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TEMPORAL VARIATIONS IN COSMOGENIC ^{10}BE PRODUCTION: IMPLICATIONS FOR RADIOCARBON DATING

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ABTRACT. A procedure is outlined for using cosmogenic ^{10}Be variations in polar ice cores and lake or inland sea sediments to correct for ^{14}C production variations in the past. Some of the requirements and problems associated with such a procedure are discussed.

INTRODUCTION

Cosmogenic ^{10}Be, like ^{14}C, is formed by the interaction of primary and secondary cosmic rays in the atmosphere. Unlike ^{14}C, this ^{10}Be is rapidly (~1 year) transferred to geophysical reservoirs, mainly by precipitation. As a result, the ^{10}Be accumulation rate in these reservoirs responds much more rapidly, and with greater amplitude, to changes in the cosmic ray production rate than does ^{14}C in its corresponding reservoirs. A study of the ^{10}Be variations should, therefore, be a sensitive technique for determining ^{14}C production variations, and the resulting correction factors for dating.

In order to carry out the above procedure, it is first necessary to establish a correlation between production variations in ^{10}Be and those in ^{14}C. Until recently, detailed investigations with ^{10}Be (half-life 1.5×10^6 years) were precluded by its very low level of radioactivity. However, we have recently developed an accelerator technique (Raisbeck and others, 1978a,b) that presently allows us to detect as few as 10^7 atoms of ^{10}Be, thus making the required measurements feasible. The most suitable period for establishing a correlation between ^{10}Be and ^{14}C variations is the last ~7000 years, in which tree-ring dated ^{14}C concentrations are available. Once such a correlation is established, ^{10}Be variations at earlier periods can be used to infer corresponding ^{14}C variations. The most favorable reservoirs for making ^{10}Be measurements, and some questions involved, are discussed below.

Source of cosmogenic production variations

Two causes believed to be the most important in giving rise to ^{14}C production variations are changes in the geomagnetic field intensity, and changes in solar modulation (Damon, Lerman, and Long, 1978). Of these, the former is thought to be the most important because, 1) magnitude of the geomagnetic changes is calculated to give larger production variations, 2) these changes occur over a longer time scale, thus allowing a larger adjustment in atmospheric ^{14}C concentration. However, Walton (1979) recently suggested that large, rapid fluctuations in geomagnetic intensity may also have occurred.

These two effects do not cause uniform changes in cosmogenic isotopic production at all points in the atmosphere. Geomagnetic effects

are, of course, most important at the equator, and become negligible near the geomagnetic poles. Solar modulation has its greatest influence on low energy cosmic ray particles, and, thus, is most important near the poles, where such particles have not already been excluded by the geomagnetic field. Production variations are also a function of altitude, with low energy cosmic rays having their greatest influence in the stratosphere, and tropospheric production being dominated by the high energy part of the cosmic ray spectrum. The situation is further complicated by the fact that, while non-gaseous cosmogenic isotopes produced in the troposphere tend to deposit near their latitude of production, those produced in the stratosphere (which represent ~70 percent of the total) are more extensively mixed, and deposit in a pattern controlled largely by stratospheric-tropospheric transfer processes (Lal and Peters, 1967).

^{14}C has a sufficiently long atmospheric residence time (as CO_2) that it is quite effectively homogenized before being incorporated in biophysical and geophysical reservoirs. The same is not true for ^{10}Be. Thus, the quantitative response of ^{10}Be to production variations of the type described above will depend on the location of the reservoir in which it is measured, and, in particular, the relative importance of stratospheric and tropospheric derived fallout at this location. Thus, any correlation that is established between ^{10}Be and ^{14}C variations will, in general, be quantitatively valid only for a given location.

Suitable reservoirs for ^{10}Be measurements

One of the most attractive reservoirs in which to study ^{10}Be production variations are polar ice cores. Such cores offer a continuous, undisturbed record back at least 10^5 years (Johnsen and others, 1972), *ie,* just that period relevant to ^{14}C dating, and with a potential time resolution that should be limited only by the atmospheric residence time of ^{10}Be, (*ie,* ~1 year). The importance of stratospheric fallout at polar latitudes is still uncertain. Lal and Peters (1967) indicate a very small stratospheric component at >70°. However, other authors suggest that stratospheric input in these regions may be very significant (see Maenhaut, Zoller, and Coles, 1979, for a recent discussion). The resolution of this question will have an important bearing on the relative sensitivity of ^{10}Be in polar ice to geomagnetic and solar modulation effects.

We have already begun a program to measure the ^{10}Be profile in an Antarctic ice core which goes back to 30,000 BP (Raisbeck and others, 1978a). We have made over 20 measurements of ^{10}Be in this core, from 0 to 15,000 BP. We did find rather dramatic variations in ^{10}Be concentration, suggestive of geomagnetic influence, and had intended to present those results at this meeting. Most of these measurements were made on samples from meltwater which had been passed through ion exchange filters "on-site", while coring was taking place (Raisbeck and others, 1978a). We have recently been able to show, however, that at least some of these resin filters give lower ^{10}Be concentrations (perhaps due to

saturation of the resin by impurities) than ice samples from the same depth treated in the laboratory. Thus, we are very suspicious of results from the on-site resins, and are remeasuring a complete profile using only ice samples treated in the laboratory. The sensitivity of our technique is now at the point where we can make such measurements on as little as lkg of ice.

