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# A HIGH RESOLUTION AUTHIGENIC $^{10}\text{Be}/^9\text{Be}$ RECORD OF GEOMAGNETIC MOMENT VARIATIONS OVER THE LAST 300 KA FROM SEDIMENTARY CORES OF THE PORTUGUESE MARGIN.

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## **Abstract**

A high resolution study of authigenic Be isotopes ( $^{10}\text{Be}$  and  $^9\text{Be}$ ) combined with continuous relative paleointensity records has been performed along the same marine sedimentary sequences from the Portuguese margin (N.E. Atlantic) covering the past 300 ka in order to assess relationships between geomagnetic moment variations and  $^{10}\text{Be}$  production rate variations. A careful examination of the various ways of taking into account environmental disturbing effects on the authigenic  $^{10}\text{Be}$  concentration leads to the conclusion that the most reliable proxy of cosmonuclide production rates is presently the authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio. Eight intervals of significant authigenic  $^{10}\text{Be}/^9\text{Be}$  enhancement evidence geomagnetic moment drops related to global paleomagnetic excursions, some being already admitted, others being proposed as new geomagnetic features. Since, contrarily to sedimentary magnetic remanence, the authigenic  $^{10}\text{Be}/^9\text{Be}$  records dipole moment variations without significant acquisition delay, it provides better constraints on their timing. Comparison of  $^{10}\text{Be}/^9\text{Be}$  and benthic  $\delta^{18}\text{O}$  records from the same cores suggests that dipole moment lows preferentially occurred during or at the end of interglacial episodes, with a quasi-period of 100 ka.

*Keywords* : authigenic Be isotopes, cosmonuclides, geomagnetic dipole lows, geomagnetic excursions.

## 1. Introduction

Production of cosmogenic nuclides that varies with space (altitude and latitude), also varies with time. Composed primarily of high energy protons and  $\alpha$ -particles, the cosmic-ray flux entering the magnetosphere is deflected by Lorentz forces. Cosmogenic production rate is thus proportional to the galactic cosmic ray flux and inversely proportional to the solar activity and the Earth's magnetic field intensity [1-4]. Measurements of cosmogenic radionuclides with different half-lives in lunar samples and in meteorites having different irradiation histories [5], and in marine sediments [6] and manganese crusts [7] yield to the conclusion that the average galactic cosmic ray flux was fairly constant on time-scales of millions of years. Solar activity varies on annual to centennial time-scales around a mean that remained roughly constant over the observed long-term (from thousands to millions of years) variations in cosmogenic production rate. Therefore, such long-term variations are most likely controlled by variations of the magnetic cutoff rigidity, directly related to the intensity of the magnetic field [8].

Since production rates of cosmogenic nuclides play a key role in their geophysical applications, mainly dating and tracing of environmental processes, the knowledge of past variations in cosmogenic nuclide production rates is a subject of considerable importance. Previous studies of the coincidence between low geomagnetic field intensity and high cosmogenic nuclide production rates were restricted to few geomagnetic events [9-12]. We present here, after the introducing paleomagnetic study [13], high resolution authigenic  $^{10}\text{Be}/^9\text{Be}$  and continuous relative paleointensity records along the same marine sedimentary sequences from the Portuguese margin (N.E. Atlantic). Covering the past 300 ka, this work allows to assess relationships between geomagnetic moment and  $^{10}\text{Be}$  production rate variations.

## 2. Description of sedimentary sequences and methodology

### 2.1. Sampling context

Authigenic  $^{10}\text{Be}$  and  $^9\text{Be}$  concentrations have been measured along three sedimentary sequences collected on the Portuguese Margin by the french vessel R. V. Marion Dufresne (Institut Français pour la Recherche et la Technologie Polaires) during IMAGES cruises using the Calypso piston corer: MD95-2042 (37°48N., 10°10W., 3146 m water depth); MD95-2040 (40°35N., 9°52W., 2465 m water depth) and MD01-2440G, a duplicate of core MD95-2042.

