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^{10}Be IN POLAR ICE AND ATMOSPHERES

by

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ABSTRACT

We briefly review the application of cosmogenic ^{10}Be measurements in ice and polar atmospheres to: (i) the dating of ice cores, (ii) the deduction of past accumulation rates, (iii) information on the influx of stratospheric aerosols in polar regions, and the mechanism of incorporation of aerosols into the ice. We find that at high latitudes (>74°), the ^{10}Be deposition rate in the ice is more constant than the ^{10}Be concentration.

INTRODUCTION

The cosmogenic isotope ^{10}Be (half-life 1.5 Ma) is formed by cosmic-ray interactions in the Earth's atmosphere. ^{10}Be atoms quickly become associated with aerosol particles, and are deposited at the Earth's surface by precipitation and dry fallout, with residence times similar to these aerosols. ^{10}Be then accumulates in various geological reservoirs, such as polar ice, and marine and lacustrine sediments. The technique of accelerator mass spectrometry (Raisbeck and others 1978) now makes it possible to measure this isotope in samples of reasonable sizes (<10 m^3 stratospheric air, <10^3 m^3 tropospheric air, <1 g of sediments, <1 kg of ice).

Such measurements can give information on past rates of production of ^{10}Be, and thus on the factors which influence this production, namely primary cosmic-ray flux, solar activity, and geomagnetic field intensity. Secondly, the study of ^{10}Be, either alone or in conjunction with other cosmogenic isotopes, can give information, such as origin, age, transport mechanism, etc., on the reservoir material in which it is measured (Raisbeck and Yiou 1984). It is this latter aspect, with particular reference to polar atmospheres and ice, that we briefly review here.

ICE-CORE DATING

Perhaps the most obvious potential application of radioactive cosmogenic isotopes in polar ice is that of dating the ice. Indeed, for a number of years it has been proposed that the measurements of ^{14}C in CO_2 trapped in the ice might serve such a purpose. It now appears that accelerator mass spectrometry will make such measurements feasible in the near future (Andrée and others 1984). However, a polar ice sample of 55 ka will contain only ~1 atom of ^{14}C per gram of ice. Thus, even with the accelerator technique, ice of this age and older will pose a serious problem for ^{14}C dating. Fortunately there are other longer-lived cosmogenic isotopes which can overcome this difficulty.

Unlike ^{14}C, however, most of these other cosmogenic species are not in equilibrium with their stable isotopes in the environment. Thus, in order to use them it is desirable to measure a pair of these isotopes having different half-lives. Such a procedure has the further advantage that it will minimize the effects of production variations due to the causes mentioned earlier. For ice older than 50 ka the most useful of these isotope pairs is probably ^{36}Cl/^{10}Be, which has an "effective" half-life of 370 ka. For even older ice (if it is ever recovered) it would also be possible to use ^{26}Al/^{10}Be (effective half-life 1.4 Ma). For young ice ^{14}C dating is also limited because of the uncertain and variable time for "close-off" of the ice bubbles to the atmosphere. Here the ratio ^{32}Si/^{10}Be (effective half-life ~110 a) should be useful. It should be mentioned that polar ice (at least in regions where it never melts) is a particularly attractive reservoir for such dating, because there is little probability that there will be "fractionation" of the different isotopes in the reservoir.

PAST ACCUMULATION RATES

Paterson and Waddington (1984) have recently emphasized that even an accurately dated ice core will not necessarily permit a calculation of past precipitation rates, because of limitations caused by the assumptions made when modelling the thinning of the ice during burial. They have also pointed out that the measurement of ^{10}Be in such ice might provide one of the few ways of avoiding such problems (since the concentration of the ^{10}Be is not affected by thinning). Indeed, our earliest measurements of an increase in the ^{10}Be concentration, in ice of the last glacial period at Dome C, Antarctica, led us to suggest that the most probable cause was a decreased precipitation rate during this time (Raisbeck and others 1981[a]). More recent measurements in a core at Vostok station have reinforced our belief in such an interpretation (Yiou and others in press) A collaboration between research groups in Bern and Zürich has found similar evidence for ice at Dye 3 in Greenland (Beer and others 1983[a]). Interestingly, we have not found this increase in Wisconsin ice at the Agassiz Ice Cap on Ellesmere Island (unpublished). Whether this is due to our limited sampling, more complicated ice flow, or actually reflects a real precipitation difference at this site, is not yet clear.

