22. ^{10}Be DISTRIBUTIONS IN DEEP SEA DRILLING PROJECT SITE 576 AND SITE 578 SEDIMENTS STUDIED BY ACCELERATOR MASS SPECTROMETRY[1]

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ABSTRACT

Extension of the ^{10}Be geochronology for deep-sea sediments beyond the limit of late Pliocene age found in published works has been attempted. The results obtained on sediments from Deep Sea Drilling Project (DSDP) Sites 576 and 578 of Leg 86 suggest the feasibility of dating sediments as old as 12 to 15 m.y. At both sites, there have been large changes in sedimentation rate, with the Pleistocene sediments accumulating several times faster than those of the Pliocene, which in turn were deposited several times more rapidly than the late Miocene sediments. The Pleistocene-Pliocene section is considerably thicker in Hole 578 than in Hole 576B: the respective depths for the 7-m.y. time boundary in the two holes are ~125 and ~25 m. These ^{10}Be-based age estimates are in agreement with the paleomagnetic stratigraphies established for the two sites. The suggested enhancement in the oceanic deposition of ^{10}Be before 7 to 9 m.y. ago, as noticed in manganese crusts, has found tentative support from the present sedimentary records. A preliminary search for ^{10}Be production variation during a geomagnetic field reversal has been conducted. In Hole 578, an enhanced ^{10}Be concentration is found in a sample close to the Brunhes/Matuyama reversal boundary. More detailed and systematic measurements are required to confirm this observation, which bears on the detailed behavior of the geomagnetic field during the reversal.

INTRODUCTION

The potential of using the long-lived ^{10}Be (half-life 1.5 m.y.) to study cosmic-ray intensity variations and deep ocean sedimentation rates was first suggested by Peters (1955). The detection of this cosmogenic radionuclide in marine sediments soon followed (Arnold, 1956; Goel et al., 1957). Since then, many papers on ^{10}Be in deep-sea sediments have been written (Amin et al., 1975; Inoue and Tanaka, 1976, 1979; Tanaka and Inoue, 1979, 1980; Tanaka et al., 1977, 1982; Somayajulu, 1977; Finkel et al., 1977; Raisbeck et al., 1979), contributing handsomely toward the realization of that potential. Most of these works have measured the beta activities of ^{10}Be. Although state-of-the-art low-level beta counting techniques have been used, the sensitivities in the measurements remain relatively low. Few such measurements give desirable precisions for samples with ages beyond one or two half-lives of ^{10}Be. And, since over 100 g of sediment are often required for each radio-counting assay, the minimum analyzed depth intervals from a conventional piston core (5-cm diameter) are larger than 10 cm. With a typical deep-sea accumulation rate on the order of 0.5 g/cm^2 per 1000 yr., these sampled intervals correspond to a time resolution of $>10^4$ yr.

The nuclear accelerator mass spectrometry developed in recent years (e.g., Muller, 1977; Raisbeck et al., 1978; SAMS, 1981) enables us to improve on the situation. It attains a measurement sensitivity for ^{10}Be of 10^7 atoms or less, which is about three orders of magnitude smaller than that achieved by the decay counting methods. It is clear that the ^{10}Be chronology of pelagic deposits can be greatly extended with the accelerator technique. The ^{10}Be chronology of sediments recovered from the Deep Sea Drilling Project (DSDP) should be particularly valuable as a supplement to the age information based on paleomagnetism and biostratigraphy.

The study presented here gives the first accelerator measurements of ^{10}Be in DSDP sediments. Measurements were made on samples from two DSDP sites in the western North Pacific: Sites 576 and 578. Site 576 (32°21.4′N, 164°16.5′E; 6217 m), which has been proposed by JOIDES panels as a "type" North Pacific red clay site, lies in an area of apparently uniform pelagic sedimentation between Shatsky Rise and the Emperor Seamounts. Site 578 is farther to the west (33°55.6′N, 151°37.7′E; 6010 m) and is located in an area covered with a thick section of late Neogene siliceous clays. Paleomagnetic studies carried out on samples from both sites give good to excellent reversal records for the last 5 m.y. (Heath et al., this volume). At Site 578, the magnetostratigraphy extends to about 15 m.y. ago, although data control for the extension is of lesser quality. Three holes were drilled at Site 576: 576, 576A, and 576B. The analyzed ^{10}Be samples are from Hole 576B, except for the two samples at sub-bottom depths of 29.68 and 40.00 m, which are from Hole 576 (material from these two depths in Hole 576B was not recovered in the coring operation). It should be noted that drilling records indicate that the sub-bottom depth of the base of the clay unit in

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Hole 576 (~55 m) is more than 10 m deeper than in Hole 576B. Adjustments of sub-bottom depth assignment have been made to correct for this discrepancy (see Site 576 chapter, this volume). The adjusted depths are used in this chapter.