The top of cores MD95-2040 and -2042 are affected by coring deformation leading to unreliable paleomagnetic records [13]. Our sampling therefore only concerned the intervals

yielding reliable paleomagnetic data: 12-30 m of MD95-2040 and 9.5-28.5 m of MD95-2042. Few complementary samples were collected from the undisturbed core MD01-2440G, in order to document the youngest part of the record. Subsampling of ~0.5 g every 50 cm was reduced to every 10 cm at and close to the intervals of low relative paleointensity assignable to geomagnetic excursions.

## *2.2. Sediment description*

The sampling area is under the influence of continental contributions arising mainly from both the Tagus and Douro rivers that flow over 800 km in the Sierra Albaraçin and over 600 km in the Sierra de la Virgen, respectively. These rivers drain sedimentary, plutonic and metamorphic formations. Deep currents and Mediterranean Outflow Waters (MOW) also contributed to the sedimentation.

The sediments mainly consist of mid-gray clayey-mud deposited during cold periods, with intercalation of beige carbonate ooze deposited during temperate periods. The clayey fraction (40 to 70%) and the “sortable silt” fraction vary in phase opposition; the later being more concentrated in carbonate layers, due to bottom current transport [14]. Carbonate contents range from 10 to 65% and from 14 to 40% in MD95-2040 [15] and in MD95-2042 [16], respectively. With a mean grain size of 7-8  $\mu\text{m}$ , the sediment matrix contains two independent coarse fractions (63 $\mu\text{m}$  – 1mm) : the carbonate biogenic fraction, and the lithogenic fraction composed of detrital carbonates, quartz, feldspars and magnetite grains, identified as ice rafted detritus linked to Heinrich events [17]. Like in most marine sediments, pyrite patches and concretions are frequent along the core.

## *2.3. Chronostratigraphy*

Chronostratigraphic data are presented in details in Thouveny et al. [13] and Moreno et al. [18]. They are based on radiocarbon data and correlation of marine isotope stages (MIS) identified in the benthic  $\delta^{18}\text{O}$  curves of cores MD95-2042 [19] and MD95-2039 [15] with the SPECMAP record [20]. Depth to time transform functions were constructed for each core using high degree polynomial best fit functions over contiguous windows, and used to transfer our data records on a time scale (Figure 1).

The studied cores cover the last climatic cycle in core MD95-2042, and the last three climatic cycles (i.e. since MIS9) in core MD95-2040. The time interval covered by our sampling thus ranges from 0 to 300 ka BP and concerns the succession of 3 glacial-interglacial cycles.

## 2.4. Chemical procedures

$^{10}\text{Be}$  concentrations measured in marine sediments depend on  $^{10}\text{Be}$  production rates as well as on environmental parameters (chemical and granulometric composition) [21-24]. We thus extracted the authigenic (i.e. adsorbed onto particles from the water column)  $^{10}\text{Be}/^9\text{Be}$  from the studied sediments, since only the soluble form of both beryllium isotopes have been homogenized in the water column before deposition in the sediment [21, 23].

Authigenic beryllium was extracted using a 0.04M  $\text{NH}_2\text{OH.HCl}$  in 25% acetic acid leaching solution at  $95^\circ\text{C} \pm 5$  during 7 hours from  $\sim 0.5$  g samples previously crushed and oven-dried. The method is similar to that fully described by Bourlès et al. [21]. An aliquot of each sample solution was taken for furnace atomic absorption determination of  $^9\text{Be}$  using the method of standard additions and a Zeeman effect background correction (Hitachi Z-8200). Uncertainties in  $^9\text{Be}$  concentrations are based on the reproducibility of measurements when more than one has been made, or estimated from the fit of the standard addition lines in the case of a single measurement. The remainder of the sample was spiked for isotope dilution with 0.3 mg of  $^9\text{Be}$  and then purified for  $^{10}\text{Be}$  measurements by a series (usually two) of solvent extractions of Be acetylacetonate in the presence of EDTA, followed by precipitation of  $\text{Be}(\text{OH})_2$  at pH 8.5. The beryllium precipitate, rinsed twice with deionized water, was finally dissolved in a few drops of  $\text{HNO}_3$ . This small amount of solution being dried in a quartz crucible,  $\text{BeO}$  was at the end obtained by heating at  $1000^\circ\text{C}$ .