In order to use ^{10}Be to deduce past precipitation rates in this way, it is necessary to take into consideration effects due to possible changes in production rate or in atmospheric circulation. As pointed out by Paterson and Waddington (1984), it may be possible to use data from one polar site, where the modelling parameters or experimental information are favourable, to monitor ^{10}Be changes, and thus deduce accumulation changes at less favourable sites. In cases where the ice is from a site away from an ice ridge it will also be necessary to take into consideration a possible difference in the ^{10}Be concentration at the location of the original precipitation (see below).

ATMOSPHERE-ICE TRANSFER FUNCTIONS

One of the main objectives in studying ice cores is to obtain information about past environmental conditions. To do this, one needs to be able to "translate" the ice-derived data. Since ^{10}Be has been formed continuously in the past, in a fairly well-defined way, it can be used as a sort of reference when interpreting deposition mechanisms of certain other components in the ice, and their variations. As an example of such a procedure, we show in Table I our available data on contemporary average ^{10}Be concentrations in ice as a function of precipitation rate at three locations on the Antarctic plateau (Dome C, South Pole and Vostok). We stress that for the latter two sites the results represent relatively few measurements, and are thus subject to improvement in the future. The most obvious observation that can be made from Table I is that there is apparently an inverse correlation of ^{10}Be

TABLE I. ^{10}Be IN POLAR ICE

Site	Latitude	Average ^{10}Be concentration in ice (10^4 atoms g^{-1})	Assumed precipitation rate (g cm^{-2} a^{-1})	^{10}Be deposition rate ($x10^5$ atoms cm^{-2} a^{-1})
Vostok	78° 28'S	7.9	2.3	1.8
Dome C	74° 39'S	5.0	3.7	1.9
South Pole	90° 00'S	3.0	8.5	2.5
Agassiz	81° 76'N	1.5	17	2.6
Camp Century	77° 11'N	0.75*	35	2.6
Milcent	70° 18'N	1.05**	48	5.0
Dye 3	65° 11'N	0.93***	50	4.7

* Beer and others (1984)
** Beer and others (1983[b]
*** Beer and others (1983[a]

concentration with precipitation rate. This is in contrast with observations involving cosmogenic and bomb-produced radioactive isotopes in precipitation in many locations, where the concentration is relatively independent of the precipitation rate for a given latitude (Lal and Peters 1967). In the present case it is the deposition rate of ^{10}Be which is most nearly constant.

One can think of at least two possible explanations for this peculiar situation in the polar regions. One is that, because of a small stratospheric component (see below), most of the ^{10}Be deposition takes place near the site of its formation in the troposphere. A second explanation would be that a large fraction of the ^{10}Be on the Antarctic plateau is deposited as dry fallout. In the limit of total deposition by this mechanism, it is obvious that the ^{10}Be concentration will be inversely proportional to the precipitation rate. Using nuclear bomb-produced fallout, Pourchet and others (1983) have previously suggested that dry deposition accounts for as much as 60% of total deposition in central Antarctica. To account for our results by this mechanism would require an even larger fraction for ^{10}Be.