The primary purpose of this study was to establish ^{10}Be geochronologies for Sites 576 and 578 and to compare these chronologies with ages obtained from magneto- or biostratigraphy. Another purpose was to check the possible deviation from constancy in the oceanic precipitation rate of ^{10}Be about 7 to 9 m.y. ago, as observed in ferromanganese crusts (Ku, Kusakabe, Nelson, et al., 1982). In addition, we examined the extent of variations in the ^{10}Be concentration in sediment layers close to a geomagnetic reversal. Information thus acquired may bear on the detailed behavior of the geomagnetic field during a geomagnetic reversal. Because of the great lengths of the cores involved (~70 m at Site 576 and ~165 m at Site 578), the number of ^{10}Be measurements made so far constitutes only a fraction of the number needed to completely fulfill the aforementioned objectives. We are currently trying to fill in the data gaps, which will become evident in the following discussion.

EXPERIMENTAL PROCEDURES

Samples were taken from the hydraulic piston cores retrieved in Holes 576, 576B, and 578. The sampled depth intervals varied from 1 to 3 cm. The sediments arrived at the lab in wet condition. After being dried at 110°C, they were homogenized in powdered form. Aliquots of about 150 mg and about 1 g were taken from each sample for analyses of $CaCO_3$ content and ^{10}Be, respectively.

The carbonate aliquots were leached with hot acetic acid. Their $CaCO_3$ percentages were estimated from calcium determinations made on the leachates using atomic absorption spectrophotometry. The accuracy was about ±10%. The ^{10}Be samples were completely dissolved with successive treatments of HCl, HF + $HClO_4$, and aqua regia. To each sample solution was added 0.9492 mg of ^{9}BeO (in the form of $BeSO_4$ solution) as Be carrier. The extraction and purification procedures for Be followed those of Ku et al. (1979) with some simplifications, since the BeO prepared for the accelerator runs does not have to be radiochemically pure. Dowex-1 anion resins were used to first separate out iron. Beryllium was then purified against Al on a Dowex-50 cation-exchange column using 0.5 *M* oxalic acid (for Al) and 4 *M* HCl (for Be) as eluants. After heating over a Bunsen burner in a covered Pt crucible to convert $Be(OH)_2$ to BeO, the BeO was mixed with a few milligrams of ultra-pure Ag powder (as a binder) and impacted into stainless steel sample holders, ready for insertion into the accelerator's ion source.

The technical details of ^{10}Be analysis, including adaptations of the McMaster University FN tandem Van de Graaff accelerator used for the analysis, have been described by Southon et al. (1983). The primary standard consists of ultra-pure ^{9}BeO irradiated with thermal neutrons to produce $^{10}Be/^{9}Be$ ratios of 10^{-9}. (A neutron capture cross section of 9.2 mb [Mughabghab and Garber, 1973] was used.) Several similarly prepared secondary standards with $^{10}Be/^{9}Be$ ratios of 10^{-10}, 10^{-11}, etc. were used for consistency check. Each measurement consisted of three separate $^{10}Be/^{9}Be$ determinations: one on the standard, one on the unknown, and a second on the standard. The measured ratio of the standard (the mean of the results from the two runs) was then used with the measured ratio for the unknown to determine the absolute ratio for the latter. Each sample was measured several times. After every second unknown run, a check was made of a secondary standard or a blank. The blank consisted of the reagents used (including 0.9492 mg of BeO carrier) which had undergone all the preparation chemistry.

RESULTS

Table 1 lists the ^{10}Be and $CaCO_3$ data of Sites 576 and 578. The measured $^{10}Be/^{9}Be$ ratios refer to the atom ratio of natural ^{10}Be to the carrier ^{9}Be added (^{9}Be in samples is negligible), before correction for the blank. The blank has a $^{10}Be/^{9}Be$ ratio of $(1.7 \pm 0.2) \times 10^{-13}$, which is small compared to the ratios for most of the samples, and it is the same as that of Sample 576-6-6, 110 cm, which has the lowest measured ratio of the samples analyzed. According to magnetic and ichthyolith studies (Heath et al., this volume; Doyle and Riedel, this volume), this sample has an age of about 30 m.y., so it should be ^{10}Be free. The quoted uncertainties in the tables are one standard deviations derived from the scatter of the several $^{10}Be/^{9}Be$ measurements on each sample.

Semilog plots of the ^{10}Be concentrations versus depth in Holes 576B and 578 are shown in Figures 1 and 2, respectively. The closely spaced data points near the Brunhes/Matuyama boundaries in both holes are plotted on an expanded depth scale in the upper part of each of the figures; their average values (and standard deviations) are plotted in the lower diagram. Sedimentation rates are derived from the slopes of the straight lines fitting the data points. The assumption is made that deposition rates of both ^{10}Be and the sediment remain constant (to within the data scatter) over the time period represented by a given straight-line segment. If zero age is taken to be the sediment/water interface, the age for a particular depth in the holes can be calculated from the sedimentation rates. A few such ages are indicated in parentheses.

