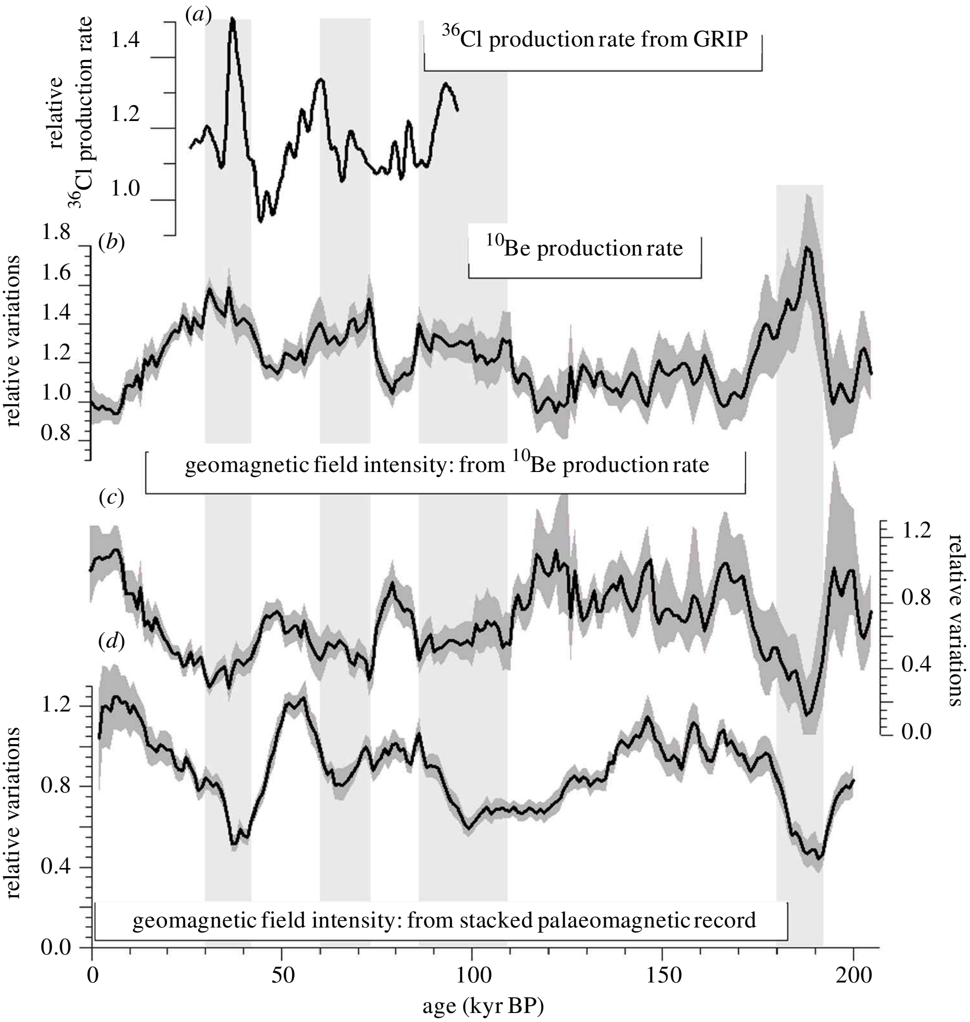

Figure 3. Relative variations of global radionuclide production rate derived from (*a*) ^{36}Cl fluxes in the GRIP ice core using an ice core chronology (Baumgartner *et al*. 1998); and (*b*) the global stacked record of ^{10}Be deposition (Frank *et al*. 1997). (*c*) Relative variations of the geomagnetic field intensity derived from the ^{10}Be-based reconstruction of cosmogenic radionuclide production rate in (*b*), which was obtained by application of the relationship given by Lal (1988) (figure 1). (*d*) Palaeofield intensity variations derived from the global stacked palaeomagnetic record of Guyodo & Valet (1999). All data in this figure are shown as a function of age in kyr BP. The dark areas in (*b*), (*c*) and (*d*) mark one standard error of the mean accounting for the scatter in the stacked data. The light-grey areas mark periods of time for which the stacked records in (*c*) and (*d*) indicate low field intensities.

ous discrepancy between the records is in the period between 125 and 115 kyr BP. Between 125 and 95 kyr BP, the palaeomagnetic stack shows a broad minimum that includes the approximate period (*ca.* 120–110 kyr BP) during which the Blake event occurred (Tucholka *et al*. 1987; Champion *et al*. 1988; Tric *et al*. 1991; Fang *et al*.

