

TERRIGENOUS SUPPLY OF ^{10}Be AND DATING WITH ^{14}C AND ^{10}Be IN SEDIMENTS OF THE ANGOLA BASIN (SE ATLANTIC)

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^{10}Be concentrations were measured in 20 (hemi)pelagic core top samples with an age control partly based on AMS ^{14}C datings. The ^{10}Be concentrations do not show any dependence on the bulk mass accumulation rates (MAR), but there is a significant linear correlation between ^{10}Be accumulation rates and MAR. This correlation is best explained by terrigenous ^{10}Be supply modified by biologic scavenging and, of secondary importance, adsorption on particulate matter in the ocean surface water in the Zaire plume. The variable term of the linear regression function indicates a maximum ^{10}Be concentration for the terrigenous component of 5×10^9 at.g⁻¹, the constant suggests an oceanic ^{10}Be precipitation of $(100\text{--}530) \times 10^6$ at.cm⁻² ka⁻¹. A 500 ka long record of ^{10}Be concentrations is in agreement with the predicted values, but short-term variations in MAR obscure the expression of a long-term break in MAR about 350 ka ago.

1. Introduction

The radionuclide ^{10}Be is produced in the Earth's upper atmosphere through cosmic radiation. It was first observed in ocean sediments by Arnold [1] and Goel et al. [2] and in ocean water by Raisbeck et al. [3]. Based on its half-life of 1.52×10^6 years [4] ^{10}Be promises to be useful for dating purposes in the time interval of $(0.15\text{--}15) \times 10^6$ years. Downcore ^{10}Be concentrations, however, can be largely variable [5–10] so that measured data sets have to cover long time intervals to provide statistically reliable trends. The major potential causes for the downcore concentration variations are changes in the accumulation rates of diluting sediment, in the ^{10}Be accumulation rates and in the cosmogenic ^{10}Be production [11]. The cosmogenic ^{10}Be in the upper atmosphere must fall on the ocean surface, most of it may be scavenged by bioactivity or adsorbed on particulate matter and precipitated to the ocean floor. Another part precipitates on land [12], is taken up in soils [13,14] and after erosion may reach the marine environment [9].

We report here a study of the importance of terrigenous supply of ^{10}Be to the ocean floor. For this purpose, surface sediments from the Zaire deep-sea fan (east equatorial Atlantic) were investigated. From this area cores were obtained with large differences in mass accumulation rates. Additionally, downcore ^{10}Be concentrations were measured on samples from a well dated pelagic core.

2. Material and experimental methods

For the study of recent ^{10}Be accumulation rates 20 samples were taken from the tops of 19 cores with mass accumulation rates (MAR) ranging from 0.27 to over 29 g cm⁻² ka⁻¹ (fig. 1, table 1). We selected cores with rather constant MAR through time to avoid short-term fluctuations which may affect the ^{10}Be concentrations. Therefore, all samples were collected from hemipelagic and pelagic cores whereas turbidites were evaded. The sampled sediments are siliceous oozes with an inorganic component consisting mainly of terrigenous clay minerals smaller than 2 μm [15,16].

Carbon samples have been prepared by treatment of sediment material with 4% HCl to form at least 1 ml of CO₂ (STP). This CO₂ was converted into graphite by reduction with finely divided iron powder in the presence of excess hydrogen [17]. The mixture of iron and graphite (2:1) is pressed into a 2 mm diameter hole of an aluminium holder. Extraction of ^{10}Be from sediment material (0.5–1.0 g) was performed by complete dissolution with the use of HF and HClO₄ at 400 K. Firstly, the sediment was spiked with 1.00 g of a 1000 ppm ^9Be solution. After separation from other elements [18] the material is oxidized into BeO, mixed with silver powder (1:5), and finally pressed into a sample holder. The ^{14}C and ^{10}Be measurements have been performed in separate runs with the use of the Utrecht tandem accelerator [18].