$^{10}\text{Be}/^9\text{Be}$  ratio measurements performed at the Tandetron AMS facility in Gif-sur-Yvette [25, 26] were calibrated directly against  $^{10}\text{Be}/^9\text{Be}$  of the National Institute of Standards and Technology (NIST) standard reference material SRM 4325. The  $^{10}\text{Be}$  uncertainties have been estimated using a conservative 5% instrumental uncertainty together with one standard deviation statistics of the number of  $^{10}\text{Be}$  events counted (less than  $\pm 3\%$ ).

## 3. Beryllium isotope results

### 3.1. Authigenic $^9\text{Be}$

The  $^9\text{Be}$  concentrations measured along MD95-2042 (Figure 2a), ranging from 3.1 to  $8.8 \cdot 10^{-7}$  g/g, are systematically higher than those measured along MD95-2040 that range from 1.4 to  $5.9 \cdot 10^{-7}$  g/g (Figure 3a). The lowest (resp. highest)  $^9\text{Be}$  concentrations measured in these two cores

yield a ratio of ~2.1 (resp. ~1.5), that may most likely be entirely attributed to the difference in sedimentation rates between these two cores, since the sedimentation rate of MD95-2042 (~13 cm/kyr) is 1.7-1.9 times higher than that of MD95-2040 (~7.5 cm/ka). Linked to the continental origin of  $^9\text{Be}$ , its higher concentrations occur in intervals of higher continental input, i.e. higher sedimentation rate. This direct linkage is confirmed by the observed increases in  $^9\text{Be}$  concentration (Figure 2a and 3a) generally coinciding with high values of magnetic susceptibility.

### 3.2. Authigenic $^{10}\text{Be}$

The  $^{10}\text{Be}$  concentrations measured along MD95-2042 and MD95-2040 are by contrast bounded within similar range, that is between 5.1 to 10.8  $10^{-15}$  g/g (mean value : ~7.3  $10^{-15}$  g/g) in MD95-2042 (Figure 2b) and between 3.5 and 11.1  $10^{-15}$  g/g (mean value : ~7.35  $10^{-15}$  g/g) in MD95-2040 (Figure 3b).

Compared to the mean values, both  $^{10}\text{Be}$  records show significant increases (above mean value  $+1\sigma$ ) of the  $^{10}\text{Be}$  concentration at the following depth intervals : 1325-1475 cm, 1800-1850 cm, 2000-2105 cm, 2245-2450 cm, 2480-2500 cm, 2590-2605 cm in MD95-2042, and 1340-1513 cm, 2094-2148 cm in MD95-2040. Compared to the base levels defined by the lowest  $^{10}\text{Be}$  concentrations ( ~5  $10^{-15}$  g/g for MD 95-2042 and ~4  $10^{-15}$  g/g for MD95-2040), sharp increases of the  $^{10}\text{Be}$  concentration appear at the following depth intervals : 1750-1950 cm, 2560-2645 cm in MD95-2042, and 2244-2305 cm, 2375-2450 cm, 2502-2600 cm and 2800-3006 cm in MD95-2040.

As stated in section 2.4, in order to interpret the previously discussed  $^{10}\text{Be}$  concentration variations in terms of production rate variations, the environmental disturbing effects have to be taken in account by i) normalizing the authigenic  $^{10}\text{Be}$  concentrations to the authigenic  $^9\text{Be}$  concentrations and ii) computing  $^{10}\text{Be}$  fluxes that are not affected by  $^9\text{Be}$  input variations mainly controlled by the eolian flux to the ocean [27, 28].

### 3.3. Authigenic $^{10}\text{Be}/^9\text{Be}$ ratio

Since authigenic  $^{10}\text{Be}$  concentrations measured along the two cores are within the same range while authigenic  $^9\text{Be}$  concentrations along MD95-2042 are ~1.8 higher than along MD95-2040, the authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios measured along MD95-2042 (0.7 to 2.4  $10^{-8}$ ) (Figure 2c), are roughly a factor of two lower than those measured along MD95-2040 (1.17 to 5.2  $10^{-8}$ ) (Figure 3c).

