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Interpreting the Production of ^{26}Al in Antarctic Meteorites

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INTERPRETING THE PRODUCTION OF ^{26}Al IN ANTARCTIC METEORITES

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Large numbers of meteorites have been concentrated at several locations in Antarctica. Glaciological mechanisms of grossly different time scales ($\sim 10^4$ to $\sim 10^6$ years) have been proposed to account for their transport by the ice, and the frequency distribution of the terrestrial ages of these objects has been suggested as a means of determining the relevant time scale(s). The upper limit to the age of ice in Antarctica which would emerge from such a project is of interest to workers in a variety of other disciplines as well. After a meteorite reaches the Earth's surface, the specific radioactivity of ^{26}Al produced by cosmic rays while it was in space decreases because shielding by the Earth's atmosphere reduces further production to a negligible level. Thus, the known half life of this species can be used to determine the object's terrestrial age if the specific radioactivity at time of fall can be estimated with reasonable accuracy and precision. The several models utilized for these predictions were based on the limited data available nearly two decades ago. In this work we have critically examined the much larger data base now available using multiple parameter regression analyses.

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INTRODUCTION

Meteoroids are subject to bombardment by high energy particles while in free space. Such projectiles include both galactic cosmic rays (GCR) and solar particles (SP) which can induce nuclear reactions that result in the transformation of some of the stable nuclei of the target to radioactive product nuclei. After the meteorite reaches the earth's surface, production of the radioactive species is esentially stopped because of the shielding effect of the earth's atmosphere against primary GCR and SP. The specific radioactivity of a given nuclide in a particular portion of a meteorite is dependent upon a number of variables: chemical composition, position in the meteorite with respect to the preatmospheric surface, the primary projectiles' intensity vs. energy spectra time dependence during exposure, etc.

Discovery of the accumulation of large numbers (~5000) of meteorites in ablation zones on the Antarctic ice sheet has lead to interest in using these objects as relict tracers for the mechanism of ice transport. It seems likely that these accumulations result when meteorites which have fallen randomly over the Antarctic surface and were incoporated into and transported with the glacier ice are left behind on the surface as this ice is lost in the ablation zone of the particular sheet. Thus, determination of the time scale for ice movement is possible if the "terrestrial age" i.e. (the time each meteorite has been on earth) can be established. The decay of a radioactive species produced in space provides a suitable "timer-clock", assuming the amount present at fall can be estimated with reasonable accuracy and precision. Interest has been focused on ^{26}Al because it has a half-life consistent with the the time scales (10^4 - 10^6) proposed for the ice transport from the fall zones to the ablation zones [1-6]. The understanding of time scales in Antarctic glaciology is of interest beyond that discipline. The identification of ice of such great age would provide dated samples for particular ocean sediment and paleoclimatogoly studies as well as for investigation of paleoatmospheric composition [e.g. 7].

Determination of the glaciological mechanism involved for a particular ice sheet would involve:

1. collection of $\sim 10^{2.5}$ meteorites from the ablation zone;
2. measurement of the current ^{26}Al specific radioactivity (D_o) in each meteorite non-destructively via gamma-gamma coincidence spectrometry to a precision of ~10%;
3. estimation of the ^{26}Al saturation specific radioactivity (D_{oo}) present at fall based on the chemical composition of the object;
4. calculation of the terrestrial age (elapsed time between fall and present) for each meteorite based on present and saturation ^{26}Al values;
5. interpretation of the terrestrial age frequency distribution observed in terms of those expected for postulated transport mechanisms.

This work has been concerned primarily with item 3. In particular, we sought to determine whether published formulae yield D_{oo} estimates sufficiently accurate and precise to permit the time resoltuion in terrestrial ages for required useful conclusions regarding glaciological mechanisms to be drawn.