DISCUSSION OF RESULTS

Measurement Precision and Sensitivity—Extending the Deep-Sea ^{10}Be Geochronology

The analytical precision of <5% in this study is a significant improvement over that of >15% generally reported in the earlier studies. The validity of the error limits is supported by the two sets of duplicate results shown in Table 1. The sensitivity of the present analyses can be estimated from $^{10}Be/^{9}Be$ ratios of $(1.7 \pm 0.2) \times 10^{-13}$ and $(1.9 \pm 0.4) \times 10^{-13}$ obtained for the blank and for the oldest sample, respectively. With the amount of the ^{9}Be carrier used, these ratios correspond to about 4×10^6 atoms of ^{10}Be, a quantity that is typically found in 1 mg of abyssal sediments of modern age. Thus, our measurement sensitivity should potentially allow the deep-sea ^{10}Be chronology to be extended beyond 15 m.y., well into the Miocene Epoch. There is no reason to discount the feasibility of ^{10}Be dating of even earlier Neogene deposits. Since accelerator mass spectrometry is capable of detecting $^{10}Be/^{9}Be$ ratios of 10^{-14} to 10^{-15} (e.g., Gove, 1981), and since the sample/carrier proportions can be readily maximized (increased) over those used in this study, one only has to reduce the blank values associated mostly with the extraction chemistry. Of course, knowledge must also be secured on the long-term constancy of ^{10}Be or $^{10}Be/^{9}Be$ of the oceanic reservoirs prior to 7 to 9 m.y. ago (Ku, Kusakabe, Nelson, et al., 1982). In this regard, cross-checks of ^{10}Be ages with K-Ar or fission-track ages obtained on intercalated volcanic ash deposits commonly found in the deep sea, as well as with magneto- and biostratigraphic ages, would be useful.

Table 1. ^{10}Be and $CaCO_3$ data for Holes 576B, 576, and 578.

Core-Section (level in cm)	Sub-bottom depth (m)	$CaCO_3$ (%)	Measured[a] $^{10}Be/^{9}Be \times 10^{-11}$	^{10}Be (10^9 atoms/g)
Hole 576B				
1-1, 49	0.49	0.39	15.1 ± 0.8	3.30 ± 0.17
1-4, 57	5.07	0.39	13.6 ± 0.8	3.01 ± 0.18
1-5, 59	6.60	—	22.5 ± 0.3	3.11 ± 0.04
1-5, 79	6.79	0.37	15.0 ± 0.4	3.38 ± 0.08
1-5, 98	6.98[b]	0.35	15.3 ± 0.3	3.12 ± 0.06
1-5, 108	7.08[b]	—	19.1 ± 0.3	2.31 ± 0.04
1-5, 120	7.20	0.31	11.2 ± 0.3	2.30 ± 0.06
1-5, 149	7.49	0.38	16.7 ± 0.6	2.75 ± 0.10
1-6, 50	8.00	0.34	14.3 ± 0.4	2.36 ± 0.07
2-1, 40	12.00	0.41	12.4 ± 0.3	2.21 ± 0.05
2-3, 40	15.00	—	15.8 ± 0.3	2.33 ± 0.05
2-4, 140	17.50	—	10.9 ± 0.2	1.50 ± 0.03
2-6, 90	20.00	0.45	4.3 ± 0.4	0.63 ± 0.06
3-6, 50	24.99	—	0.90 ± 0.02	0.127 ± 0.003
Hole 576				
5-1, 148[c]	29.68	0.60	1.9 ± 0.2	0.20 ± 0.02
5-1, 148[c]	29.68	—	1.28 ± 0.05	0.18 ± 0.01
6-6, 110	40.00	1.22	0.019 ± 0.004	0.0003 ± 0.0006
Hole 578				
1-1, 50	0.50	0.39	13.2 ± 0.4	2.96 ± 0.09
3-4, 120	20.00	0.49	9.6 ± 0.5	1.81 ± 0.09
4-1, 120	25.00	0.46	10.6 ± 0.2	1.58 ± 0.03
4-2, 103	26.33	0.34	14.8 ± 1.0	2.27 ± 0.15
4-2, 130	26.60	0.37	12.2 ± 1.0	1.94 ± 0.16
4-3, 10	26.90[d]	0.44	20.0 ± 1.8	3.18 ± 0.29
4-3, 20	27.00	0.39	11.7 ± 0.3	2.20 ± 0.06
4-3, 50[c]	27.30	0.19	2.7 ± 0.1	0.56 ± 0.02
4-3, 50[c]	27.30	—	2.9 ± 0.1	0.60 ± 0.02
4-3, 70	27.50	0.35	13.2 ± 0.5	2.08 ± 0.08
4-3, 92	27.72	0.36	9.5 ± 0.1	1.84 ± 0.02
4-3, 120	28.00	0.34	10.4 ± 0.3	1.77 ± 0.05
6-5, 120	50.00	0.29	6.4 ± 0.2	1.16 ± 0.04
11-6, 20	98.00	0.38	2.85 ± 0.06	0.435 ± 0.009
12-6, 143	108.73	—	1.89 ± 0.05	0.265 ± 0.007
14-5, 64	125.44	0.34	0.82 ± 0.02	0.113 ± 0.003
16-2, 75	140.05	—	0.087 ± 0.008	0.009 ± 0.001
17-2, 148	150.28	0.56	0.061 ± 0.012	0.005 ± 0.002

Note: — means not measured.
[a] Atom ratios before correction for blank which has a ratio of $(1.7 \pm 0.2) \times 10^{-13}$.
[b] Brunhes/Matuyama magnetic reversal found near these two levels at 7.05 m.
[c] Duplicate analyses made on two different aliquots of the sample.
[d] Location of Brunhes/Matuyama reversal.