1997). This is only mirrored by the maximum in ^{10}Be production rate data up to *ca.* 110 kyr BP, whereas during the period of the Blake event itself, the production rates of the ^{10}Be stack remain low. A possible explanation for this discrepancy may originate from the selection of available sedimentary records of ^{10}Be and ^{230}Th. A number of these records show peak ^{230}Th activities during this period, which may not be entirely explainable by low sedimentation rates and sediment focusing. This has led to some speculation on their significance with respect to variations in ocean circulation (Mangini *et al.* 1990). In view of the total number of 15 cores covering this period of time it is, however, most likely that the low ^{230}Th-normalized average ^{10}Be deposition rates are biased by the selection of cores. The ^{10}Be stack-based field intensity record may, therefore, not represent realistic production rate variations for the period 125–115 kyr BP. Alternatively, a high number of cores included in the stack, in which the high northern latitudes from the Pacific and Atlantic are somewhat under-represented, may just have experienced low local ^{10}Be deposition during this period. Additional records would be required to resolve this problem. Overall, however, the correspondence between the independent stacked palaeomagnetic record and the ^{10}Be production rate record and, in addition, the ^{36}Cl-based production rate record from the GRIP ice core, strongly suggests that the reconstruction of the palaeofield intensity from sedimentary records is reliable.

3. Influences of the Earth's orbital parameters and climate change on palaeointensity records

The potential influence of variations of the Earth's orbital parameters on the strength of its magnetic field has been a subject of discussion in palaeointensity research for many years. Apparent periodicities were shown to be a consequence of inadequate normalization for climatically controlled variations of lithological parameters (Kent & Opdyke 1977; Kent 1982). However, even in normalized palaeointensity records obtained from marine sediments, a residual climatic seemed to have survived normalization procedures (Schwartz *et al.* 1996; Kok 1999). In addition to this, considerable uncertainties in the ages and durations of most geomagnetic excursions have even led to the speculation that excursions might be related to cold stages of the palaeoclimate (Worm 1997). Palaeointensity records from two cores in the northern Atlantic published by Channell *et al.* (1998), however, cast doubt on the assumption that orbital periodicities found in the palaeointensity records, in particular the one representing the 41 kyr obliquity period, were all caused by inadequate normalization. The main argument in their study was that the 100 kyr periodicity was found in both the palaeointensity and the lithological records and could be ruled out by normalization, whereas the 41 kyr period was only present in the palaeointensity record. Channell *et al.* (1998) argued that obliquity variations may have influenced the precessional angular velocity in the Earth's core, as previously suggested by, for example, Kent & Opdyke (1977). Contrary to the results of Channell *et al.* (1998), the 41 kyr periodicity was not found in palaeointensity records of other cores (see Yamazaki 1999), and the recent 800 kyr palaeointensity stack (Guyodo & Valet 1999) also does not show evidence for any dominant periodicities, although one might argue that some of the high frequencies were suppressed in this record due to the stacking procedure and the low time resolution of individual records.

