

The theory is important to interpretations of ice-marginal changes. As developed above, the theory does not directly describe the reaction of the outer portions of ice sheets because the flow there is dominated by bottom sliding. The ice thickness in these outer portions is controlled, in large part, by the supply of ice from the interior. Increased ice export from the central areas, as a delayed response to climatic warming, must be accommodated by ice thickening and an advance of the ice sheet margin. Because of central ice sheet warming, ice sheets are expected to advance some thousands of years after the warming. A marginal advance or at least a thickening of the marginal areas of West Antarctica is therefore expected in the future. The rather rapid final advance of the Laurentide and Scandinavian ice sheets (11) may have been in response to such a warming and not to a cooling, as has sometimes been inferred.

These considerations are important to the interpretation, in terms of climate, of changes in continental ice volumes obtained from studies on ocean bottom cores. A general and simple climatic warming would immediately affect ice volume by increasing net ablation and runoff from the ablation zones. This would be followed, some thousands of years later, by an ice advance and by an increase in the area of ablation zones due to the delayed warming effect on the central ice sheet. The most dramatic decrease in the continental ice volumes may be expected after the climatic warmth penetrates into the central ice sheet and the ice sheet margin subsequently advances.

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perturbation are expended there in more or less ice freezing or melting. Parameters used in the calculations are as follows: ice thickness, 3000 m; vertical velocity, 0.17 m year^{-1} downward at the top surface, decreasing linearly to zero at the bottom; and thermal diffusivity, $1.2 \times 10^{-6} \text{ m}^2 \text{ sec}^{-1}$. The constraint on bottom temperature does not greatly affect the results because, even for an unconstrained bottom temperature, the warming at the bottom is very small after 10,000 years.

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Oceanic Residence Times of Dissolved Beryllium and Aluminum Deduced from Cosmogenic Tracers ^{10}Be and ^{26}Al

Abstract. *The residence times of the soluble fractions of beryllium and aluminum in seawater are estimated to be 1500 years or more. These residence times are estimated from a comparison of the annual deposition rates of cosmogenic beryllium-10 and aluminum-26 with the concentrations of beryllium-10 and aluminum-26 in seawater estimated from the specific activities of these radionuclides in an authigenic mineral assembly such as a manganese nodule. These residence times are greater by an order of magnitude than the mean residence times of beryllium and aluminum estimated from the geochemical balance.*

The relative reactivities of elements in the marine hydrosphere can be determined from a knowledge of the average time an element spends in the oceans (1). Barth (2) and Goldberg and Arrhenius (3) have defined the mean residence time T of an element as

$$T = A/Q \quad (1)$$

where A is the total quantity of the element in the sea and Q is its rate of introduction or removal; in the steady state, these two rates become equal and either can be used (4). As a first approximation, Goldberg and Arrhenius considered a single cycle of introduction and deposition, and estimated the residence times of 15 major and minor elements. The results obtained were found to vary between 2.6×10^8 years for the most soluble element, Na, and between 100 and 160 years for the most quickly precipitating elements such as Al, Fe, and Ti. Using the same method, Merrill *et al.* (5) estimated the residence time of Be to be 150 years (6).

Arnold (7) has examined the usefulness of more complex models, in particular, one that consists of three independent cycles: a cycle for the soluble fraction (including exchangeable sorbed ions), an inshore particulate cycle, and a pelagic particulate cycle. He concluded that the bulk of each of the three elements, Al, Fe, and Ti, pass through the ocean in particulate form, so that their residence times are largely controlled by the particulate cycles. Assuming a very

short residence time for the nearshore particulates, Arnold deduced that the residence time of the pelagic clay particles may be much more than a hundred years and therefore comparable to the estimated general mixing time for the oceans (which is on the order of 10^8 years). This residence time may therefore represent a geophysical phenomenon, the mixing of the oceans, through which the residence times for nearly all elements in particulate form should be about the same (8).

The true reactivity for each element should therefore be reflected in the residence time of the soluble fraction. Since the particulate cycles dominate over the cycle for the soluble fraction for Al, Fe, and Ti, however, it has been very difficult to estimate the residence time of the soluble fraction from classical considerations of the geochemical balance of each element. We propose here the use of the naturally occurring radioactive tracers ^{10}Be and ^{26}Al for this estimate. These nuclides are produced by the bombardment of atmospheric constituents by cosmic rays. Their half-lives [1.5×10^6 years for ^{10}Be and 0.716×10^6 years for ^{26}Al (9)] are long enough so that the radioactive decay is negligible in comparison with the residence times in the marine hydrosphere.

We consider an average 1-cm² column in the ocean. We use Eq. 1, but here A is the total quantity of ^{10}Be (or ^{26}Al) in the column and Q is the annual deposition rate of ^{10}Be (or ^{26}Al) per square centime-

ter. In the steady state, Q is equal to the production rate of ^{10}Be (or ^{26}Al) in the atmosphere (in the case of ^{26}Al , there is a small but practically negligible contribution due to cosmic dust bearing ^{26}Al) (10). The influx rates of ^{10}Be and ^{26}Al have been estimated to be 4.7×10^{-7} and 5.3×10^{-9} dpm cm^{-2} year^{-1} , respectively (10, 11).