Constancy of ^{10}Be Deposition

The temporal variations in the oceanic deposition of ^{10}Be have been assessed to be within ±10% when the deposition is integrated over time periods of 2 to 7 × 10^5 yr. (Inoue and Tanaka, 1979; Tanaka and Inoue, 1980). For shorter intervals of 10^4 to 10^5 yr. corresponding approximately to glacial–interglacial cycles, the limits have been placed at ±(25–30)% (Tanaka and Inoue, 1980; Ku, Kusakabe, Huh, et al., 1982). These assessments are based on the ^{10}Be distributions in sediment cores covering time spans up to 2.5 m.y. ago. The time coverage has been extended by the records in two ferromanganese crusts from the seafloor of the Pacific and the Atlantic (Ku, Kusakabe, Nelson, et al., 1982). Measurements on these crusts, when averaged over time intervals of about 1 m.y., record a variation of ±6% in ^{10}Be deposition during the last 7 to 9 m.y. Further back in time, the crustal records indicate a possible two- or threefold increase of ^{10}Be influx.

The average sedimentation rates shown in Figures 1 and 2 are derived with the above background information in mind. As will be seen, a comparison between the ^{10}Be-based ages and the magnetic reversal ages supports the general consistency of ^{10}Be precipitation since about 7 m.y. ago.

Tantalizing evidence exists for the possible increase of ^{10}Be input in the late Miocene. At Site 576, the "anomalously high" ^{10}Be concentration in Sample 576-5-1, 148 cm at 29.68 m (Fig. 1) appears to reflect a threefold increase of ^{10}Be flux before 7 m.y. ago. At Site 578, the check for high ^{10}Be influx is complicated by the fact that a rapid slowdown of sediment accumulation occurred earlier than 7 m.y. ago, as shown by the magnetic record (Heath et al., this volume) as well as our ^{10}Be data (Fig. 2). The ^{10}Be age of Sample 578-16-2, 75 cm (at

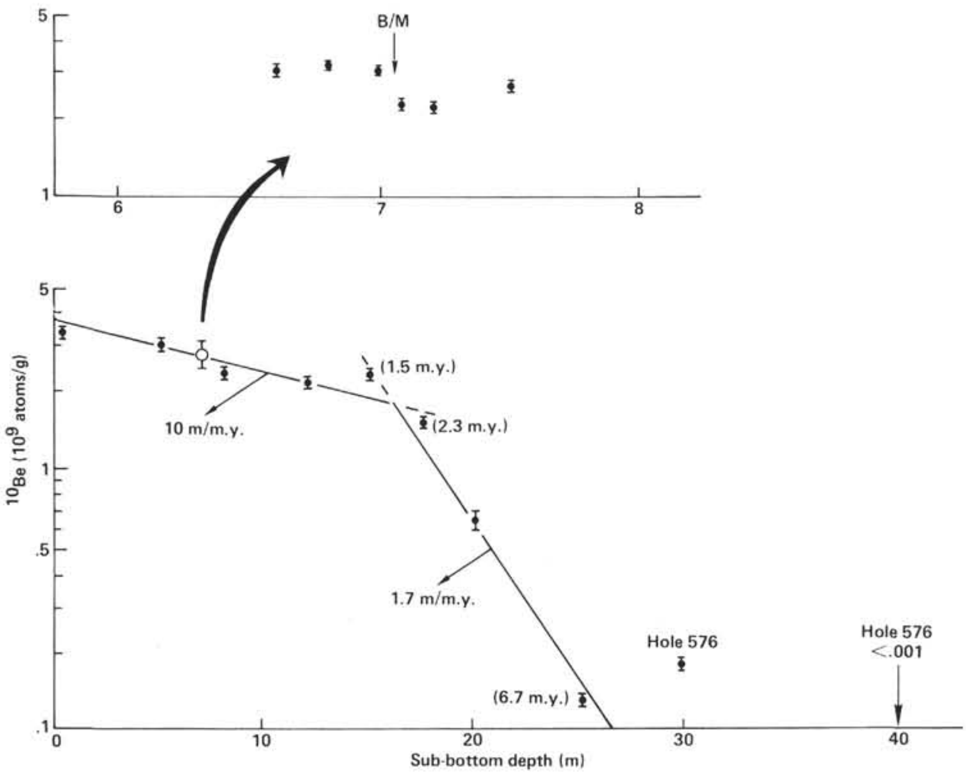

Figure 1. ^{10}Be concentrations versus depth in Site 576 sediments. All samples are from Hole 576B, except for the two deepest ones from Hole 576 as noted. Estimated average sedimentation rates and ages are shown, as is the position of the Brunhes/Matuyama reversal boundary (B/M). See text for further explanation.

