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Nuclear Instruments and Methods in Physics Research B 172 (2000) 555–561
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.nl/locate/nimb

Geomagnetic modulation of the late Pleistocene cosmic-ray flux as determined by ^{10}Be from Blake Outer Ridge marine sediments

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Abstract

The cosmic-ray flux incident upon the Earth during the late Pleistocene, 20–60 kyr B.P., was studied by measuring the cosmogenic radionuclide ^{10}Be from a marine sediment core at site CH88-10P on the Blake Outer Ridge. The paleointensity of the geomagnetic field for this core was determined by various methods. The variance in the concentration of ^{10}Be in the authigenic fraction of the sediments from Blake Ridge closely correlates with the inverse of the variance in the paleointensity of the geomagnetic field. The ^{10}Be signal lags, up to 1000 years of sedimentation, the measured paleointensity of the sediments. In contrast, the data from several other elements, some climatically sensitive, and from beryllium show relationship neither to ^{10}Be nor to the paleomagnetic data. The relationship between ^{10}Be concentration and the dipole field intensity (M/M_o) as measured in the sediments is consistent with theoretical models.

1. Introduction

Evidence gathered over the last decade indicates that the production rate of cosmogenic radionuclides has varied substantially over the late Pleistocene. For example, calibration of the radiocarbon time scale against U/Th [1] for corals older than the Holocene has shown large discrepancies between the two methods indicating that the rate of production of ^{14}C has varied greatly during that period. The concentration of ^{10}Be in Antarctic ice at 35 and 60 ka is anomalously high relative to expectation resulting from changes in precipitation alone [2]. Elevated levels of ^{10}Be from the younger event were confirmed from marine sediments [3–5] and lake sediment [6]. These increases of ^{10}Be, and ^{36}Cl, in ice are attributed to decreases in the geomagnetic field [7], even though other work fails to show a strong relationship between the accumulation of cosmogenic radionuclides in polar ice and the dipole-field intensity out to 40,000 B.P. [8].

Furthermore, in recent years the intensity of the geomagnetic field of the late Pleistocene has been measured directly by the magnetization of marine

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0168-583X/00/$ - see front matter
PII: S0168-583X(00)00092-6

and lake sediments [9–17] and the individual measurements show wide variations of paleointensity. These paleointensity studies are broadly similar and show that from 35 to 45 ka the geomagnetic field may have decreased to as little as 10% of the present-day field. The Laschamp geomagnetic excursion as seen in several North Atlantic marine sediment cores occurs at about the same time [18].

Our work began by measuring ^{10}Be from a partly varved sediment core, Leg 64, DSDP 480. The site lies on a slope of the Guaymas basin in the Gulf of California at 660 m depth [3]. The work continued with sediments from a core from a ridge in the Sea of Japan, KH-79-3, C-3 (935 m). In this paper we present results from a marine sediment core from the Blake Outer Ridge, CH88-10P (3818 m), Fig. 1. The Blake Outer Ridge is composed of drift deposits, i.e., sediments transported along the continental slope by deep-sea currents and over millennia deposited on the ridge. This site has several advantages, some to be reviewed later, including a high sedimentation (25 cm/kyr) for abyssal depths. The geomagnetic-field paleointensity of the sediments was independently measured by Schwartz, Lund and Johnson [33] and our ^{10}Be measurements can be directly compared to their paleointensity measurements.

2. Procedure

Sediment samples that had been measured for paleomagnetism were provided by Martha Schwartz and Steven Lund at the University of Southern California. One to two grams of sediment were leached in a solution of 25% acetic acid and 0.04 hydroxylamine–HCl to separate the "authigenic" fraction of the sediment from the "terrigenous" fraction [20]. The authigenic fraction, thought to reflect more closely the composition of seawater, is mostly composed of

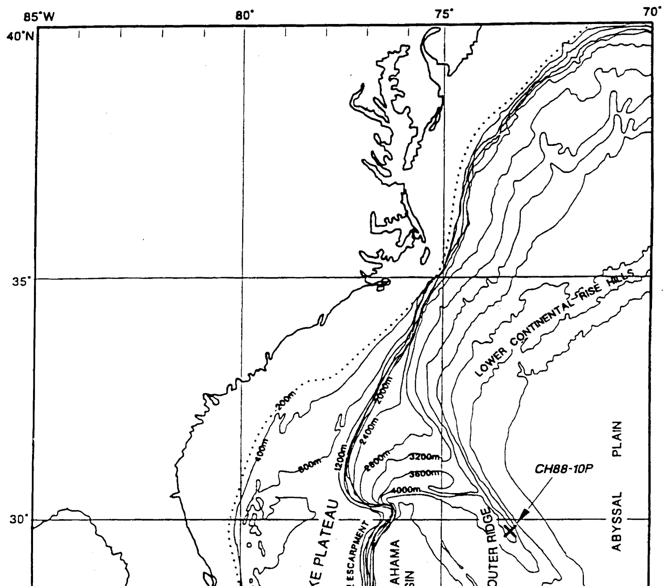

Fig. 1. Map of the Blake Outer Ridge and location of marine sediment core CH88-10P (3818 m).