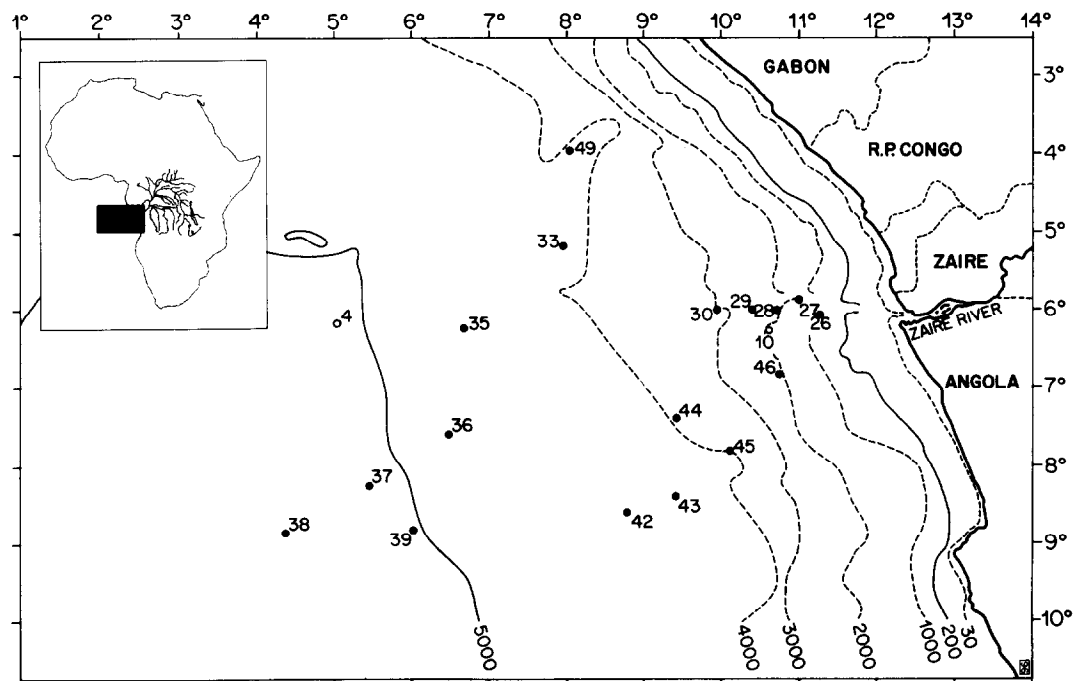


Fig. 1. Locations of the investigated piston cores. ● T78-26 etc., ○ T80-4 etc.

3. Absolute ages

Stratigraphy: The Quaternary (hemi)pelagic sediments show fluctuations in CaCO_3 concentrations which

are typical of the entire Atlantic Ocean: high concentrations during warm (interglacial) periods and low during cold (glacial) periods. The fluctuations, which are primarily controlled by variations in postdepositional car-

Table 1

Locations, corrected water depth, mass accumulation rates (MAR) for top intervals, and ^{10}Be concentrations for 20 cores from the Zaire deep-sea fan. Age control is based on carbonate stratigraphy (Ca), microfossils (M), oxygen isotopes (I), radiocarbon dating (C) and ^{230}Th -excess dating (T).

Core	Latitude	Longitude	Water depth (m)	MAR ($\text{g cm}^{-2} \text{ ka}^{-1}$)	Age control	Depth in core (cm)	^{10}Be (10^9 at. g^{-1})	Date no.
T78-26	6°05.0'S	11°16.6'E	605	22	Ca, M, C	10	0.61 ± 0.03	UBe-261
T78-27	5°52.5'S	10°59.9'E	1450	22	Ca	13	2.67 ± 0.15	UBe-340
T78-28	6°00.0'S	10°43.0'E	1940	17	Ca	13	2.01 ± 0.12	UBe-319
T78-29	5°59.0'S	10°24.8'E	2310	18	Ca, C	6	1.98 ± 0.10	UBe-320
T78-30	5°59.6'S	9°56.6'E	3040	> 29	C	17	0.82 ± 0.06	UBe-298
T78-33	5°11.0'S	7°58.0'E	4120	1.6	Ca, M, C	7	3.09 ± 0.09	UBe-321
T78-35	6°13.7'S	6°41.7'E	4560	1.0	C	10	1.41 ± 0.07	UBe-322
T78-36	7°35.2'S	6°29.5'E	4980	0.27	C	8	2.07 ± 0.19	UBe-341
T78-37	8°15.5'S	5°27.4'E	5060	0.7	Ca	11	4.71 ± 0.18	UBe-323
T78-38	8°51.2'S	4°23.7'E	5490	0.21	Ca, M, T	14	5.4 ± 0.2	UBe-342
T78-39	8°49.7'S	6°01.9'E	5070	2.0	Ca, C	16	3.36 ± 0.14	UBe-344
T78-42	8°36.4'S	8°47.8'E	4470	0.49	Ca, C	2	3.03 ± 0.10	UBe-345
T78-43	8°23.4'S	9°25.0'E	4300	0.7	Ca	24	3.66 ± 0.11	UBe-324
T78-44	7°24.2'S	9°25.8'E	3990	1.4	Ca	9	2.46 ± 0.08	UBe-299
T78-45	7°47.8'S	10°07.0'E	4070	1.4	Ca, M, C	3	2.66 ± 0.10	UBe-350
T78-46	6°50.1'S	10°45.3'E	2100	7.6	Ca, M, I, C	7	2.00 ± 0.14	UBe-325
T78-49	3°57.8'S	8°03.7'E	4340	1.9	Ca, M, C	13	3.14 ± 0.15	UBe-349
T80-4	6°08.4'S	5°01.9'E	5059	4.2	Ca, M, C	11	1.20 ± 0.06	UBe-351
T80-10	6°13.1'S	10°34.5'E	1988	7.4	Ca, M, C	31	2.57 ± 0.08	UBe-352