ESTIMATION OF SATURATION ^{26}Al SPECIFIC RADIOACTIVITY

This problem was first addressed systematically by Fuse and Anders [8] nearly two decades ago. A regression of observed ^{26}Al D_o versus Si, Al, and S content was performed for 34 meteorites assumed to have long exposure ages, with contributions due to Ca and Fe+Ni assumed to be known. Contributions from other elements, including Mg, were assumed to be negligible.

Two years later a different approach was taken by Cressy [9], who used the D_o and elemental composition of eight fractions separated from a single meteorite as the set of observations. The independent variables in Cressy's regression were Mg, Al, and Si, with contributions due to S, Ca, and Fe+Ni assumed to be known.

In 1980, Hampel, et al. [10] used six fractions obtained from three meteorites to derive a third set of coefficients for Mg, Al, and Si, while assuming the values for S, Ca, and Fe+Ni to be known.

Keith and Clark [11] made such an analysis on a set of moon rocks in 1974, but the obvious differences in irradiation conditions (2pi vs. 4pi) and sample surface preservation (atmospheric ablation at fall) cause uncertainty as to the applicability of those results to meteorites.

In order to facilitate comparison of the results of the models cited, each set of coefficients (a_i) has been normalized to yield a_{Si} = 1. These results are shown in Table 1, and it is obvious that the three sets based on meteorites are quite disimilar, with the coefficient for such a significant element as Al varying by a factor of 3.

These discrepancies may be due to the small numbers of meteorites considered in two of the studies, to differences in exposure conditions or data selection criteria, and/or to the use of inadequate chemical data. (It might be noted here that cases such as those faced here, where the independent variables show considerable covariance amongst themseves, are particularly prone to yielding biased results from small and/or poor quality data bases.) Therefore, it seems worthwhile to assemble as large a data base as feasible (within a reasonable time) from which to assess the three models proposed. Reported ^{26}Al specific radioactivities numbering over 500 for 299 non-Antarctic meteorites have been obtained from the literature along with 203 (full or partial) chemical analyses and 165 ^{21}Ne cosmic ray exposure ages. Where more than one value for a parameter has been found, the mean value was employed in this study. In a few cases, extreme deviant values were rejected prior to taking the mean. All results reported here were obtained using SAS running under VMS 5.03 on the NASA Johnson Space Center Solar System Exploration Division's VAX 11/780 during the period 19 May to 8 August 1986.

The efficacy of the published models in accounting for the variability in observed ^{26}Al specific radioactivty due to variation in chemical composition was determined in the following manner. For each meteorite of known exposure age (t), the predicted value of the ^{26}Al saturation specific radioactivity was calculated via the prescription for each of the models (D_{pi}), and the observed D_o value was corrected to the saturation value (D_{oo}) as follows:

$$D_{oo} = D_o/(1-T) \quad \text{where } T = \exp(-R) \text{ and } R = t*\ln(2)/t_{26}$$

t_{26} being the known half life of ^{26}Al (0.72 Ma). The extent to which the ratio of D_{pi} to D_{oo} conforms to unity is a measure of the accuracy and precision of the model in predicting the parameter of interest.

Results for the mean value of this ratio over all meteorites for which exposure ages were available in the data base are presented in Table 2, along with their precisions. Although each of the models provides agreement within 15% of the desired D_{oo} value, the large size of the data base provides sufficient precision to confirm that the deviation from the desired value of unity is significant for each of the models. This indicates the presence of systematic errors. If the principal cause of these discrepancies is variation (or inaccuracy) in chemical compositions, a significant difference in D_{pi}/D_{oo} would be expected among the different classes of meteorites. Mean values for the ratio of interest for meteorites of known exposure age in several major classes are also presented in Table 2, and it is seen that such variation is absent.