exchangeable ions, carbonates and Fe–Mn hydryoxides. Two aliquots of the leachate are extracted and diluted by 5% HNO_3. Elements of interest were analyzed by ICPAES at the Soils, Water, and Engineering Department at the University of Arizona. The remaining leachate was further processed by solvent extraction, precipitation of $Be(OH)_2$, and combustion to produce BeO.

After separation of beryllium from the authigenic fraction of the sediments and combustion to BeO, ^{10}Be was measured on the Tandem Accelerator Mass Spectrometer at the University of Arizona. With a standard beryllium carrier the $^{10}Be/^{9}Be$ blank averages about 2×10^{-14}. Typically, the ratio for marine sediment is about 10^{-11}. If beryllium is analyzed in the +3 charge state, the error of measurement for the accelerator is about 1% for a NIST standard and 2–3% for sediment.

For this paper, the chronology of core CH88-10P was adopted from earlier work, predominantly that of Martha Schwartz and Steven Lund [19]. The chronology was based on radiocarbon and oxygen isotope measurements of core CH88-10P and correlations with other sediment cores on the Blake Ridge.

3. Results

Fig. 2(a) shows the ^{10}Be concentration of the authigenic fraction of the sediments for core CH88-01P analyzed thus far, from 450–1500 cm in depth. Also shown is the magnetic field intensity of the Earth normalized to present values (M/M_o). ^{10}Be normalized to ^{9}Be is shown in Fig. 2(b) and tracks ^{10}Be concentrations. Despite the lack of correlation between ^{10}Be and ^{9}Be, as will be shown later, the ratio still tracks ^{10}Be due to the lower variance of ^{9}Be. As can be seen in Fig. 2(a) there are three prominent increases of ^{10}Be concentration. The shallowest ^{10}Be maximum in the sediments, 42–41 ka, is contemporaneous with the ice and marine-sediment core chronologies [4,21,22] and possibly the Laschamp excursion in North Atlantic marine sediments [18]. The deepest anomaly, about 62–64 ka, may be contemporaneous with an increase in ^{10}Be concentrations in the Vostok ice core [2]. A smaller increase in ^{10}Be concentrations lies in between the other two at about 55–57 ka. The paleointensity of the geomagnetic field inversely correlates with the ^{10}Be maxima. For example, the approximate doubling of ^{10}Be concentrations at 41 ka is associated with a

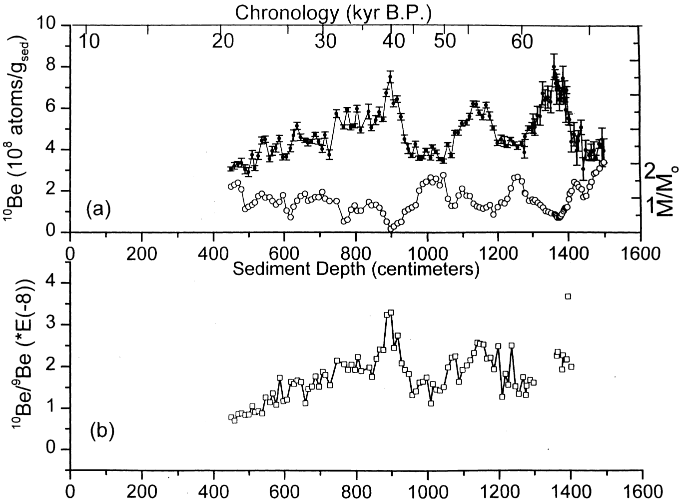

Fig. 2. (a) The ^{10}Be concentration and M/M_o as determined from measured NRM/ARM ([33], Fig. 8) of core CH88-10P versus depth and time. Error bars for ^{10}Be are one sigma. (b) The ratio of ^{10}Be to ^{9}Be. Some measurements of ^{9}Be below a depth of 1300 cm were unreliable.

decrease in the geomagnetic field from values stronger than the present day to about 10%.