Table 2

AMS radiocarbon ages for piston cores from the Zaire fan. For locations see fig. 1 and table 1.

Core	Depth in core (cm)	^{14}C age	Date no.
T78-29	7	990 ± 100	UtC-444
T78-29	55	1760 ± 100	UtC-443
T78-30	17	9640 ± 180	UtC-459
T78-33	313	27300 ± 700	UtC-315
T78-33	316	30400^{+1100}_{-1000}	UtC-435
T78-35	56	10100 ± 200	UtC-460
T78-36	8	9800 ± 200	UtC-457
T78-39	40	5620 ± 170	UtC-458
T78-41	3	12060 ± 140	UtC-445
T78-45	313	27800 ± 800	UtC-316
T78-45	371	38000^{+3000}_{-2000}	UtC-317
T78-46	987	37000^{+4000}_{-2000}	UtC-434
T78-46	1068	37000^{+3000}_{-2000}	UtC-318
T78-49	253	26700^{+700}_{-600}	UtC-225
T78-49	369	> 45000	UtC-227
T80-4	159	10930 ± 120	UtC-321
T80-10	314	18000 ± 400	UtC-456
T80-10	454	25700 ± 700	UtC-455
T80-10	768	45000^{+11000}_{-5000}	UtC-320
T80-10	982	> 45000	UtC-319

bonate dissolution, can be used to develop a carbonate stratigraphy with carbonate stages defined conforming to the oxygen isotope stages of Emiliani [19] and Shackleton and Opdyke [20] [15,21]. The stratigraphy has been confirmed by investigations of microfossils [22–26], ^{14}C and ^{230}Th -excess dating [15] and stable isotopes [27]. For ages older than 40 000 years the SPECMAP time scale of Imbrie et al. [28] modified by Martinson et al. [29] was applied.

Dating with ^{14}C : The time resolution could be substantially improved by applying the Utrecht tandem accelerator for mass-spectrometric radiocarbon measurements to mg-size samples. Previously, because of the low carbonate concentrations of the sediments, sometimes large samples of 20 cm or more had to be collected or organic carbon had to be dated, which gives results not accurate enough for the purpose of this study [15]. Mass accumulation rates (MAR) for the measured core tops were calculated from the new ^{14}C measurements (table 2) and the ages mentioned above (table 1).

4. Accumulation of ^{10}Be

Terrigenous supply: The ^{10}Be concentrations of the surface samples (table 1) and the sediment MARs do not show an inverse linear relation (fig. 2) as is to be expected when oceanic precipitation is the only ^{10}Be

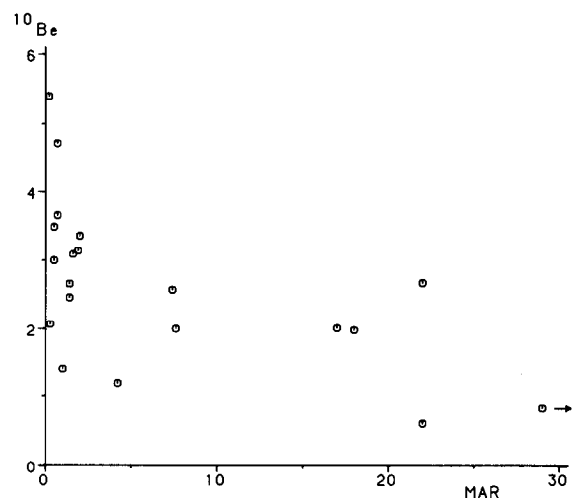


Fig. 2. Relation between mass accumulation rate MAR ($\text{g cm}^{-2} \text{ ka}^{-1}$) and ^{10}Be concentration (10^9 at.g^{-1}) for 20 surface samples from the Zaire deep-sea fan.