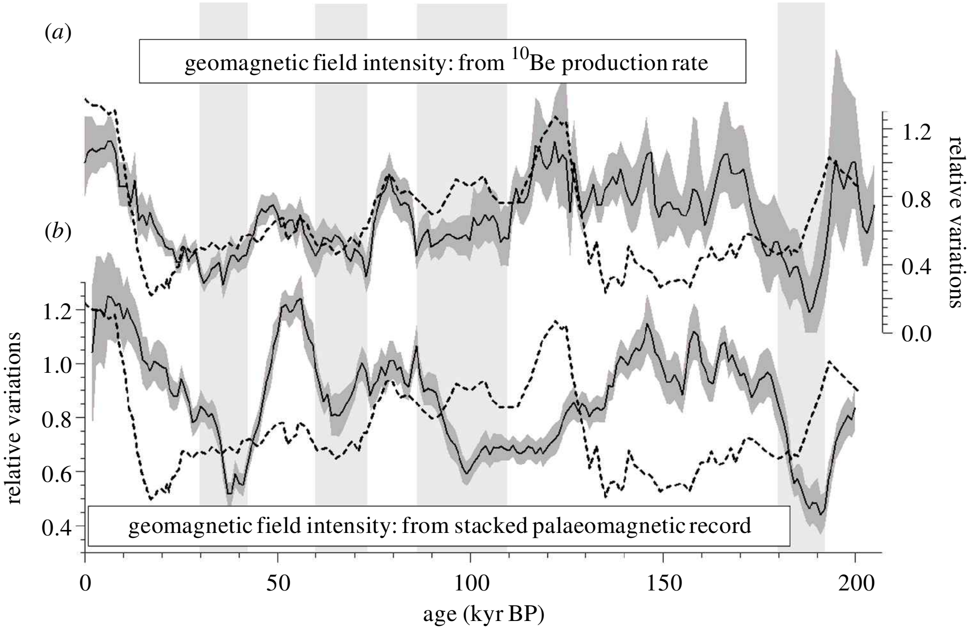

Figure 4. Comparison of the palaeointensity records derived from (*a*) ^{10}Be production rates (Frank *et al*. 1997) and (*b*) the palaeomagnetic stack (Guyodo & Valet 1999), with the global δ^{18}O stacked record (Martinson *et al*. 1987) for the last 200 kyr (dashed line). According to convention, the δ^{18}O record is plotted on a reverse scale so that glacial periods are represented by minima of the plotted curve and interglacial periods by maxima. Uncertainties and minima of field intensities are the same as in figure 3.

As mentioned above, the stacked palaeointensity records based on ^{10}Be and palaeomagnetic approaches correlate very well for the past 200 kyr, which clearly argues in favour of the validity of the palaeointensity reconstructions from marine sediments by normalized NRM records (Frank *et al*. 1997; Guyodo & Valet 1996). Spectral analysis, however, suggests that there may be some correspondence to the frequency maxima of the orbital 41, 23 and 19 kyr periodicities in the stacked records (Kok 1999), although both are quite short for an evaluation of the influence of orbital parameters of the Earth, in particular for the 41 periodicity. These frequency maxima in the palaeointensity records are not nearly as sharp as in the δ^{18}O record and also not exactly centred at the orbital frequencies. Additional cross-spectral analyses suggest that the coherence between δ^{18}O, and, thus, climate, and the palaeomagnetic stacked record is very weak, but the ^{10}Be-based reconstruction apparently shows some correspondence with δ^{18}O for some periods of time, which may point towards an incomplete correction for climatic signals (Kok 1999) (figure 4).

(*a*) *50 kyr BP until the present*

In the following, a detailed direct comparison of the independent palaeointensity records and climate variability for particular periods is shown. It is suggested that any small residual climatic signals, as derived from spectral analysis, have not significantly biased the palaeointensity reconstructions. The period between 50 kyr BP