With these data sets it is feasible to begin to evaluate the standard methods used to measure paleointensity. For example, a standard method is to normalize natural remanent magnetization (NRM), which is a function of both alignment and concentration of the magnetic particles in the sediments, to laboratory induced magnetizations: (a) saturation isothermal remanent magnetization (SIRM) that is acquired in a strong direct field; (b) anhysteretic remanent magnetization (ARM) acquired by subjecting sample in simultaneously alternating and direct magnetic fields; (c) and chi (χ) low-field susceptibility. A more direct comparison between the data sets than in Fig. 2(a) can be made by converting the data sets to variance about a linear regression for ^{10}Be and the inverse of the variance about a linear regression for the paleointensity data. In Fig. 3(a), the inverse variance of three paleointensity methods were plotted together with the variance in ^{10}Be concentration. In general, the inverse variance of paleointensity for the three methods track the ^{10}Be concentrations. In Fig. 3(b), only the inverse variance of NRM/ARM

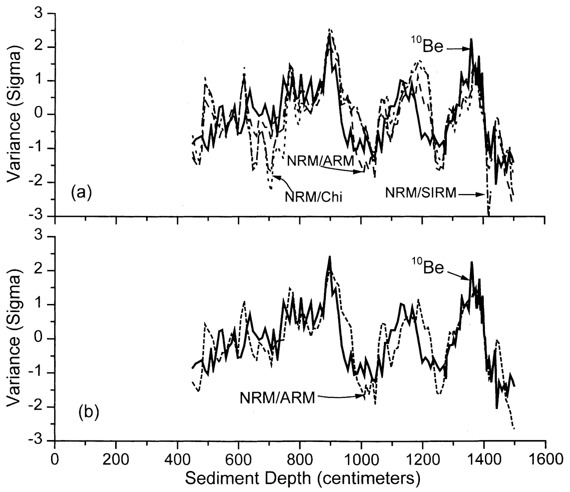

Fig. 3. (a) ^{10}Be (solid line), NRM/ARM (dashed line), NRM/χ (small dash), and NRM/SIRM (dash-dot) ([33], Fig. 5) in units of their variance about the mean of linear regressions through the data. (b) The variances of ^{10}Be (heavy solid line) and of NRM/ARM (dashed line) from linear regressions through their data sets.

was plotted because it best fits the variance of ^{10}Be data. The NRM data normalized to SIRM and χ were more variable than those normalized to ARM. At two depth intervals they indicate a stronger geomagnetic field than indicated either by NRM/ARM or by the ^{10}Be variances. As can be seen in Fig. 3(b) NRM/ARM covaries with the ^{10}Be data very well ($r > 0.8$) if allowance is made for the lag of the ^{10}Be signal after that of NRM/ARM. This lag can cover more than 1000 years of sedimentation but can be much less as seen at the deepest ^{10}Be maxima. Such a lag can be expected from the relative contributions of the delays due to the time of transport of ^{10}Be from the surface of the sea to bottom sediments, and due to the effects of bioturbation on magnetic particles and ^{10}Be within the deposited sediments.

Before we assume that the close correspondence between the ^{10}Be and NRM/ARM data sets was due to the effects from the modulation of the geomagnetic field on the cosmic-ray flux and consequently ^{10}Be production, we must take into account the effects of climate. Kok [23] suggested that the correlation between the stacked records of ^{10}Be cores to paleointensity measurements from several marine-sediment [21] may, in fact, only reflect similar responses of both to Pleistocene climate, because they both also correlate to δ ^{18}O which is known to be sensitive to climatic influences. In this study, this is, in part, answered by the analyses of elements from the authigenic fraction of the sediments (Fig. 4). Four elements with predominantly terrigenous origins: iron, aluminum, zinc and beryllium covary with one another, having low concentrations in oxygen-isotope stage 3, and concentrations which increase toward stages 2 and 4. The ^{10}Be data set is independent of these elements, including that of beryllium (correlation coefficient near 0). The fact that only ^{10}Be in the authigenic fraction of the sediments covaries with the paleointensity data set indicates very little terrigenous ^{10}Be is deposited on the Outer Blake Ridge. Furthermore, the ^{10}Be concentrations are independent of climatically sensitive calcium concentrations that are high in stage 3 (mostly $CaCO_3$ diluting the terrigenous contribution but apparently not ^{10}Be). The ^{10}Be concentrations are also independent of diagenetically sensitive magne-