Along MD95-2042, increases of at least a factor of two relative to the authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio base line (1.1  $10^{-8}$ ) are evidenced at the following depth intervals : 1405-1425 cm (Interval I),

2265-2330 cm (Interval II) and 2420-2440 cm and 2490-2530 cm (Interval III). In addition, minor but significant increases are observed at the following depths : 1850 cm, 2105 cm and 2210 cm.

Along MD95-2040, numerous major significant increases corresponding at least to a doubling of the authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio base line ( $\sim 1.5 \cdot 10^{-8}$ ) are also clearly evidenced. Because, based on susceptibility records, the top of core MD95-2040 overlaps with the bottom of core MD95-2042, depth intervals from 1372 to 1414 cm and from 1473 to 1513 cm in MD95-2040 correspond to previously noticed intervals II and III. Additional major increases appear at depth intervals from 2094 to 2118 cm (interval IV) and from 2216 to 2244 cm (interval V). Less constrained but major significant increases are recorded from 2375 to 2424 cm (interval VI), and at  $\sim 2550$  cm (interval VII). Finally, the last major increase is observed between 2891 and 2931 cm (interval VIII). Like in core MD95-2042, minor but significant increases are also observed at 1255-1274 cm and 1996-2024 cm.

### 3.4. $^{10}\text{Be}$ flux

Another way of reconstructing  $^{10}\text{Be}$  production rate variations is to compute  $^{10}\text{Be}$  flux variations along the sedimentary cores.  $^{10}\text{Be}$  concentrations in marine sediments being inversely proportional to the carbonate content [21, 29, 30],  $^{10}\text{Be}$  flux values were calculated using the following equation:  $^{10}\text{Be}$  flux =  $^{10}\text{Be}$  concentration \* bulk density \* sedimentation rate \* (100/100-CaCO<sub>3</sub>%). As shown in Figures 2c, d and 3c, d, the  $^{10}\text{Be}$  flux significantly increases coincidentally with authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios. This confirms that the normalization of authigenic  $^{10}\text{Be}$  to authigenic  $^9\text{Be}$  takes into account -as expected- all biases that may result from differences in sources and pathways of both isotopes, and therefore implies that the observed increases should not result from environmental effects. However, given uncertainties about density and sedimentation rates estimation, flux determinations are less accurate than authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios.

Since a recently published study [29] of the influence of particle composition on sorption of  $^{230}\text{Th}$  and  $^{10}\text{Be}$  from sea water shows that the  $^{10}\text{Be}/^{230}\text{Th}$  ratio depends on the silica/ carbonate ratio, the authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio presently remains the only reliable proxy for reconstructing cosmonuclide production rates.

### 3.5. Relation with $\delta^{18}\text{O}$ variations ?

Authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios generally present significant increases at levels corresponding to interglacial conditions, as documented by  $\delta^{18}\text{O}$  records measured on the same cores [15, 19] (Figures 2e and 3e). Such a correlation was previously reported [30-32] and attributed to a

dependence of  $^{10}\text{Be}$  fluxes to glacial /interglacial alternation. However, close examination of Figures 2 and 3 reveals that : i) interval IV and VII, fall at the transition between interglacial MIS7 and glacial MIS6 and within glacial MIS 8, respectively ; ii) as evidenced by intervals I, II and VIII, falling in MIS 3, MIS 5.3, and MIS 8.2, respectively, the amplitudes of authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio variations are not comparable with the amplitudes of  $\delta^{18}\text{O}$  signals. These observations lead to the conclusion that climatic variability is probably not the main forcing parameter.

#### 4. Relations with relative paleointensity variations

As previously stated, variations of the authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio thus most likely reflect variations of the cosmonuclide production rate induced by variations of the geomagnetic moment. In this section, we recall major observations and conclusions drawn from the paleomagnetic study, and introduce the comparison with the beryllium isotopes record.

In the paleomagnetic stack [13], large amplitude deviations of the inclination occur during periods of low relative paleointensity (RPI) : some are excursions, while the others remain within the limits of paleosecular variation and may represent excursions smoothed out by post-depositional processes.

Significant phases of low RPI, defined in Figure 4 by values significantly lower than the average value minus  $1\sigma$ , are observed at successive depths in the two studied cores (Figures 4b and 4d). These are related to the authigenic  $^{10}\text{Be}/^9\text{Be}$  significant increases as indicated in the following table.