accumulating mechanism. Consequently, another ^{10}Be accumulating process must be acting. The ^{10}Be accumulation rates (BAR), however, show a strongly significant positive correlation with the MARs (fig. 3); the statistically best fit is linear. Three deviating values are attributed to strong variations in MAR (T78-26, T80-4) or to a large admixture with reworked sediments (T78-30). Therefore, these values are not included in the two regression functions displayed in fig. 3.

The positive correlation, proving that the BARs depend greatly on the MARs, point to terrigenous supply or biologic scavenging as ^{10}Be accumulating processes. At present, there is no tool available to discriminate between these two processes, but the linearity of the relation suggests that terrigenous clays are the major ^{10}Be supplying carrier. There is no reason to assume that oceanic productivity would be able to cause scavenging rates which are proportional to the mainly terrigenous MARs. A third potential accumulation process is adsorption on particulate matter in the Zaire river plume and subsequent deposition on the ocean floor. Although this will certainly occur, it would only give a minor contribution to the fan sediments because the majority of the particles derived from the river is transported into the Angola Basin through deep waters by turbidity currents or bottom nepheloid layers [15,30,31].

Other locations: A comparable positive correlation between BAR and sedimentation rate (expressed in cm ka^{-1}) is reported by Mangini et al. [8] for sediment cores from the central N Pacific (core GPC-3) and from high productivity areas off NW Africa (cores 12309 and 12310) and in the Circumpolar Convergence Zone in the SW Pacific (cores KN 7812-10 and KN 7812-12).

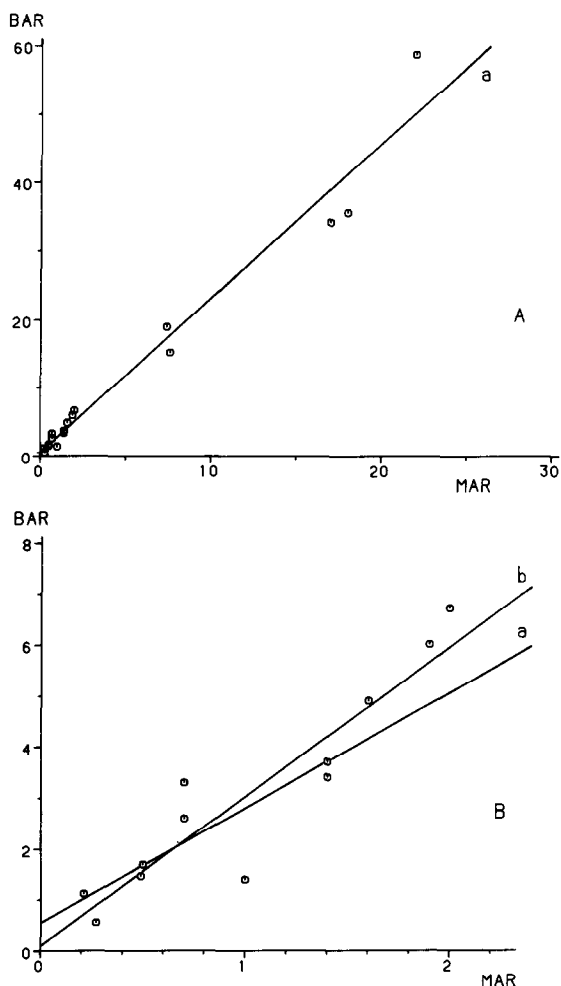


Fig. 3. Relation between mass accumulation rate MAR ($\text{g cm}^{-2} \text{ ka}^{-1}$) and ^{10}Be accumulation rate BAR ($10^9 \text{ at. g cm}^{-2} \text{ ka}^{-1}$) and least-square regression lines (a, b). A and a: for all samples except T78-26, T78-30 and T80-4; B and b: for the 12 samples with the lowest MAR and BAR.

a: $\text{BAR} = 0.53 + 2.26 \times \text{MAR}$, $r = 0.98$;

b: $\text{BAR} = 0.10 + 2.93 \times \text{MAR}$, $r = 0.93$.