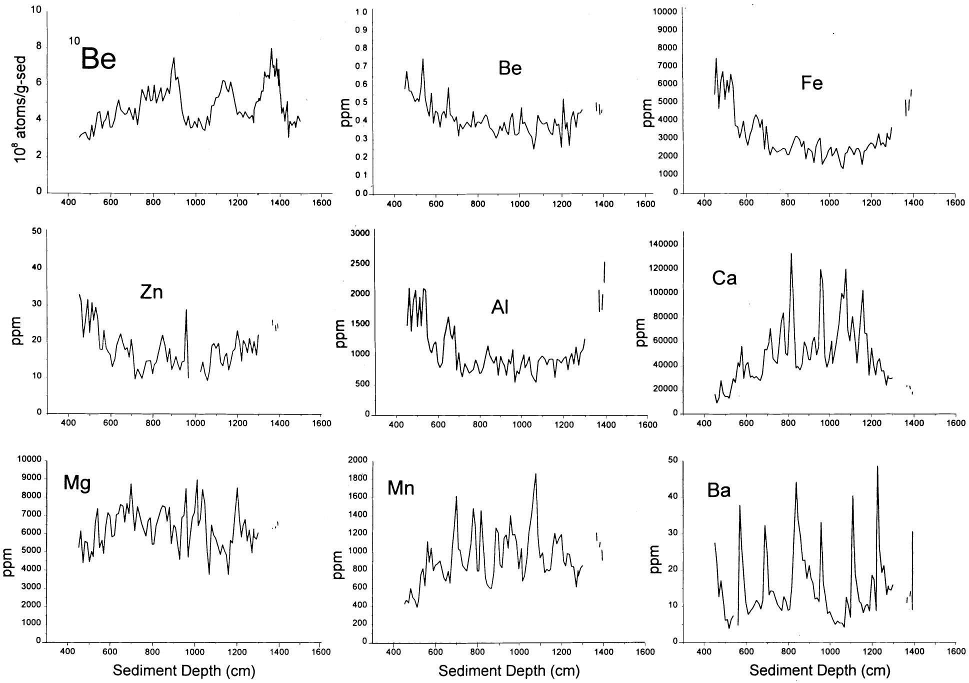

Fig. 4. Selected elements and ^{10}Be of the authigenic fraction of sediments: Be (beryllium), Fe (iron), Zn (zinc), Al (aluminum), Ca (calcium), Mg (magnesium), Mn (manganese), Ba (barium). Oxygen isotope stage boundaries 2/3 and 3/4 are at 540 and 1220 cm in core depth, respectively.

sium, and manganese which is sensitive to bottom and sediment water oxygen concentrations.

Of particular interest are the periodic variations in the concentration of barium in the sediments [24]. Barite forms within the shells of settling biogenic particles as the result of reducing conditions from decaying organic matter [25,26]. Barium in some deep-sea marine sediments varied in response to glacial and interglacial paleoproductivity of surface waters [27]. Moreover, ^{10}Be can correlate with barium because both are scavenged from shallow waters [28]. Barium and ^{10}Be do not correlate at the Blake Ridge. This would be inconsistent if both barium and ^{10}Be are transported together from shallow waters. An alternative explanation is that diagenesis concentrates barium in narrow zones within marine sediments [29,30]. However, there is no relationship between diagenetically sensitive manganese and barium at the Blake Ridge as might be expected [31]. A terrigenous source for barium has been ruled out because it does not correlate with aluminum and the Ba/Al ratio for the barium maxima is typical of a biogenic source. The most plausible explanation for the ^{10}Be and barium results is that the barium "spikes" are biogenic, formed in response to dramatic changes in paleoproductivity near the Blake, whereas ^{10}Be is scavenged from the deeper waters of the North Atlantic or directly deposited in the recycled drift deposits. A possible explanation for the periodicity of the barium maxima that alternate between 120 and 150 cm in depth, are that they form in response to precessional forcing of the North Atlantic circulation during that period of time.