Low RPI Interval	Depth (cm) (in corresponding core)	Corresponding high authigenic $^{10}\text{Be}/^9\text{Be}$ interval
A	1415 – 1530 (MD95-2042)	I
B (B1 and B2)	2284 - 2613 (MD95-2042) 1391 – 1522 (MD95-2040)	II and III
C	2100 – 2169	IV
D	2230 - 2296	V
E	2384 - 2408	VI
F	2539 – 2558	VII
G	2867 – 2982	VIII

A careful analysis of the relative depth position of RPI lows and authigenic  $^{10}\text{Be}/^9\text{Be}$  peaks (Figure 4) reveals either that they occur at the same depth, or that RPI minima are significantly shifted downwards relatively to authigenic  $^{10}\text{Be}/^9\text{Be}$  maxima. Namely, the mid-point of the

minimum RPI of interval A leads by ~30 cm the authigenic  $^{10}\text{Be}/^9\text{Be}$  maximum of interval I ; the mid-point of interval B1 leads the mid-point of interval II by ~16 cm in core MD95-2042 ; the mid-point of interval B2 leads by ~26 cm the mid-point of interval III in core MD95-2040. The minimum RPI of interval C leads by ~24 cm the authigenic  $^{10}\text{Be}/^9\text{Be}$  maximum of interval IV.

Given the sedimentation rates of these sequences, beryllium isotopes residence time in the water column in continental margin environments on the order of 200 to 300 years [33] may induce maximum shifts of 6 cm for interval A in core MD95-2042 and 2 cm for other intervals. Therefore, lags on the order of 14 to 24 cm remain to be explained by other effects.

Former studies suggested that post-depositional processes not only impose a smoothing of the geomagnetic input signal [34 - 36] but also lead to a delayed lock-in of the magnetization beneath a critical thickness which depends on grain size distribution, clay concentration, organic matter concentration and bioturbation. More recent studies [e.g. 37] tend to consider that such effects are negligible in quiet and undisturbed sedimentation environments. However, the lags evidenced by our results confirm that lock-in depth are not negligible, and agree with lock-in depth of ~25 cm revealed in a core of the Blake Outer Ridge [38].

## 5. Discussion

Measurements of the relative paleointensity and authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios along the same cores offer the unique opportunity to construct stacked records of both measured parameters. This allows to directly compare the proxy record of the cosmonuclide production rates to the proxy record of the geomagnetic forcing. The composite record of authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio has been reconstructed using all data measured along MD95-2042 and MD95-2040; 8 values from another short core MD01-2440G complete the record in its upper part (electronic annex Figure). In order to account for sedimentation rate differences between MD95-2042 and MD95-2040, authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio were readjusted by dividing the MD95-2040 data serie by a constant factor 1.8 (cf section 3.1.). Then, wheighted averages have been computed within 1ka time windows.

Using these reconstructions we first discuss the relationship between the two proxies. As shown in Figure 5, the averaged  $^{10}\text{Be}/^9\text{Be}$  ratios plotted against averaged paleointensity values yields a simple exponential best-fit relationship, analogous to the Elsasser algorithm [2]:

$$P/P_0 = \sqrt{(M_0/M)}.$$

When compared to the global stack formerly established for the interval 0-200 ka BP by Frank et al. [39] (Figure 6), both records show similar trends. However, our authigenic  $^{10}\text{Be}/^9\text{Be}$  variations have significantly stronger amplitudes than the stacked  $^{10}\text{Be}$  deposition rates, equivalent

to a  $^{10}\text{Be}$  flux, presented in [39] as the  $^{10}\text{Be}$  production rate. Namely, the equivalent of Interval I has a restricted amplitude (~60%), between 30 and 42 ka BP, instead of a more significant spike (~100%) centered at 41 ka BP in our record. Equivalent of Interval II and III appears as a unique massive phase of relatively enhanced  $^{10}\text{Be}$  flux (~30%) between 85 and 110 ka BP instead of two separate phases of enhancement (~140% and ~120%) lasting from 90 to 105 ka BP and from 112 to 120 ka BP, respectively. The equivalent of Interval IV is expressed by a ~70% increase of  $^{10}\text{Be}$  flux, instead of a ~130% increase in our record, centered at 185 ka BP in both cases.