Mangini et al. attributed the correlation to scavenging by bioproductivity, based on the observation that the ratios of the ^{10}Be to the ^{230}Th deposition fluxes are about 4 times as large as the ratios of the production fluxes. This was interpreted as an indication that ^{10}Be is scavenged more efficiently than ^{230}Th . Such enlarged deposition flux ratios were also reported for cores from DSDP site 580 (N Pacific) by Eisenhauer et al [10] who gave the same explanation.

In our opinion, however, the high rates essentially point to processes which preferentially accumulate either ^{10}Be or ^{230}Th or both, including different sources or transport processes. Moreover, for all above-mentioned cores the allochthonous sediment supply is important.

Table 3

^{10}Be concentrations for core T78-38 from the Zaire fan. For location see fig. 1 and table 1.

Depth in core (cm)	^{10}Be (10^9 at. g^{-1})	Date no.
14	5.4 ± 0.2	UBe-342
70	5.12 ± 0.19	UBe-343
180	4.84 ± 0.10	UBe-297
235	5.79 ± 0.13	UBe-318
291	1.66 ± 0.18	UBe-326
318	4.48 ± 0.18	UBe-262
433	4.01 ± 0.15	UBe-296
465	4.44 ± 0.13	UBe-317
500	4.5 ± 0.2	UBe-295
533	3.9 ± 0.14	UBe-316

In the core off NW Africa, situated well outside the upwelling region [32], the sedimentation rates are high ($2.5\text{--}12 \text{ cm ka}^{-1}$) and the terrigenous fraction is abundant [32–34]. This is also true for the cores from the SW Pacific with sedimentation rates of about 2.6 cm ka^{-1} and terrigenous quartz contents of 4–9% [35]. Reimer and Suess [35] suggest that frequent winnowing and resuspension by bottom currents and admixture of up-slope sediment has taken place at the location of these cores. Site 580 in the N Pacific is located in the zone of windborne dust supply from Asia. The sedimentation rates of about 5 cm ka^{-1} [36], the presence of 3–15% of eolian quartz [36–38] and the elemental composition [39] show a dominant contribution of terrigenous detritus. Also the sediments in core GPC-3, with relatively low sedimentation rates (0.25 cm ka^{-1}), contain a strong eolian component [40–44]. We conclude, therefore, that terrigenous supply should be considered as a major source of ^{10}Be accumulation in these 4 regions.

Oceanic precipitation: The two regression lines in fig. 3, one calculated from all values minus the three exceptions and one from the lowest 12 values, intersect the vertical axis at 530×10^6 and $100 \times 10^6 \text{ at. cm}^{-2} \text{ ka}^{-1}$ respectively. This suggests an oceanic ^{10}Be precipitation rate of $(100\text{--}530) \times 10^6 \text{ at. cm}^{-2} \text{ ka}^{-1}$ for the eastern equatorial Atlantic. These rates are close to the calculated global-average production rates of ^{10}Be of $(350\text{--}1890) \times 10^6 \text{ at. cm}^{-2} \text{ ka}^{-1}$ as summarized from literature data by Monaghan et al [12] and the $(520\text{--}2600) \times 10^6$ (average 1210×10^6) $\text{at. cm}^{-2} \text{ ka}^{-1}$ based on data from precipitation collectors throughout the USA by the same authors. The supposed oceanic precipitation rate does not contradict the ^{10}Be accumulation rates of $(160\text{--}1300) \times 10^6 \text{ at. cm}^{-2} \text{ ka}^{-1}$ which can be calculated from data for slow accumulating sediments in the Pacific given by Somayajulu [11] and Tanaka and Inoue [5], the $190 \times 10^6 \text{ at. cm}^{-2} \text{ ka}^{-1}$ given by Somayajulu, Sharma and Berger [7] for a sediment box in the North Atlantic, and the 1600×10^6

at. $\text{cm}^{-2} \text{ka}^{-1}$ derived by Raisbeck et al. [45] from measurements on Lake Bosumtwi, a crater lake in Ghana. Oceanic sediments with higher BAR, about 3200×10^6 at. $\text{cm}^{-2} \text{ka}^{-1}$, are reported by Raisbeck et al [6] for a location in the North Pacific.