A relationship between the intensity of the geomagnetic field and the production of ^{10}Be can be derived. The NRM/ARM data set converted to paleointensity M/M_o was provided by Schwartz and Lund ([33], Fig. 8). The ^{10}Be data were normalized by setting to unity the average of those ^{10}Be concentrations of the sediments when the magnetic field from the paleointensity data was equivalent to that of the present ($M/M_o = 1$) and for normal solar activity ($\Phi = 450$). The normalized ^{10}Be concentrations and the corresponding M/M_o for each sample were plotted in Fig. 5 along with a polynomial through the data. The large scatter between the data points is attributed to the lag in time between the two data sets as seen in Fig. 3(b). Typically the ^{10}Be data set lags that of NRM/ARM because of the effects listed above with the result that the sediment record often shows the geomagnetic field to be low when the ^{10}Be deposited in those sediments shows it to be high, and vice versa. To overcome this problem, shown in Fig. 3(b), a paleointensity data point was paired with a ^{10}Be data point that seemed to best correspond to it, i.e., a prominent high of ^{10}Be concentration with a prominent low in the geomagnetic field, or a prominent low with a prominent high, etc. These selected points are plotted with the corresponding polynomial that best fits them. In addition, theoretical values for ^{10}Be in the atmosphere are plotted with respect to paleointensity and solar modulation (Φ) as dashed lines in Fig. 5 (from Lal [32]). The production of ^{10}Be in the atmosphere is not only sensitive to the variations in the geomagnetic field but also to solar activity. For example, when solar activity is low ($\Phi = 100$) the primary cosmic-ray flux incident upon the Earth increases, and when it is high ($\Phi = 1000$) the primary cosmic-ray flux is low. The selected pairs of ^{10}Be and the paleointensity data lie within the helio-geomagnetic modulation envelope and are close to the average of the present day solar activity ($\Phi = 450$).

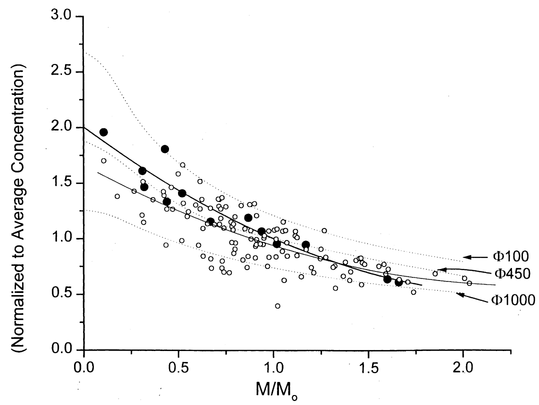

Fig. 5. The inferred production rate of ^{10}Be as a function of M/M_o (the geomagnetic dipole field normalized to the present field). The dashed lines are the theoretical production in the atmosphere as a function of low ($\Phi = 100$), average ($\Phi = 450$), and high solar modulation ($\Phi = 1000$) [32]. Also shown are the ^{10}Be concentrations (normalized to average concentration when $M/M_o = 1$) and NRM/ARM [33] for each sample. The open circles are the "production rate" and M/M_o for each sample. The large solid dots are matches between distinctive features of the ^{10}Be data and NRM/ARM as seen in Fig. 3(b). The solid curves are second order polynomials through the open circles (light) and the solid dots (heavy).

4. Conclusion

The Outer Blake Ridge offers an excellent site to study the effects of the geomagnetic field and the flux of cosmic rays incident upon the Earth on the production of ^{10}Be during the late Pleistocene. Unfortunately, it does not appear that short-term events (less than 100 years) which are of interest, such as solar activity or fluctuations in the primary galactic cosmic-ray flux, will be seen because of the residence time of several centuries for ^{10}Be in the deep sea. Nevertheless, this study shows that the geochemical methods of ^{10}Be measurement and the geophysical methods of geomagnetic-field paleointensity measurement can be directly correlated. This may have value in subsidiary studies such as the transport of ^{10}Be in the sea, the locking in of the paleomagnetic signal in sediments, or the relationship of the inferred global dipole field as evidenced by ^{10}Be to the local field as measured by paleointensity methods. In addition, theoretical models concerning topics like the long-term generation of the geomagnetic field or the primary cosmic-ray flux can be evaluated.

Acknowledgements

The authors would like to thank Martha Schwartz and Steven Lund for useful discussions concerning this work, and for providing the sediment samples. Funding was provided by NSF grant EAR 9730699, and the State of Arizona.