A major difference between the two records is the occurrence of a ~40% increase located between 60 and 75 ka BP in the global stack expressed in our record by a non-significant peak at 75 ka BP.

These discrepancies likely result from the fact that the global curve was constructed by stacking mostly data sets from central areas of oceanic basins, i.e. relatively low sedimentation rate areas, while our records result from a high resolution sampling focused on depth intervals recording low RPI features, in high sedimentation rate sequences.

A record of the relative virtual dipole moment (VDM) has been derived from the cosmonuclide record using the algorithm of Elsasser et al. [2] with a  $P_0$  value = 1. As introduced in section 4 and evidenced by the comparison of Figures 7a, b and c, the authigenic  $^{10}\text{Be}/^9\text{Be}$  oscillations are translated in terms of relative VDM variations tightly connected to relative paleointensity variations.

The interval 0-25 ka BP, documented in core MD01-2440G, exhibits high relative VDM values for the Holocene period, reaching a maximum at 20 ka BP in coincidence with high RPI values (17-22 ka BP). Although the relative VDM trend for this time interval reasonably agrees with the RPI records, one single relative VDM at 20 ka BP reaches a value contrasting with absolute values obtained from volcanic rocks (e.g. Teanby et al. [40]).

Beyond 20 ka BP, the evolution of relative VDM is coherent with trends revealed by RPI sedimentary records (Figures 7c and d) and with available volcanic VDM data [42]. Low VDM phases derived from the authigenic  $^{10}\text{Be}/^9\text{Be}$  record (Figures 7a, b) are confronted with those reported from the RPI record (Figures 7c, d) and with paleomagnetic excursions documented in the studied time interval [13].

The minimum VDM at 41 ka BP of interval I well corresponds to interval A identified as the Laschamps excursion recorded in lavas flows from France [43] and Iceland [44], as well as in lacustrine [45] and marine sediments [46].

Intervals II (90-105 ka BP) and III (110-120 ka BP) confirm the long period of low RPI with two minima centered at ~95 ka (B1) and ~117 ka BP (B2) also documented in the Sint-record. While interval B2 can easily be ascribed to the well-known Blake event, interval B1 may be related to an excursionsal feature previously described as a post-Blake excursion [36]. The Blake event, first reported in sediments [47, 48], was described in details by Tric et al. [49] as a full reversal, but also as two successive anomalous inclination features in the soil of the last interglacial of a loess sequence of the China plateau and accurately dated at 114 and 120 ka BP by thermoluminescence [50].

Interval IV centered at 190 ka BP coincides with the low RPI interval C (~190 ka BP), which is accompanied by an excursion ascribed to the “Icelandic basin event” at ODP sites 983 and 984 [51] and particularly well expressed in the Sint-record.

Intervals V (205-208 ka BP), VI (~230 ka BP) and VII (250 ka BP), corresponding respectively to intervals D, E and F, can be ascribed to the Jamaica and/or Pringle falls [52, 53], the Mamaku excursion [54], and the Calabrian ridge excursion [53], respectively.

Interval VIII centered at 290 ka BP, corresponds to the low RPI phase of interval G (285-295 ka BP) which correlate to a low RPI phase of small amplitude lasting from 265 to 295 ka BP in the Sint-curve. The excursionsal directions linked to interval G were named “Portuguese margin excursion”, because, the Levantine excursion, formerly dated at ~290 ka BP, has been reassessed to an excursion occurring in older sediments in the reference location [53].

Although the extremely low RPI phases associated to excursions are well constrained along the Portuguese sequence, the VDM record derived from authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios, in contrast to the relative equilibrium of “oscillations” along the RPI stacks, appears to be dominated by long lasting phases of medium or low VDM (25-125 ka BP, 170-240 ka BP, 275-300 ka BP). This may be an artefact of the used simple algorithm while translating extreme authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios into VDM values, which emphasizes the need to perform a calibration based on the assignment of authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios to absolute VDM values along this time interval (Carcaillet et al. in prep.).

