COSMIC RAY INTERACTIONS IN THE GROUND: TEMPORAL VARIATIONS IN COSMIC RAY INTENSITIES AND GEOPHYSICAL STUDIES; D. Lal, Scripps Institution of Oceanography, Geological Research Division, A-020, La Jolla, CA 92093 (USA).

Temporal variations in cosmic ray intensity have been deduced from observations of products of interactions of cosmic ray particles in the moon, meteorites, and the earth (1). Of particular interest is a comparison between the information based on earth and that based on other samples. Differences are expected at least due to (i) differences in the extent of cosmic ray modulation, and (ii) changes in the geomagnetic dipole field. Any information on the global changes in the terrestrial cosmic ray intensity is therefore of importance. As an illustration, it is generally believed that the slow variation in $^{14}C/^{12}C$ ratios as observed in tree rings is indicative of an appreciable change in the earth's dipole field during the past 10,000 yrs (2). However, I have recently shown (3), on the basis of theoretical considerations and oceanic paleodata covering the past glaciation, that climate-induced changes in the carbon cycle are large and may be responsible for a greater part of the observed variation. To check on this, one would have to study the temporal variations in the production rate of another terrestrial cosmic ray-produced isotope. One of the obvious ways to achieve this goal is to study the temporal variations in the fallout of an isotope. The potential usefulness of ^{10}Be for this purpose was explored earlier (4) and also recently (5). However, this method presents some difficulties since the fallout of ^{10}Be depends also on meteorological factors (6).

In this paper we present another possibility of detecting changes in cosmic ray intensity. The method involves human intervention and is applicable for the past 10,000 yrs. Studies of changes over longer periods of time are possible if supplementary data on "age" and history of the sample are available using other methods. We also discuss the possibilities of studying certain geophysical processes, e.g. erosion, weathering, tectonic events based on studies of certain cosmic ray-produced isotopes for the past several million years.

(a) Cosmic ray intensity studies. A direct method of measuring cosmic ray intensity on the earth will be to measure the activation products in a sample exposed to the secondary cosmic ray beam for a known period of time, in a known geometry at atmospheric depth, x ($gm \cdot cm^{-2}$) and geomagnetic latitude, λ. At great depths in the atmosphere, the nucleonic component attenuates with a mean free path of 165 $gm \cdot cm^{-2}$. Consequently, samples which are buried underground at depths exceeding 10 m.f.p. (5-6 meters of typical surface materials) will be appreciably shielding so that the unshielded production over periods of the order of (10^3-10^4) yrs will considerably exceed the earlier production. The in-situ production of ^{10}Be, ^{26}Al, ^{36}Cl, ^{3}H and other isotopes can be conveniently measured in rocks exposed for periods of the order of 10^3 yrs, in samples of the order of 100 grams. This is based on production rates given earlier (6).

We therefore propose that changes in the cosmic ray intensity can be directly measured from a study of in-situ production of radionuclides in documented samples. A number of possibilities arise; one of the obvious possibilities is to study the pyramidal stones. The pyramids at Dahsur and Giza seem ideal for providing samples exposed for (4500-4600) yrs. The low latitude of the pyramids is favorable for studying decreases in geomagnetic dipole field. Tree rings may also serve as ideal in-situ materials for isotope ^{10}Be in particular. Of course, it would have to be ascertained that no appreciable contributions arise from ^{10}Be in ground waters. Geological specimens, e.g. volcanics may well provide ideal samples exposed in fixed geometry for longer periods of time, (10^4-10^5) yrs.

The in-situ method proposed above was considered earlier (7) for the study of long term variations in the flux of high energy primary cosmic rays (E >130 GeV). The present proposal for studying variations in the low energy flux of cosmic rays, in the GeV region which is sensitive to changes in the earth's dipole field, is being made for the first time. This would supplement any information based on the fall-out of nuclides, such as that based on ^{10}Be in polar ice (5).

(b) Geophysical studies. Considering the present detection limits for several isotopes, in the range of 10^5-10^6 atoms (8), one can investigate production rates of $\gtrsim 10^{-11}$ atoms/g·sec in a sample of 1 Kg exposed for a period of 10^6 yrs.

At sea level, the nuclear reactions are produced primarily by neutrons and negative mu-mesons (6). At depths exceeding 2-3 meter rock equivalent, fast mu-mesons and slow negative mu-mesons (captures by nuclei) produce most of the nuclear reactions; neutrons are not important at these depths. Fast mu-mesons produce nuclear disintegrations with larger kinetic energy dissipation in the spallation products than in the case of capture of negative mu-mesons. The nuclear disintegration rate at a depth of say 25 meters rock equivalent is about 2×10^{-9}/gm·sec (6, 7). Compared to sea level, this is lower by a factor of 10^4, but nevertheless such disintegration rates can be monitored using present day atom detection methods.

The main aim of the study (9, 10, 11) would be to measure departures from equilibrium concentrations and then determine the rates of geophysical processes responsible using certain models. If, for example, a sample of rock exposed to elements is continually undergoing weathering, the in-situ cosmic ray production rate of isotopes at a test point will change in view of the reduction in the overlying amount of rock. Let Q(t) be the rate of production. The concentration of a radionuclide in the rock, C(T), after an elapse of time T will then be given by the convolution integral

$$C(T) = C(0)\, e^{-\lambda T} + \int_0^T Q(t)\, e^{-\lambda(T-t)}\, dt \qquad (1)$$

where λ is the disintegration constant of the nuclide and C(0) is the concentration of the nuclide at t = 0. If one isotope is measured, equation (1) can put some constraints in the temporal changes in the rock geometry due to physical processes. It is clearly advantageous to study as many isotopes as possible and also call on supplementary geophysical evidence to model the isotope production with changing geometry of irradiation, due to geophysical processes.

The crux of application of in-situ production of cosmic ray nuclides to geophysical studies lies in equation (1) and the capabilities to model Q(t) in a realistic manner. If this can be achieved, a number of applications should become possible:

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i) Rates of erosion of exposed rocks and problems of similar nature involving changes in rock geometry (fragmentation of rocks, sediment burial/denudation, etc.).
ii) Tectonic uplift or subduction.
iii) Residence time of materials in particular settings, e.g. ages of glaciers, and turn-over time of sand dunes.

We will present worked out examples to support the above suggestions, and indicate the type of information which is possible with the isotopes which can currently be detected with high sensitivity. Reference is made to the first application of the method by Hampel et al. (10) to study rock erosion rates, and to a paper by Jha and Lal (11) who have specifically considered the application of ^{10}Be and ^{26}Al to the study of tectonic movements. These isotopes should allow convenient study of vertical movements in the range $(10^{-4}-10^{-5})$ $cm \cdot yr^{-1}$.

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