In view of the systematic deviations found for predictions from the published models, the recent increase of interest in this problem, and the ready availability of the large data base assembled in this work, it seems worthwhile to perform a new search for a more accurate formula for the prediction of D_{oo}. Such a search was undertaken with quite interesting results. Inverse variance weighted and unweighted regressions of the experimentally derived saturation specific radioactivty values for ^{26}Al vs. a number of parameters were performed. Presentation of the detailed results of this work is beyond the scope of this report, but the following equation has been found to fit the experimenatal data base with an R-squared of 0.96:

$$D_{oo} = (3.0 \pm 0.5)*Si + (3.6 \pm 1.9)*Al + (0.1 \pm 0.5)*Mg$$

where the chemical symbols stand for the respective elemental abundances in % by weight. This regression was based on 81 cases for which the specific radioactivity of ^{26}Al, the ^{21}Ne exposure age, and

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the three elemental abundances were all known.

Since the data base includes finds (i.e. objects identified as meteorites but which have not been observed to fall), as well as observed falls, it is worthwhile to see if both subpopulations show the same systematic deviation. The results shown in Table 3 indicate that the mean values for the ratio of interest are significantly different for falls and finds. From this disagreement we infer that the frequency of finds with D_o significantly less than D_{oo} (i.e. those unsaturated at fall plus those with terrestrial age greater than about 0.2 Ma) is greater than the frequency of unsaturated falls (~8%). Therefore, the inclusion of finds as well as falls would appear to bias the data base toward lower D_{oo} values . This is an important conclusion because all of the Antarctic meteorites recovered to date are finds for most of which there is an absence of measured exposure ages.

CONCLUSIONS

It has been shown in this work that there is a systematic bias in estimates of the amount of ^{26}Al expected to be present at fall in a meteorite of known major element composition when previously published formulae are employed. The mean specific radioactivity of this nuclide in finds was also found to be distinguishable from that of falls. An improved formula for estimating the saturation specific radioactivty of ^{26}Al expected to be present at fall has been derived from the large data base on non-Antarctic meteorites established for this study. Despite the relatively poor precision yielded by any of the formulae, estimates of this quatity were found to be adequate for use in distinguishing between the principal proposed mechanisms for Antarctic glacier ice transport between the accretion and the ablation zones. Further non-destructive radioactivity measurements in order to establish a large data base for Antarctic meteorites from each of the ice sheets of interest would be a logical next goal.

Table 1. Comparison of Elemental Coefficients in ^{26}Al Estimation Models

Model	Normalized Model Target Coefficient*					
	Mg	Al	Si	S	Ca	Fe+Ni
Fuse & Anders	=0	1.5	=1	.12	=.02	=.007
Cressy	.11	4.6	=1	.54	=.10	=.009
Hampel, et al.	.15	1.8	=1	=.49	=.09	=.011

* = means parameter was set equal to relative value given by original authors and was not a free variable in their regression except the coefficient for Si which was adjusted to unity in this work for ease of comparison.

Table 2. Comparison of Model-predicted Radioactivity by Meteorite Class

Model	Saturation ^{26}Al (Experimental/Predicted) by Class ± 1 s(m)*			
	H	L	C	All
Fuse & Anders	.92 ± .02 (22)	.90 ± .04 (15)	.93 ± .03 (13)	.90 ± .02 (65)
Cressy	.91 ± .02 (22)	.89 ± .04 (15)	.86 ± .07 (13)	.89 ± .02 (65)
Hampel, et al.	.91 ± .02 (22)	.88 ± .04 (15)	.90 ± .03 (13)	.88 ± .02 (66)

* inverse variance weighted mean values ± one sigma of the mean taken over the number of meteorites of known exposure age given in parentheses.

Table 3. Comparison of Model-predicted Saturation Specific Radioactivities

Model	^{26}Al (Experimental/Predicted) Ratio $\pm$ 1 s(m)* Finds	Falls
Fuse & Anders	.81 $\pm$ .06 (19)	.91 $\pm$ .02 (100)
Cressy	.78 $\pm$ .06 (19)	.85 $\pm$ .02 (100)
Hampel et al.	.78 $\pm$ .05 (21)	.88 $\pm$ .02 (103)

* weighted mean of observed values (uncorrected for nonsaturation) $\pm$ one sigma of mean based on number of meteorites in parenthses.

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