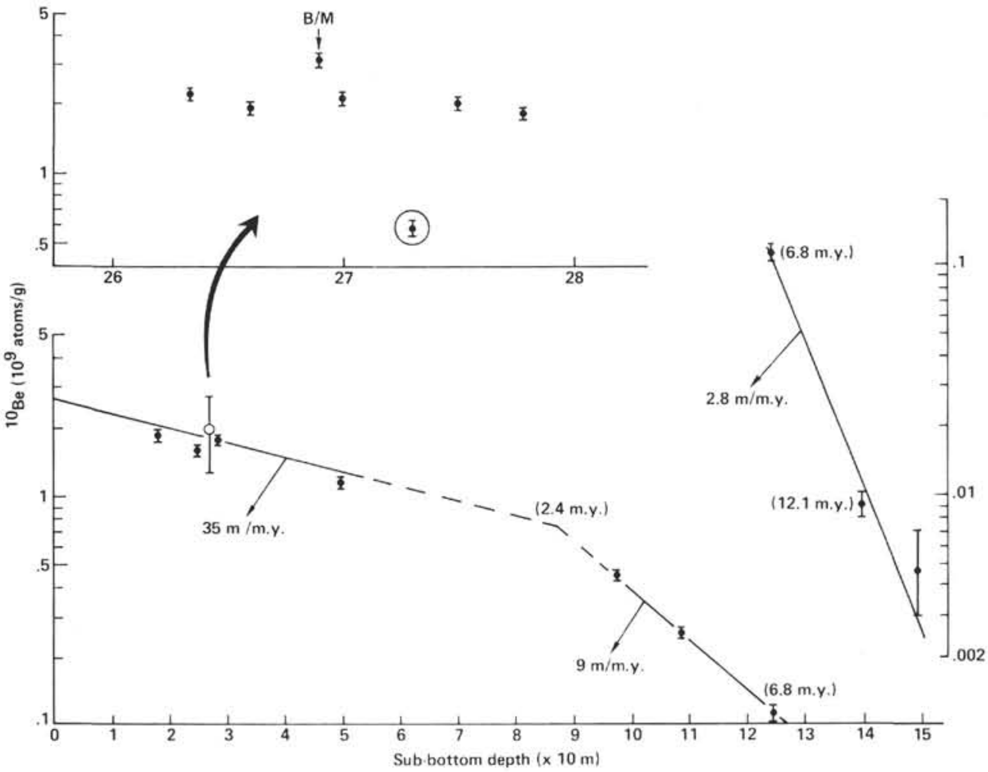

Figure 2. ^{10}Be concentrations versus depth in Site 578 sediments, with estimated average sedimentation rates and ages shown. The position of the Brunhes/Matuyama reversal boundary* (B/M) is indicated. Note a shift in the ^{10}Be concentration scale for the three deepest samples on the right-hand side of the graph. The encircled data point is from a sample with abundant volcanic material. See text for further explanation.

140.05 m) is younger than its magnetic age by one half-life of ^{10}Be (12.1 versus 13.6 m.y.), a discrepancy consistent with a late Miocene higher ^{10}Be input. However, the uncertainties of these ages render their difference inconsequential.

Although evidence appears to be present in support of a higher ^{10}Be deposition rate before 7 to 9 m.y. ago, it should be viewed with qualification at this time. A firmer check would require a series of closely spaced measurements on sediments of uniform accumulation rate near and below the 7 m.y. boundary. It should also be noted that a factor of two uncertainty in the ^{10}Be input causes an age uncertainty of 1.5 m.y., which becomes less serious for older samples. Interest in the 7–9 m.y. demarcation lies more in the realm of paleoceanography than of geochronology, since the ^{10}Be fluxes near the boundary may reflect a major change in the global abyssal circulation (Ku, Kusakabe, Nelson, et al., 1982).

^{10}Be Chronologies at the Two Sites

The sedimentation rates derived from the rate of decrease in ^{10}Be concentration with depth permit the establishment of absolute chronologies for the two sites. It is apparent from Figures 1 and 2 that in both holes drastic changes in sedimentation rate have taken place. The Pleistocene rates are several times more rapid than those of earlier times. In Hole 576B, the change occurred between 15 and 17.5 m, about 1.5 to 2.3 m.y. ago (Fig. 1). In Hole 578, relative sparsity of data brackets the change between 50 and 98 m. As shown in Figure 2, extrapolations of the two rate-determining lines would place the beginning of accelerated sedimentation near 2.4 m.y. ago (86 m depth), in late Pliocene/early Pleistocene times. Farther down the hole, another major change occurred around 7 m.y. ago (Fig. 2), with earlier deposits having accumulated considerably more slowly. The slow accumulation rate is also suggested by the large difference in ^{10}Be concentrations between 30 and 40 m in Hole 576 (Fig. 1). The data density precludes precise definition of the time intervals involved in the changes—they could have spanned millions of years. But the changes themselves and their magnitudes are clearly apparent from the data.

The paleomagnetic records for the two sites have been thoroughly examined (Heath et al., this volume) and can be correlated with the ^{10}Be age results. Figure 3 shows the correlation between the interpolated magnetic ages and the ^{10}Be ages estimated from the mean sedimentation rates for each of the data points shown in the lower plots of Figures 1 and 2. The two dashed lines represent $\pm 20\%$ deviations from the 1:1 correlation denoted by the solid line.