The total quantity of ^{10}Be (or ^{26}Al) is the product of its concentration in seawater and the volume of the average 1- cm^2 column (380 liters). Up to the present, however, as far as we know, no direct measurements of ^{10}Be and ^{26}Al concentrations in seawater have been made. We can estimate these concentrations, nevertheless, by assuming that (i) the tracer equilibrium between dissolved Be and ^{10}Be (and also between Al and ^{26}Al) is established in seawater and (ii) the Al and Be contents of authigenic mineral assemblages such as Mn nodules originate from seawater (12), so that the specific activities $^{10}\text{Be}/\text{Be}$ and $^{26}\text{Al}/\text{Al}$ in such authigenic minerals represent those of the seawater at the moment of mineral formation. We have measured the activities of ^{10}Be and ^{26}Al in the Techno-1 Mn nodule dredged at a depth of 4020 m at the north end of the Tuamotu archipelago (13). The activities extrapolated to the surface were 25 ± 2 dpm of ^{10}Be per kilogram and 0.3 ± 0.2 dpm of ^{26}Al per kilogram; these values correspond to specific activities of 5×10^3 dpm of ^{10}Be per gram of Be and 4×10^{-2} dpm of ^{26}Al per gram of Al. The Be and Al contents of the nodule are 5 ppm and 0.8 percent, respectively (13, 14).

The concentrations of dissolved Be and Al in open ocean waters have been determined by Merrill *et al.* (5), Alberts *et al.* (15), and Hydes (16) as 3.9×10^{-10} and 5×10^{-7} g liter^{-1} , respectively. If these concentrations are multiplied by ^{10}Be (or ^{26}Al) specific activities, we estimate the ^{10}Be and the ^{26}Al concentrations in seawater to be 2×10^{-6} and 2×10^{-8} dpm liter^{-1} , respectively. The residence time of ^{10}Be is then calculated from Eq. 1 as

$$T = \frac{2 \times 10^{-6} \times 380}{4.7 \times 10^{-7}} = 1600 \text{ years}$$

and that of ^{26}Al as

$$T = \frac{2 \times 10^{-8} \times 380}{5.3 \times 10^{-9}} = 1400 \text{ years}$$

There will be a large uncertainty in the estimate of the ^{26}Al residence time because of the large statistical errors in the ^{26}Al measurements. Nevertheless, the good agreement found between the ^{10}Be and the ^{26}Al residence times is most

likely due to the similarity in geochemical behavior of the two nuclides in seawater.

Our values represent the residence times of the soluble fraction. McCorkell *et al.* (17) have shown that ^{10}Be and ^{26}Al in Greenland ice are present in soluble form. Moreover, Silker *et al.* (18) have shown that the major fraction of cosmogenic ^7Be is present in seawater in a soluble form; this presumably holds for ^{10}Be and ^{26}Al also. The residence times of dissolved Be and Al are therefore greater by an order of magnitude than the mean residence times of Be and Al calculated in the manner of Goldberg and Arrhenius (3) (about 150 years). The mean residence time of 150 years is the average of those of the soluble and the particulate fractions, and so it reflects the short residence time of particles, especially those near the shore.

Merrill *et al.* (5) estimated the residence time of the soluble fraction of Be to be 570 years by assuming that all Be occurring in pelagic clays originates from the soluble fraction in seawater. If we take into account in the calculation of Merrill *et al.* the fact that there is probably some Be in detrital minerals of pelagic sediments, there should be a better agreement between our estimates and that of Merrill *et al.*

Our estimates are based on the assumption that all Be and Al in the nodule originate from seawater. If a part of these elements derives from other sources such as detrital matter or hydrothermal waters, the specific activities $^{10}\text{Be}/\text{Be}$ and $^{26}\text{Al}/\text{Al}$ in seawater would be higher than those in the Mn nodule, which would result in even longer residence times. Therefore, the value of about 1500 years is a lower limit (19). In addition, on a time scale of 1500 years, regional fluctuations of a factor of 2 or more seem possible. The low ^{10}Be deposition rate in the Arctic Ocean reported by Finkel *et al.* (20) may be due to an extreme oceanic environment, such as a quasi-permanent ice cover or a lack of scavengers.

The apparently similar mean residence times of Be, Al, Fe, Ti, and Th (about 100 years) is mainly due to the particulate cycles, whereas the residence time of the soluble fraction really reflects the differences or similarities in the chemical behavior of these elements. An example can be seen in the extremely short residence time of dissolved Th (70 years or less) (21) as compared with the relatively long residence times of dissolved Be and Al (1500 years or more) deduced here.

Our estimated relatively long residence times of Be and Al strengthen the

validity of ^{10}Be and ^{26}Al dating of marine deposits, because one can expect a better homogeneity of these isotopes in seawater with a longer residence time. The use of a cyclotron to detect very small quantities of ^{10}Be and ^{26}Al has recently been proposed by Muller (22). This method should be useful for the direct measurements of these nuclides in seawater.

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