Parallel to the ice core studies, we have recently initiated an investigation of ^{10}Be concentrations in rapidly accumulating lake and inland sea sediments. While the time resolution in such sediments will be inferior to that in ice cores, there may be a larger stratospheric component, and, thus, particular suitability for studying long-term geomagnetic variations.

Necessary chronologic information

In order to determine ^{14}C corrections from the type of ^{10}Be data described above, it is necessary to have two types of independent chronologic information. The first is an absolute time scale for the reservoir in which the ^{10}Be is measured. Methods used thus far to establish a chronology for polar ice cores include stable isotope variations, ice flow models, climatic horizons, and extrapolation from well-established precipitation rates near the surface. One hope for the future is that the increased sensitivity of nuclear accelerator spectrometry will permit direct dating of the ^{14}C occluded in the ice. Since we are discussing correction factors for the ^{14}C time scale, this may, at first glance, seem like a circular process. However, because of the very different "damping" factors for ^{10}Be and ^{14}C, this is not really the case. The proposed procedure is to initially use an uncorrected ^{14}C chronology, which is then corrected for production variations on the basis of the ^{10}Be data. Using the modified ^{14}C time scale, the process is then repeated. Because the ^{14}C concentration in the ice is so much less sensitive to production variations than the ^{10}Be, such an iterative procedure should converge rapidly.

The other information needed, at least for short-term variations, is a fine relative time-scale chronology at the location in the reservoir where the ^{10}Be has been measured. This is necessary to ensure that changes in ^{10}Be concentration are not due simply to changes in precipitation (or sedimentation) rates. Because of inherent errors, a ^{14}C chronology could probably never provide this information, except on a fairly coarse time scale. In ice cores, such a fine scale chronology has already been shown to be feasible in some cases using seasonal variation of stable isotope ratios (Johnsen and others, 1972; Hammer and others, 1978). Another interesting possibility that we are presently investigating, would be to use the seasonal variation of ^{10}Be itself in precipitation (Raisbeck and others, 1979). The advantage would be that diffusion effects for ^{10}Be at great depths in the ice are expected to be much smaller than for hydrogen or oxygen isotopes.

With either of the above techniques, we could eventually end up with a "glacial tree ring" record — *ie,* a source of sample in which we

would have both a continuous yearly chronology and the corresponding cosmic ray production rate, without time lag or damping, for a time which potentially could go back 10^5 years. Such a situation would enhance enormously the usefulness of ^{14}C for absolute dating over this period.

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DISCUSSION

Korff: Would one expect differences between hemispheres? Does the stratosphere transfer its contents to the troposphere at a different time in the southern hemisphere?

Raisbeck: The experiment on the monthly precipitation measurements of ^{10}Be were carried out at Orsay (50°N). Because of the different land/ocean ratios in the two hemispheres, the detailed atmospheric circulation patterns are different. However, I would still expect a seasonal maximum in the ^{10}Be deposition rate in the southern hemisphere due to stratosphere-troposphere transfer.

Lal: At the onset, I must congratulate Dr Raisbeck for his pioneering work on ^{10}Be in ice cores. I have two comments:

1. Can the ^{10}Be data be presented also as ^{10}Be atoms per cm^2/yr in addition to ^{10}Be atoms/g snow?
2. Would it be feasible to delineate the month of precipitation from the ^{10}Be concentrations by sampling successive layers within one year's deposition?

Raisbeck: We have presented our data in ice as ^{10}Be concentrations because, to the best of my knowledge, most of the present data on cosmogenic nuclides (including some of Prof Lal's) is more coherently interpreted as being more closely proportional to precipitation rates (at a given latitude) than to time. This certainly appears to be the case for ^{10}Be in precipitation at Orsay, where we have several measurements for the same

month in different years. The ^{10}Be concentrations in these samples are quite constant, despite, in some cases, very different precipitation rates. Prof Lal is, of course, correct in suggesting that a similar dependence must be demonstrated for polar regions before any conclusions can be drawn regarding ^{10}Be in ice.

Currie: Could you comment on the variation of dilution with ^{9}Be as a function of time—is it quite variable?

Raisbeck: I should have emphasized that in our experiments we have always added a quantity of ^{9}Be carrier that is much larger than the ^{9}Be from the sample itself. Because the sources of ^{9}Be and ^{10}Be are different, there is, in fact, no "natural" initial ratio, and this is one of the problems that prevents any direct interpretation of ^{10}Be/^{9}Be ratios in terms of "ages" as is done with ^{14}C/^{12}C.