Spectral analyses of the 300 ka authigenic  $^{10}\text{Be}/^9\text{Be}$  composite record (Figure 7a) using the Maximum Entropy and Blackman-Tukey methods [Analyseries program of Paillard et al. [55]] (Figure 8) evidence one single significant periodicity at 100 ka that also dominates paleointensity and inclination variations [13]. Major authigenic  $^{10}\text{Be}/^9\text{Be}$  increases of the studied time serie are thus most likely essentially related to overproductions of cosmogenic  $^{10}\text{Be}$  induced by geomagnetic moment drops associated with excursions or events.

Due to the lack of lock-in delays in the authigenic  $^{10}\text{Be}/^9\text{Be}$  record, the apparent coincidence of most authigenic  $^{10}\text{Be}/^9\text{Be}$  increases with interglacial (section 3.5) can be critically examined. We note that for 7 out of 8 cases, the exception being interval VII, cosmonuclide overproductions occur during or at the end of interglacial periods, supporting the hypothesis of a preferential occurrence of geomagnetic excursions during interglacials [51] or during interglacial/glacial transitions.

## 6. Conclusions

The records along the same sedimentary sequences of relative virtual dipole moment variations, authigenic  $^{10}\text{Be}$  and  $^9\text{Be}$  concentrations allow to demonstrate that over the last 300 ka, the geomagnetic moment variations exert the main control on  $^{10}\text{Be}$  production variations. Phases of overproduction of  $^{10}\text{Be}$  confirm the global occurrence of well-recognized and well-dated phases of low geomagnetic moment associated to the Laschamps excursion, the Blake event and the Jamaica/Pringle Falls excursion. They strengthen the validity of the recently identified Icelandic basin and Calabrian Ridge 0 excursions, and distinguish the Mamaku excursion (~240 ka BP), formerly assigned to the Jamaica/Pringle falls excursion. Moreover, they confirm two new excursions evidenced by [13] : the Post-Blake excursion (~95 ka BP) and the Portuguese margin excursion (290 ka BP).

Because they are not affected by post-depositional lock-in depths of ~15-24 cm, the authigenic  $^{10}\text{Be}/^9\text{Be}$  results allow an accurate determination of ages of VDM minimas associated with excursions, which strongly suggest that most of them occurred during, or at the end of, interglacials or interstadials.

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Figure 1: Chronological reconstruction of the sequences. Ages listed in [13] are plotted along the depth of each core (a: MD95-2042; b: MD95-2039; c: MD95-2040): calibrated  $^{14}\text{C}$  ages (dots), Heinrich events 3 and 4 (H), and dated paleoclimatic markers (circles). Best-fit polynomial curves were computed in successive windows to obtain age/depth function used to transfer the data from each core depth scale to the time scale. The grey vertical band locate the transition between the anomalous (left) and normal (right) sedimentary fabrics.

Figure 2 : Core MD95-2042. (a)  $^9\text{Be}$  concentrations ( $10^{-7}$  g/g) ; errors express reproducibility or statistical error of the fit of the standard addition lines (see text). (b)  $^{10}\text{Be}$  concentrations ( $10^{-15}$  g/g) ; errors include counting statistics and instrumental uncertainty (see text). (c)  $^{10}\text{Be}/^9\text{Be}$  ( $10^{-8}$ ) ratios ; errors result from the propagation of the  $^9\text{Be}$  and  $^{10}\text{Be}$  concentration errors ; bold line corresponds to the mean value, thin line to mean value+ $1\sigma$ , grey bars underline  $^{10}\text{Be}/^9\text{Be}$  values higher than mean value+ $1\sigma$ . (d)  $^{10}\text{Be}$  carbonate-free flux ( $10^{10}$  at/cm<sup>2</sup>/ka). Note the flux scale change at 1900 cm. (e) Benthic  $\delta^{18}\text{O}$  (‰) [19].