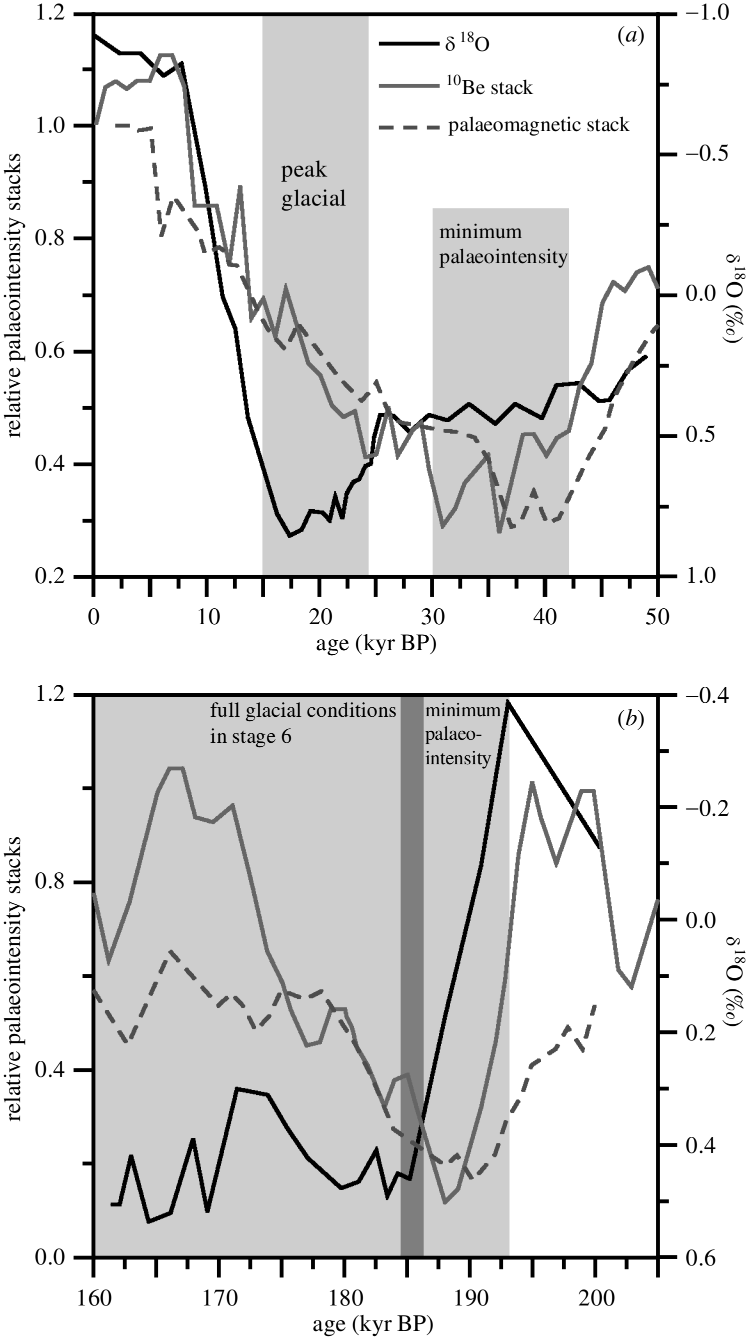

Figure 5. Detailed comparison of the palaeointensity records of Guyodo & Valet (1996) (dashed line), Frank *et al.* (1997) (solid grey line) and the global δ^{18}O stacked record (Martinson *et al.* 1987) given as a solid black line for (*a*) the last 50 kyr and (*b*) the period between 205 and 160 kyr BP. The grey areas mark minima in field intensity and the peak glacial conditions (maximum ice volume) deduced from δ^{18}O.

and the present day is certainly best documented and dated in all records. In figure 5*a*, the stacked palaeointensity records (Frank *et al*. 1997; Guyodo & Valet 1996) are plotted together with the global δ^{18}O stacked record (Martinson *et al*. 1987). It is immediately evident that the two palaeointensity records and the climate record cannot have been controlled by the same factors. The maximum in δ^{18}O defines maximum ice volume and, thus, the peak glacial between *ca.* 24 and 15 kyr BP. In contrast, the palaeofield intensity records show a pronounced minimum between 42 and 30 kyr BP, corresponding to the Laschamp event, and document a continuous rising trend during the whole of the following glacial period. The small phase shift between the two stacked palaeointensity records between 42 and 30 kyr BP originates from the slightly different dating methods used in the two studies: for the palaeomagnetic approach, the sedimentation rate was assumed constant between 59 and 24 kyr BP (isotope stage 3); whereas, in the ^{10}Be-based approach, a ^{230}Th constant flux model was used to determine changes in the sedimentation rate within this period. It has deliberately not been attempted to adjust the chronologies of the two independent records, because this provides some kind of confidence estimate for the stack-based approaches. Even without adjusting the chronology, correlation coefficients (r) between the two stacked records are 0.77 for the last 100 kyr and 0.89 for the last 50 kyr.