We have also included in Table I results of ^{10}Be deposition at the Agassiz Ice Cap on Ellesmere Island, and Camp Century, Greenland, two high-latitude sites in the Arctic. Once again it can be seen that deposition rather than concentration appears most constant, and even the absolute deposition rates are surprisingly similar to the Antarctic ones. In fact between Vostok and Camp Century there is more than an order-of-magnitude difference in precipitation rate, but approximately only a 25% difference in the ^{10}Be deposition rate. At two other Greenland sites included in Table I (Dye 3 and Milcent) the ^{10}Be deposition rates are larger. We feel that this may reflect a greater stratospheric input at these lower-latitude sites, as predicted by the deposition curve of Lal and Peters (1967).

We can now use the above data to try to estimate the influx of stratospheric aerosols to the ice caps. Let us for the moment ignore tropospheric production, and assume that all the ^{10}Be in the ice cores comes from the stratosphere. We thus have

$$D = F.S, \qquad (1)$$

where D is the ^{10}Be deposition rate, F the influx of stratospheric air , and S the concentration of ^{10}Be in the polar stratosphere. We have measured ^{10}Be in 12 high-latitude (58° to 75°) stratospheric air filters (Raisbeck and others 1981[b], and unpublished) and find values ranging from 6.6 to $12.3x10^6$ atoms SCM^{-1}. If we adopt a value of $9x10^6$ atoms SCM^{-1} ($=7x10^3$ atoms g^{-1}) for S, and $2.2x10^5$ atoms cm^{-2} a^{-1} for D, we get F ~ 30 g cm^{-2} a^{-1}. Since the total mass of stratospheric air in the polar regions is ~300 g cm^{-2}, we see that only a very small fraction of stratospheric aerosols are input directly to the ice. Even allowing for a larger ^{10}Be deposition rate in Antarctic coastal regions, the above results would seem to be incompatible with the massive (5 to 6 g cm^{-2} d^{-1}) stratospheric influx rates suggested by Sanak (unpublished) for certain periods at Dumont d'Urville, Antarctica.

Even the stratospheric influx calculated above is clearly an upper limit, however, since we have ignored the ^{10}Be produced in the troposphere. The estimate of this contribution is complicated by the fact that there is still an uncertainty in the total ^{10}Be production rate, with estimates ranging from 1.8 to $4.2x10^{-2}$ atoms cm^{-2} s^{-1} (Raisbeck and others 1979). Using the relationship of Lal and Peters (1967), these give a troposphere production rate in the polar regions of ~1.4 to $3.3x10^5$ atoms cm^{-2} a^{-1}, respectively. Thus we find that tropospheric production can account for anywhere from 60% to essentially all of the ^{10}Be deposition rates observed on the Antarctic plateau and high Arctic sites of Table I. We thus conclude that only a very small fraction of stratospheric aerosols are deposited in these regions (<15% of the global average rate). It will be interesting to see whether a similar distribution occurred in pre-Holocene climates. This information can then be used to help interpret ice-core data of other stratospherically transported species (volcanic emissions, trace metals, dust, etc.).

If the above interpretation is correct, it will also influence the analysis of ice cores as records of ^{10}Be production variations. For example, Beer and others (1984) have interpreted the absence of ^{10}Be variations in the Camp Century ice core during the last 5000 a as evidence that the geomagnetic dipole has not varied significantly in intensity over this period. However, the production variations due to geomagnetic field variations are most pronounced in the equatorial regions, and will only be reflected in polar ice by the input of stratospheric air from these equatorial latitudes. Thus the absence of a geomagnetic signal in the Camp Century ice may simply reflect a small stratospheric component in this ice.

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CONCLUSIONS

The technique of accelerator mass spectrometry permits greatly expanded applications of ^{10}Be and other long-lived cosmogenic nuclides. We have tried above to outline several ways in which such studies can contribute to an improved understanding of present-day incorporation of atmospheric species into polar ice, and to improved interpretation of polar ice records as indicators of past environments. It appears that at latitudes above 74° there is a very small stratospheric influx of aerosols, and that the ^{10}Be deposition rate is much more constant than ^{10}Be concentration.

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