The linear regression line of the data set gives a y-intercept (magnetic age) of -0.1 m.y. and a slope of 1.06, and it has a correlation coefficient of 0.985. The average of the percent standard deviation of the means for the 19 pairs of data is $\pm 5.4\%$. All these statistics are better than expected, in view of the errors involved in the determination of both the ^{10}Be and the magnetic ages. In any case, the following implications can be drawn from Figure 3:

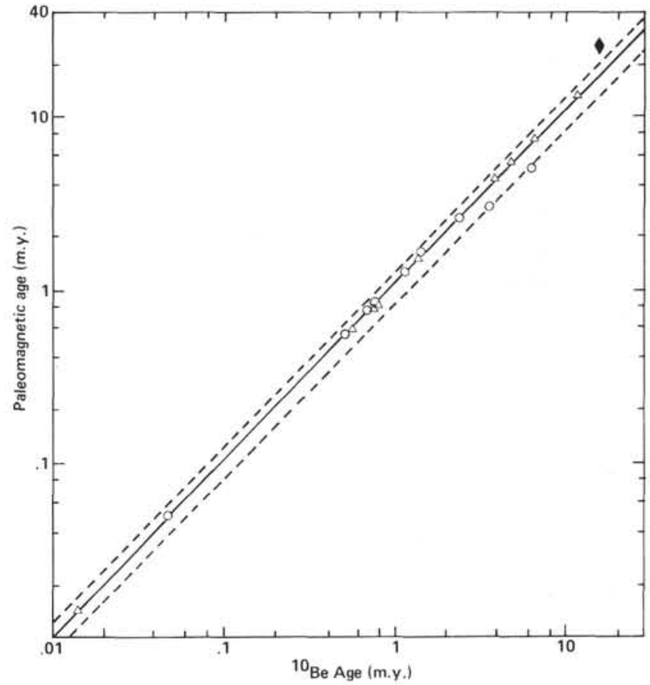

Figure 3. A correlation plot between ^{10}Be ages derived from the sedimentation rate data shown in Figures 1 and 2 (open circles, Site 576, open triangles, Site 578) and the paleomagnetic ages of Heath et al. (this volume). The two dashed lines bracket the $\pm 20\%$ deviations from a 1:1 correlation (solid line). The solid diamond-shaped data point represents the ^{10}Be age of Sample 578-17-2, 148 cm plotted against age based on ichthyoliths (Doyle et al., this volume). The ^{10}Be ages of this sample and the ~12 m.y. old sample may be 1.5 to 3 m.y. too young, because of the possible two- to threefold higher ^{10}Be flux before 7–9 m.y. ago.

1. The ^{10}Be geochronology in deep-sea sediments can be applied at least to the last 7 m.y., with an excellent prospect of being extended to 15 m.y. ago.

2. The two sites are located near or in an area of the western North Pacific where occurrence of large-scale depositional hiatuses during Cenozoic times is suspected (van Andel et al., 1975). The Figure 3 data imply continuous deposition at the two sites for the last 12 m.y. or thereabout. Were the large decrease in sedimentation rates caused by hiatus, one might expect stepwise patterns in ^{10}Be concentration versus depth plots. On the other hand, it could be that the hiatuses are too brief and our data are too sparse for the hiatuses to show up as steps in the depth distribution of ^{10}Be. More detailed ^{10}Be analyses in the future should provide further information on the matter.

3. The ^{10}Be ages are obtained on samples from Hole 576B only, whereas the magnetic records are based on samples from both Hole 576 and Hole 576B. It would seem that the adjustments made to correct for the ~10 m sub-bottom depth offset between the two holes in the drilling records (Site 576 chapter, this volume) might have largely restored the *in situ* stratigraphy.

4. The data represent as good a "geological" calibration for the ^{10}Be half-life of 1.5 m.y. (Yiou and Raisbeck, 1972) as presently exists over a 7-m.y. span.

^{10}Be Input Variation near Geomagnetic Reversal

Earlier workers (Raisbeck et al., 1979) have searched for an increased ^{10}Be flux into the marine sediments during a geomagnetic reversal. The search is based on the belief that a geomagnetic reversal is accompanied by the lowering of the dipole intensity to a near-zero level. During this zero-field period, which has been variously estimated to last for about 1000 yr. (Kawai et al., 1975) to 5000 yr. (Harrison and Somayajulu, 1966; Cox et al., 1975), cosmogenic isotope production would be increased two- or threefold (Black, 1967; O'Brian, 1979). If so, a change in ^{10}Be concentration might be found in sediments deposited during that period.

The Hole 578 sediments may be used to test this hypothesis. Assume that the zero-field period lasted 1000 yr. During the Brunhes/Matuyama transition, 3.5 cm of sediments would have been deposited having, say, twice the ^{10}Be concentration of those deposited during the normal field intensity. If mixing due to bioturbation is assumed to affect a 7-cm sediment interval, this 7-cm interval at the Brunhes/Matuyama boundary would have a ^{10}Be concentration 50% higher than normal. If we apply the above conditions to sediments at the Brunhes/Matuyama boundary in Hole 576B, we find only a 14% increase of ^{10}Be concentration in the zero-field period. The smaller increase is due to the slower sediment accumulation at Hole 576B, where accumulation was 3.5 times slower than at Hole 578.