The pattern of palaeointensity derived from the two stacked records is further independently supported by the record of atmospheric Δ^{14}C for the last 30 kyr. In figure 6, the Δ^{14}C changes derived from dendrochronological calibration of ^{14}C ages (Stuiver *et al*. 1986; Kromer & Becker 1993; Kromer & Spurk 1998) and U/Th calibration of ^{14}C ages in corals (Bard *et al*. 1990, 1993, 1996, 1998; Edwards *et al*. 1993) are compared with Δ^{14}C variations predicted by using the results of the stacked palaeointensity records as inputs into a carbon cycle box model (Bard *et al*. 1990; Bard 1998). The correspondence between the three independent records is very good and supports the view that most of the observed variability in all three records is caused by field intensity variations. This reconstruction is in agreement with earlier studies using the same carbon cycle box model (Bard *et al*. 1990) to convert field intensity variations derived from palaeomagnetic results of a smaller number of sediment cores into ^{14}C production rates (Mazaud *et al*. 1991). There is also agreement with a reconstruction based on palaeointensity results derived from three sediment cores from the Açores, using a different four-box ocean model without an atmosphere, assuming that the mixing time between surface ocean and atmosphere is much shorter than the time resolution of the field intensity records (Laj *et al*. 1996).

These reconstructions support the view that only about 100‰ of the observed *ca.* 500‰ Δ^{14}C increase during the last glacial period between 30 and 20 kyr BP can be accounted for by changes of the carbon cycle (Bard *et al*. 1990; Broecker *et al*. 1990; Mazaud *et al*. 1991; Laj *et al*. 1996; Bard 1998). Contributions to such changes were probably lowered atmospheric CO_2 levels, a reduction of the global biosphere reservoir, and a more sluggish thermohaline circulation, causing a less efficient transfer of ^{14}C to the deep ocean (see Bard (1998) for a summary).

Between 30 and 45 kyr BP, the results obtained from ^{14}C-based calibration studies (Edwards *et al*. 1993; Kitagawa & van der Plicht 1998; Voelker *et al*. 1998) show large uncertainties. For some periods, the results do not even agree within these large errors and also deviate from the well-correlated palaeointensity stack-based