Figure 3 : Core MD95-2040. (a)  $^9\text{Be}$  concentrations ( $10^{-7}$  g/g) ; errors express reproducibility or statistical error of the fit of the standard addition lines (see text). (b)  $^{10}\text{Be}$  concentrations ( $10^{-15}$  g/g) ; errors include counting statistics and instrumental uncertainty (see text). (c)  $^{10}\text{Be}/^9\text{Be}$  ( $10^{-8}$ ) ratios ; errors result from the propagation of the  $^9\text{Be}$  and  $^{10}\text{Be}$  concentration errors ; bold line corresponds to the mean value, thin line to mean value+ $1\sigma$ , grey bars underline  $^{10}\text{Be}/^9\text{Be}$  values higher than mean value+ $1\sigma$ . (d)  $^{10}\text{Be}$  carbonate-free flux ( $10^{10}$  at/cm<sup>2</sup>/ka). (e) Benthic  $\delta^{18}\text{O}$  (‰) [15].

Figure 4 : Comparison of authigenic  $^{10}\text{Be}/^9\text{Be}$  and relative paleointensity records. (a) MD95-2042  $^{10}\text{Be}/^9\text{Be}$  ratios ( $10^{-8}$ ). (b) MD95-2042 relative paleointensity, bold line corresponds the mean value, thin line to mean value- $1\sigma$ , grey bars underline relative paleointensities lower than mean- $1\sigma$ . (c) MD95-2040  $^{10}\text{Be}/^9\text{Be}$  ratios ( $10^{-8}$ ). (d) MD95-2040 relative paleointensities : open circles correspond to discrete specimens, open triangles to U-channels. Bold line is the mean value, thin line the mean values- $1\sigma$ , grey bars underline relative paleointensities values lower than mean- $1\sigma$ . Vertical lines connecting  $^{10}\text{Be}/^9\text{Be}$  peaks to relative paleointensity features point out several shifts due to lock-in depths of the remanence.

Figure 5 : Authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios as a function of relative paleointensities. The black curve represents the best exponential fit of the data. The grey curve represents the  $^{10}\text{Be}/^9\text{Be}$  values

derived from the Elsasser algorithm, with  $P_0$  equal to the  $^{10}\text{Be}/^9\text{Be}$  ratios average value and  $M_0$  equal to the relative paleointensities average value.

Figure 6 : Comparison of the authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio record from the Portuguese margin stack with the global  $^{10}\text{Be}/^{230}\text{Th}$  stack of Frank et al. [39].

Figure 7 : Comparison of the authigenic  $^{10}\text{Be}/^9\text{Be}$  stack and the dipole moments reconstructed from authigenic  $^{10}\text{Be}/^9\text{Be}$  with relative paleointensity and VDM curves. (a) Relative Authigenic  $^{10}\text{Be}/^9\text{Be}$  ratio stack ; (b)  $M/M_0$  reconstructed from authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios ; errors are propagated from  $^{10}\text{Be}/^9\text{Be}$  errors (see text) (c) Portuguese paleointensity stack [13]. New excursions are distinguished from well-known by bold italic characters (d). Sint-800 VDM stack [41]

Figure 8 : Spectral analysis of the authigenic  $^{10}\text{Be}/^9\text{Be}$  record using analysis series [56] (a) Maximum Entropy Method and (b) Blackman Tukey Method. Periods are expressed in ka.

## Electronic annex

Figure EA : Results from core MD01-2440G. (a)  $^9\text{Be}$  concentrations ( $10^{-7}$  g/g) ; errors express reproducibility or statistical error of the fit of the standard addition lines (see text). (b)  $^{10}\text{Be}$  concentrations ( $10^{-15}$  g/g) ; errors include counting statistics and instrumental uncertainty (see text). (c) Authigenic  $^{10}\text{Be}/^9\text{Be}$  ( $10^{-8}$ ) ratios.

Comment : While  $^9\text{Be}$  data of the 23-30 ka interval are comparable to those of the upper part of core MD95-2042, a doubling of the  $^9\text{Be}$  concentrations occurs at 20 ka BP with a maximum value at 17 ka BP. Similarly,  $^{10}\text{Be}$  concentrations are comparable to those obtained at the upper part of MD95-2042, but with a decreasing trend to minimum values at 20 and 17 ka BP. Therefore, authigenic  $^{10}\text{Be}/^9\text{Be}$  ratios of this latter interval are reaching anomalously low values. At least for the 17 ka BP data, this can be explained by the accidental sampling of a layer of Ice rafted debris linked to Heinrich event n°1 ; indeed it appears that this sample corresponds to a high susceptibility layer.