These scenarios are in agreement with our observations. In Hole 576B, the ^{10}Be near the reversal (i.e., the six data points shown in the upper part of Fig. 1) show variations no greater that those of the age-corrected concentrations for all the data points above 25 m: the standard deviations from the means in both cases are about $\pm 15\%$. Hence, we either have yet to obtain or are unable to identify the signals we search for. In Hole 578, the ^{10}Be concentration found at 26.90 m is about 54% higher than concentrations nearby. This may be of significance, because the standard deviation from the average ^{10}Be concentration of the five points adjacent to the reversal (see upper Fig. 2; the data at 27.30 m are excluded) is about $\pm 9\%$, and this value is also the scatter about the age-corrected mean ^{10}Be concentration for all the data points (the sample at 27.30 m is again excluded) down to 125.44 m. We exclude the data for the sample at 27.30 m in our discussion because microscopic examination shows this sample to contain abundant volcanic glass fragments. It could well be from one of the many ash layers present in the hole, and its low ^{10}Be concentration results from dilution by the ash material.

Before accepting the above interpretations, one should also be aware of the following complications. First, variations in ^{10}Be concentration due to variations in sediment composition and sedimentation rate must be considered. Volcanic sediments and biogenic carbonates are two types of material that act as a dilutant for ^{10}Be contents (Tanaka et al., 1977; Ku, Kusakabe, Huh, et al., 1982). Data in Table 1 shows that the effect of $CaCO_3$ dilution should be minimal. We also need biogenic silica data for Hole 578, but those data are currently unavailable. One further notices that the ^{10}Be concentration varies rather weakly with sedimentation rate; namely, the surface concentrations in the two holes differ by about 30%, whereas sedimentation rates differ by a factor of 3.5. This dependence of ^{10}Be scavenging efficiency on sedimentation rate, which has been noted previously (e.g., Tanaka et al., 1982), and the generally uniform lithologies of the samples studied do tend to reduce the "noise" attributable to the composition–rate factor. Nevertheless, composition and sedimentation rate should be considered when small differences in ^{10}Be concentration (e.g., $<20\%$) are compared among adjacent layers.

The second complication, as pointed out by Raisbeck et al. (1979), is the so-called depth-lag. Depth-lag is the depth below the sediment/water interface where the magnetic grains become held firmly enough in position so that changes in the Earth's magnetic polarity do not result in movements of the grains. Estimates of the depth-lag vary from a few centimeters (hence within the bioturbated zone of 5–10 cm) to over 1 m (Dymond, 1969). Therefore, search for the ^{10}Be input variations should be conducted on sediments above as well as at the level where the magnetic reversal is found.

The examples given above assume that the average residence time of Be in the ocean is negligible compared with the zero-field period. Available data on Be in seawater point to a residence time of about 1000 yr. (Yokoyama et al., 1978; Measures and Edmond, 1982). Therefore we must also consider the "damping" effect of ocean mixing (as well as of bioturbation) on the amplitude of the ^{10}Be concentration variations in sediments relative to that of the atmospheric ^{10}Be input changes due to geomagnetic field variation. This effect can be explained mathematically as follows.

The time variation of the amount of ^{10}Be in seawater, $M(t)$, depends on the input and removal rates of ^{10}Be.

$$dM/dt \text{ (atoms/cm}^2 \cdot \text{yr.)} = P - RM. \quad (1)$$

Here, the removal is expressed in terms of first-order rate constant R, the value of which can be taken as 10^{-3}/yr.

The stationary ^{10}Be standing crop in the water column is thus:

$$M(\text{atoms/cm}^2) = P/R. \quad (2)$$

Let the production rate P increase by a factor of n over a time period t:

$$dM/dt = nP - RM. \quad (3)$$

If Eq. (3) is solved with the initial condition $M(0) \equiv M_0 = P/R$,

$$M/M_0 = (1 - n) \exp(-Rt) + n. \quad (4)$$

This relationship depicts the change of water-column ^{10}Be inventory in response to the input change. It is illustrated in Figure 4 by the example cited earlier: a twofold increase ($n = 2$) of ^{10}Be input over a zero-field period of 1000 yrs. This increase results in an increase of 1.6 times M at the end of the period.

What are the corresponding changes of ^{10}Be concentration in sediments? The flux of ^{10}Be in sediments can be written

$$F = RM. \quad (5)$$

If it is assumed that bioturbational mixing is rapid compared to sediment accumulation (so that within the mixing zone of L cm, the ^{10}Be concentration C is uniform), it becomes possible to use the following equation from Berger and Heath (1968):

$$dC/dt = (F - wC)/L, \quad (6)$$

where w is sedimentation rate (cm/yr).

At steady state,

$$C = F/w = P/w. \quad (7)$$

Again, let the system be initially at steady state (i.e., $C(0) \equiv C_0 = P/w$) and solve Eq. (6) for the zero-field period with a ^{10}Be production nP:

$$C/C_0 = w(1 - n)/(w - RL) \exp(-Rt) + (1 - n)[1 - w/(w - RL)] \exp(-wt/L) + n. \quad (8)$$

As shown in Figure 4, if $L = 7$ cm, $n = 2$, and $R = 10^{-3}$/yr., a zero-field period of 1000 yr. gives rise to a merely 16% increase of the ^{10}Be concentration in Hole 578 sediments near the Brunhes/Matuyama boundary ($w = 3.5$ cm/10^3 yr.). Matching the 54% increase as observed requires (with the given values for L and R) a zero-field period of 1500 yr. with $n = 3$, or of 3000 yr. with $n = 2$ (Fig. 4).