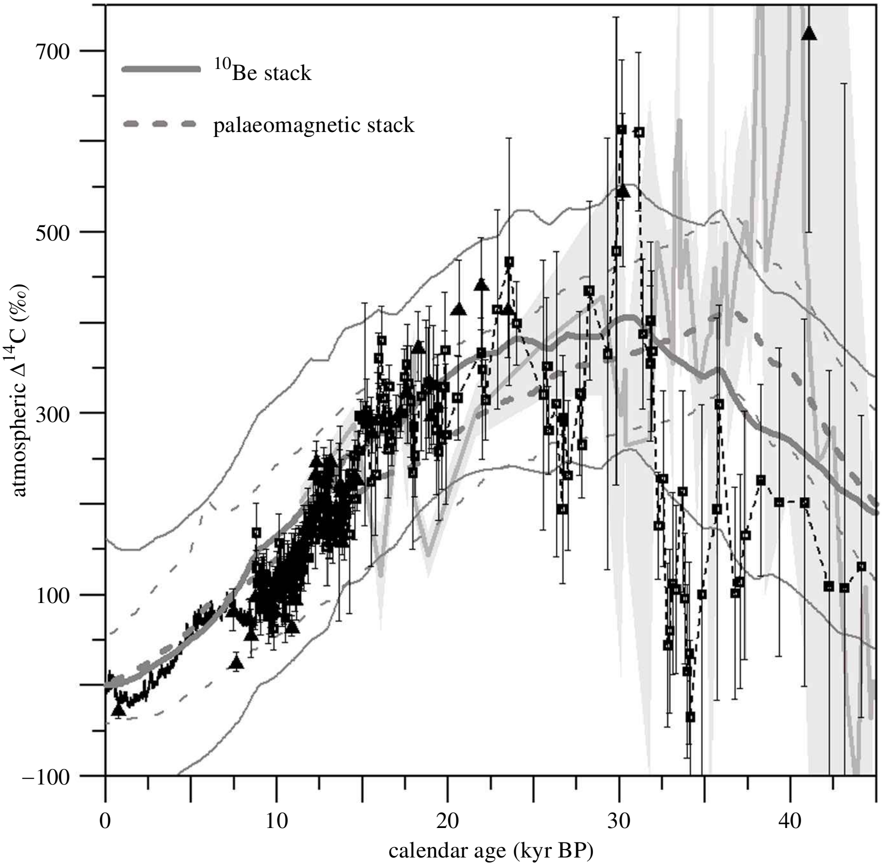

Figure 6. Atmospheric Δ^{14}C variations as shown in figure 2, again plotted with the 2σ errors, compared with the expected changes of atmospheric Δ^{14}C, which were calculated using the cosmogenic radionuclide production rates derived from the stacked ^{10}Be deposition rates (Frank *et al.* 1997) (solid grey line), and translated from the palaeomagnetic stack of Guyodo & Valet (1996) applying the relationship given by Lal (1988) (dashed grey line), as inputs into a carbon cycle box model (Bard 1998). The 2σ errors of these calculations are given as corresponding thin lines.

reconstructions (Frank *et al.* 1997; Bard 1998). The Δ^{14}C variations derived from the varved sedimentary record of Lake Suigetsu are in relatively good agreement with the stack-based reconstructions, except that there is a Δ^{14}C minimum between 35 and 32 kyr BP that is not reflected by the palaeointensity stacks (Kitagawa & van der Plicht 1998). This Δ^{14}C minimum might either not be resolvable in the stacked records or, alternatively, not be within the 2σ uncertainties of the predicted Δ^{14}C variations because some sections in the lower part of the varved sediment record might be missing. The record of Voelker *et al.* (1998), which is also mostly within the error of the stack-based reconstructions prior to 30 kyr BP, apparently supports this by indicating a continuous maximum of ^{14}C production between 32 and 42 kyr BP, which is also in better agreement with the other reconstructions above (Mazaud *et al.* 1991; Laj *et al.* 1996; Guyodo & Valet 1996; Frank *et al.* 1997; Bard 1998).

(*b*) *50–200 kyr BP*

For the period between 200 and 160 kyr BP, which includes the Biwa I event, there is also a remarkable correspondence between the two independent field intensity reconstructions based on the stacked palaeomagnetic record and the stacked ^{10}Be-deposition rates, although the number of cores included for this period is much smaller than for the last 50 kyr (figure 5*b*). While the increase of the δ^{18}O record at the transition from interglacial stage 7 to glacial stage 6 appears to correspond to the decrease in field intensity, the climate signal remains at high values for the following glacial stage, whereas the palaeointensities increase again and reach levels similar to those before the Biwa I event by 170–180 kyr BP. The apparent correspondence between the climate transition at *ca.* 190 kyr BP and the decrease in the field intensity records is, therefore, considered coincidental.

Despite the clear disagreement between the palaeointensity records and the δ^{18}O record for the periods covering the Laschamp and Biwa I events, there may still be some correspondence between the ^{10}Be stack-based palaeointensity record and δ^{18}O, in particular because of the apparent reflection of climatic substage 5e (130–111 kyr BP) and the transitions between stages 5 and 4 (74 kyr BP) and between stages 4 and 3 (59 kyr BP) in the palaeointensity record. For substage 5e, the apparent correspondence may be explained by the selection of the cores for the ^{10}Be stack, as discussed before. The other observed patterns may still suggest an insufficient normalization or averaging of the palaeointensity record derived from the ^{10}Be deposition rates for the period between 50 and 125 kyr BP. The records of the ^{36}Cl fluxes (Baumgartner *et al.* 1998) obtained from the GRIP ice core, however, which were established independently of the δ^{18}O record, show very similar features to the stacked palaeointensity records for the period between 50 and 96 kyr BP, although the timing appears not to be exactly in phase. Residual climatic signals in the stacked ^{10}Be record related to the climatic transitions derived from δ^{18}O must consequently be small.