Terrigenous concentration: If we consider the terrigenous clays as the only ^{10}Be source, the variable terms of the regression functions in fig. 3 would describe the ^{10}Be that reached the ocean floor after accumulation on land and subsequent erosion and transport by the Zaire river. To estimate the ^{10}Be concentration of this terrigenous component, the factor 2.26 in the regression formula should be multiplied with 2 because about 50% of the sediment consists of biogenic opal. It suggests that this terrigenous material would contain on average 5×10^9 at. $^{10}\text{Be} \text{g}^{-1}$ although within wide limits. If biologic scavenging plays also a role of importance, which is probable, then this value is to be regarded as a maximum concentration. For comparison: for soils in Virginia and California ^{10}Be concentrations were reported of $(0.1-1) \times 10^9$ at. g^{-1} [13,14] and in marine sediments near the California coast a terrigenous component is calculated to contain $(0.3-0.55) \times 10^9$ at. g^{-1} [46], an order of magnitude lower. This may be explained by the fact that the greater portion of the terrigenous component in the Zaire fan has grain sizes smaller than $2 \mu\text{m}$ [15,16]; it forms a selection of the clay mineral fraction which is capable to adsorb Be.

5. Dating with ^{10}Be

The ^{10}Be concentrations were measured in the well dated pelagic core T78-38. (See the section dealing with the stratigraphy.) This core has rather constant MARs of ca $0.60 \text{ g cm}^{-2} \text{ka}^{-1}$ for the interval 3–7 m below the core top and $0.21 \text{ g cm}^{-2} \text{ka}^{-1}$ for the upper 3 m [15,47]. In the lower interval, short-term increases of terrigenous input are indicated by the presence of quartz and mica grains and of a few turbiditic laminae.

The ^{10}Be concentrations of T78-38 (table 3, fig. 4) show an exponential decrease in the upper 3 m, which indicates also a constant BAR during the last 350 000 years with an original ^{10}Be concentration of 5.3×10^9 at. g^{-1} . Assuming that the constancy is valid for the entire period of accumulation and using a half-life of 1.52×10^6 years [4], we calculated a theoretical ^{10}Be curve. Fig. 4 demonstrates that most ^{10}Be measurements are in agreement with the predicted values. There are, however, deviations, especially below 3 m, which can be attributed to short-term fluctuations in MAR escaping from observation with the time scale available. The measured ^{10}Be concentrations allow only to calculate an average sedimentation rate for the entire core, giving an age at 635 cm of 820 ka. This is about 340 ka too old compared with the known age of 478 ka, which

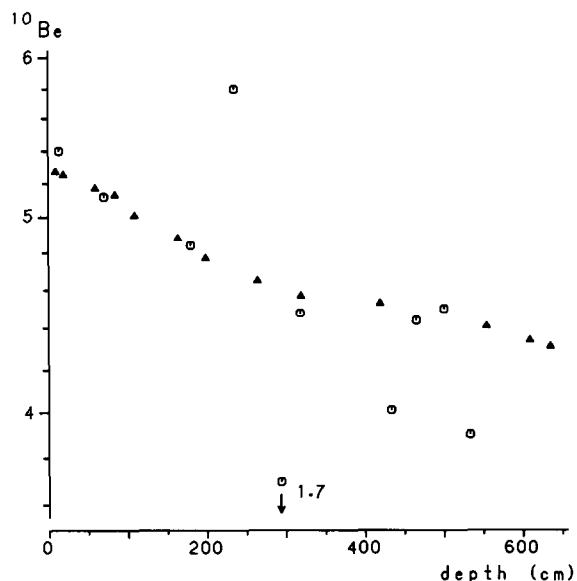


Fig. 4. ^{10}Be concentrations (10^9 at.g^{-1}) for core T78-38. O measured value, ▲ predicted value. For age control see Jansen et al. [15], for location see fig. 1 and table 1.

is due to the relatively low concentrations at 291, 433 and 533 cm most probably caused by dilution with inert coarser-grained terrigenous components.

Consequently, ^{10}Be measurements are worthwhile as a dating tool for time intervals of at least 1 million years which enable to eliminate the effect of short-term variations in MAR. For shorter time intervals, the downcore profiles of the concentrations can be greatly influenced by these variations, which on the other hand gives an insight into the occurrence of these variations. This is particularly true for the detection of sedimentary hiatuses which are often not easily detected.

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