In light of the discussion above, further detailed measurements at intervals of 5 to 10 cm near and above the level of 26.90 m in Hole 578 are warranted to determine whether the high ^{10}Be signal at that level has indeed recorded the geomagnetic reversal event. We believe that it may be possible to infer from these measurements information regarding the intensity and duration of the geomagnetic field at reversal, depth-lag, and/or the thickness of the bioturbated zone.

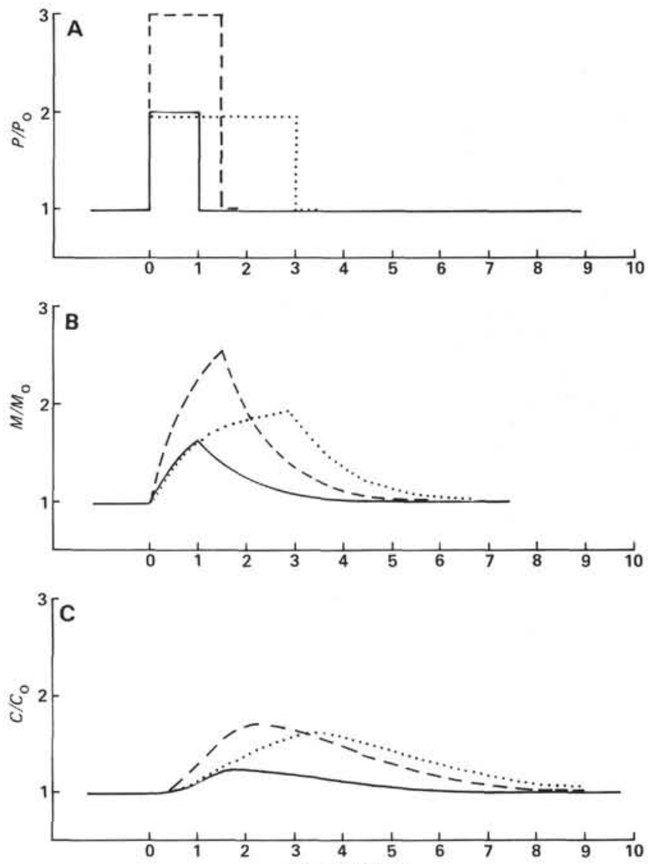

Figure 4. Relationship among changes in (A) ^{10}Be input P, (B) water-column ^{10}Be inventory M, and (C) ^{10}Be in sediments C. Calculations are done using oceanic ^{10}Be scavenging constant $R = 10^{-3}$ per year, sedimentation rate $w = 3.5$ cm/1000 yr. and bioturbated mixed layer thickness $L = 7$ cm. Three cases with respect to the duration (Δt) and increase (n) in ^{10}Be production are shown: solid line: $\Delta t = 1000$ yr., $n = 2$; dashed line: $\Delta t = 1500$ yr., $n = 3$; and dotted line: $\Delta t = 3000$ yr., $n = 2$. The latter two cases will give rise to the observed 54% increase in ^{10}Be concentration in Hole 578 sediments near the Brunhes/Matuyama boundary. Note a time lag of about 500 yr. for the peaks in Figure 4C relative to those of Figure 4B. The lag is mainly a function of L. The zero-subscripts for P, M, and C denote the unperturbed conditions, that is, the steady-state properties prior to the ^{10}Be production increase.

CONCLUSIONS

Use of ^{10}Be as a geochronometer for marine sediments has been successfully tested against the paleomagnetic reversal time scale for the past 2.5 m.y. (Tanaka et al., 1977; Inoue and Tanaka, 1979). The high-sensitivity ^{10}Be analysis afforded by nuclear accelerator mass spectrometry enables us to demonstrate that the ^{10}Be geochronology can be extended to about 15 m.y. ago. Our measurements on sediments from Sites 576 and 578 show a correlation between ^{10}Be ages and magnetostratigraphy of $\pm 15\%$ or better. The high ^{10}Be concentration found in Sample 576-5-1, 148 cm may be evidence of an elevated oceanic ^{10}Be flux prior to ~ 7 m.y. ago; high concentrations have also been found in manganese crusts. The potential of this long-lived radioberyllium as a tracer for cosmic-ray intensity changes during a geomagnetic field reversal is explored. The data on hand are somewhat too limited to permit any except tentative conclusions. Nevertheless, they strongly suggest that the search for an increase of ^{10}Be concentration in marine sediments recording geomagnetic reversals is warranted. If the high ^{10}Be concentration found at 26.90 m in Hole 578 proved to record a higher production of the isotope during the Brunhes/Matuyama reversal, then the data would imply that the duration of the reduction in dipole intensity during the reversal was not much longer than a few thousand years and that the depth-lag for the "freezing" of magnetization in Hole 578 sediments is no more than the normal bioturbated interval of 5 to 10 cm.

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