References

[1] E. Bard, B. Hamelin, R.G. Fairbanks, A. Zindler, Nature 345 (1990) 405.
[2] G.M. Raisbeck, F. Yiou, D. Bourles, C. Jouzel, Barkow, Nature 326 (1987) 273.
[3] L.R. McHargue, P.E. Damon, D.J. Donahue, Geophys. Res. Lett. 22 (1995) 659.
[4] C. Robinson, G.M. Raisbeck, F. Yiou, B. Lehman, C. Laj, Earth Planet. Sci. Lett. 136 (1995) 551.
[5] G.C. Castagnoli, A. Albrecht, J. Beer, G. Bonino, C. Shen, E. Callegari, G. Taricco, B. Dittrich-Hannen, P. Kubik, M. Suter, G.M. Zhu, Geophys. Res. Lett. 22 (1995) 707.
[6] A. Aldahan, G. Possnert, J. Peck, J. King, S. Colman, Geophys. Res. Lett. 26 (1999) 2885.
[7] S. Baumgartner, J. Beer, J. Masarik, G. Wagener, L. Meynadier, H.-A. Synal, Science 279 (1998) 1330.
[8] R.C. Finkel, K. Nishiizumi, J. Geophys. Res. 102 (1997) 26699.
[9] E. Tric, J.-P. Valet, P. Tucholka, M. Paerne, F. Laberyrie, F. Guichard, L. Tauxe, M. Fontugne, J. Geophys. Res. 97 (1992) 9337.
[10] L. Meynadier, J.-P. Valet, N.J. Shackleton, V.L. Hagee, Earth Planet. Sci. Lett. 114 (1992) 39.
[11] N. Thouveny, K.M. Creer, D. Williamson, Global Planet Change 7 (1993) 157.
[12] T. Yamazaki, N. Ioka, Earth Planet. Sci. Lett. 128 (1994) 527.
[13] J.S. Stoner, J.E.T. Channel, C. Hillaire-Marel, Earth Planet. Sci. Lett. 134 (1995) 237.
[14] R.J. Weeks, C. Laj, L. Endignoux, A. Mazaud, L. Labeyrie, A.P. Roberts, C. Kissel, Phys. Earth Planet. Inter. 87 (1995) 213.
[15] Y. Guyodo, J.-P. Valet, Earth Planet. Sci. Lett. 143 (1996) 23.
[16] B. Lehman, C. Laj, C. Kissel, A. Mazaud, M. Paterne, L. Labeyrie, Phys. Earth Planet. Inter. 93 (1996) 269.
[17] J.A. Peck, J.W. King, S.M. Colman, V.A. Kravchinsky, J. Geophys. Res. Solid Earth B 101 (5) (1996) 11365.
[18] C. Kissel, C. Laj, L. Labeyrie, T. Dokken, A. Voelker, D. Blamart, Earth Planet. Sci. Lett. 171 (1999) 489.
[19] M. Schwartz, S.P. Lund, T.C. Johnson, Geophys. Res. Lett. 23 (1996) 2693.
[20] D.L. Bourles, G.M. Raisbeck, F. Yiou, Geochim. Cosmochim. Acta 53 (1989) 443.
[21] M. Frank, B. Schwarz, S. Baumann, P.W. Kubik, M. Suter, A. Mangini, Earth Planet. Sci. Lett. 149 (1997) 121.
[22] F. Yiou, G.M. Raisbeck, S. Baumgartner, J. Beer, C. Hammer, S. Johnsen, J. Jouzel, P.W. Kubik, J. Lestringuez, M. Stievenard, M. Suter, P. Yiou, J. Geophys. Res. 102 (1997) 26783.
[23] Y. Kok, Earth Planet. Sci. Lett. 166 (1999) 105.
[24] L.R. McHargue, EOS Trans. 78 (1997) F383.
[25] F. Dehairs, R. Chesselet, J. Jedwab, Earth Planet. Sci. Lett. 49 (1980) 528.
[26] J.K.B. Bishop, Nature 332 (1988) 341.
[27] D.W. Lea, E.A. Boyle, Nature 347 (1990) 269.
[28] M. Frank, J.-D. Eckhardt, A. Eisenhauer, P.W. Kubik, B. Dittrich-Hannen, M. Segl, A. Mangini, Paleoceanography 9 (1994) 559.
[29] G.J. de Lange, G. Catalano, G.P. Klinkhammer, G.W. Luther, Mar. Chem. 31 (1990) 205.
[30] M.T. Breymann, K.-C. Emeis, A. Camerlenghi, Proc. ODP Sci. Res. 112 (1990) 491.
[31] B.J.H. van Os, J.J. Middleburg, G.J. de Lange, Mar. Geol. 100 (1991) 125.
[32] D. Lal, Soc. Italiana di Fisica-Bologna-Italy, XVC corso (1988) 216.
[33] M. Schwartz, S.P. Lund, T.C. Johnson, J. Geophys. Res. B 103 (12) (1998) 30,407.