In summary, there is no reason why all these independent datasets and parameters (stack of palaeomagnetic data, stack of ^{10}Be deposition rates, calibration of ^{14}C ages, and cosmogenic radionuclide fluxes in ice cores) should reflect climate forcing in the same way and to the same extent. Additionally, the features of the extended stacked 800 kyr palaeointensity record based on palaeomagnetic methods clearly shows no indication of systematic residual climatic influences or orbital forcing and, at the same time, fully documented all known excursions of the Earth's magnetic field within the Brunhes Chron (Guyodo & Valet 1999). In view of that, it is argued that the apparent correspondence between the ^{10}Be-based palaeointensity reconstruction and the δ^{18}O record is coincidental and may vanish with the inclusion of more records into the stack.

4. Conclusions

Reconstructions of cosmogenic radionuclide production rate derived from different records and sources provide independent and coherent evidence for variations of the intensity of the Earth's magnetic field over the last 200 kyr. A global stacked record of ^{10}Be deposition rates, which translates into a reconstruction of relative production rate variations and, further, into variations of the magnetic field intensity over time, strongly argues for the validity of palaeomagnetic reconstructions of relative field intensity from marine sediments. Independent support comes from reconstructions of the production rate of ^{14}C by calibrating ^{14}C ages in corals to precise U/Th ages, from calibration of ^{14}C ages to absolute ages obtained by tree ring chronology and by varve chronology in sediments from Lake Suigetsu in Japan, and from calibration of ^{14}C ages obtained from a sediment core in the Iceland Sea by correlation of its stable oxygen isotope data with the GISP2 oxygen isotope record. Patterns of ^{10}Be and ^{36}Cl fluxes in ice cores confirm the field intensity patterns derived from marine sediments. This adds up to four independent and coherent sources of palaeointensity reconstruction, and it is highly unlikely that they would all respond in the same way and with the same amplitude to climatic influences. Despite some indications from spectral analyses, there is no clear evidence for a significant orbital forcing of the palaeointensity signals. Neither the presence of significant residual climatic signals, which may originate from inadequate normalization and correction of the data for climatic influences, nor an influence of the Earth's orbital parameters on the intensity of its magnetic field can be deduced from all these records with confidence.

5. Outlook

It would be highly desirable to be able to reconstruct cosmogenic radionuclide production rates independent of palaeomagnetic methods beyond the presently reached ages, in particular across reversals. There are, however, restrictions for each isotope system for different reasons. ^{14}C cannot be reliably measured at ages higher than 50 kyr BP. The Vostok ice core record has recently been extended back until *ca.* 420 kyr BP (Petit *et al.* 1999), which offers potential for an extended reconstruction of ^{10}Be and ^{36}Cl production rates for this period.

The half-life of ^{10}Be (1.5 Myr) theoretically permits its application back to around 10 Myr ago, which would allow a study of the pattern of radionuclide production rates across magnetic reversals in marine sediments. Sedimentary records cannot, however, be reliably corrected for sediment redistribution using ^{230}Th beyond *ca.* 300 kyr BP, due to its much shorter half-life (75 kyr). A reconstruction based on the extraction of the authigenic ^{10}Be/^{9}Be signal might not give unambiguous results due to possible effects of climatically driven changes of ocean circulation and variations in water mass distribution patterns, which have characteristic ^{10}Be/^{9}Be ratios. An approach based on authigenic ^{10}Be/^{9}Be would thus also require stacking of a number of records from different regions, unless there was a tool available for a particular site that could confirm an unchanged deep-water mass composition.

A promising candidate for the correction of sediment redistribution without an age restriction is stable ^{3}He retained in interplanetary dust particles (IDPs), which are found in marine sediments. The idea is that the IDPs have rained down to the Earth's surface at a constant rate, which would allow their flux into sediments to be used in a similar way as ^{230}Th but without the restriction of radioactive decay. A comparison of the ^{3}He and ^{230}Th fluxes into Pacific sediments has shown that the IDP flux did not vary by more than 75%, which suggests that this approach should be pursued further (Marcantonio *et al.* 1996). However, even if this tool proves to be applicable with a reasonable uncertainty, a reliable reconstruction of the ^{10}Be production rate from ^{10}Be/^{3}He ratios across a geomagnetic reversal would still require stacking of a number of records from different ocean regions in order to account for climatically driven boundary scavenging variations.

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