

ACCUMULATION AND ISOTOPIC EVOLUTION OF CARBON ON THE LUNAR SURFACE

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Whereas the regolith at most Apollo landing sites is a heterogeneous mixture of chemically, and petrographically, distinct components, soil from the Apollo 16 site at Cayley-Descartes is more nearly homogeneous with respect to distribution of the major rock-forming elements (1). Apollo 16 soil samples may therefore be regarded as monitors for the interaction between the lunar surface and the interplanetary medium, with less risk of secular changes being masked by chemical or mineralogical differences. We exploit this feature to follow the development with time of the extralunar contribution to the abundance and isotopic composition of carbon.

The first step in our approach is to construct a model describing the accumulation of C in the lunar regolith as a function of time and the corresponding evolution of its ^{13}C content, expressed as $\delta^{13}\text{C}$. Then, since we lack a reliable measure of the surface exposure age of each sample, we eliminate this term by expressing C abundance as a function of $\delta^{13}\text{C}$. Finally, the model relationship between C and $\delta^{13}\text{C}$ is compared with data for Apollo 16 samples (2,3)

In constructing the model we make the following assumptions;

- (1) Only the solar wind is considered as a source of extralunar C.
- (2) Some loss of C occurs as a result of hydrogen stripping. Solar wind H reacts with implanted C to form CH_4 most of which is subsequently lost by thermal diffusion. Isotopic fractionation occurs at this stage as a result of the mass dependence of the diffusion process.
- (3) Agglutination converts a proportion of the surficial, implanted C into a volume-correlated fraction, shielded from stripping. During agglutination C is lost from the molten material with no isotopic fractionation.
- (4) Impact comminution causes the surface area of lunar soil to increase with time, until balanced by the competitive effect of agglutination.
- (5) "Recycling" of formerly volume-correlated C to fresh surfaces is ignored.

An expression for C content in terms of the various processes described above has been derived, but because of its length we simply state here the resulting equations for surficial, C_s , and volume, C_v , carbon in terms of t which we define as the average, cumulative residence time of a constituent grain on the very surface.

$$C_s(t) = \frac{Fq}{P+K} [1 - e^{-(P+K)t}] [A_0 + A(1 - e^{-Bt})]$$

$$C_v(t) = \frac{(1-y)FqP}{P+K} \left[\frac{(A_0+A)(1 - e^{-yPt})}{yP} + \frac{A(e^{-yPt} - e^{-Bt})}{yP - B} \right. \\ \left. + \frac{(A_0+A)(e^{-(P+K)t} - e^{-yPt})}{(1-y)P + K} + \frac{A(e^{-yPt} - e^{-(P+K+B)t})}{(1-y)P + K + B} \right] + C_0 e^{-yPt}$$

F = flux of C in the solar wind. A value of $5 \times 10^{-5} \mu\text{g cm}^{-2} \text{y}^{-1}$ is derived from Cameron's cosmic abundances (4) and the measured solar wind proton flux.
 q = shape factor, since only one side of a grain is irradiated at a time. A value of 0.25 is taken.

A_0 = geometrical surface area of pristine ejecta, and

A = increase in surface area on maturation. Comprehensive measurements of

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surface areas are not available for lunar soils. However, measurements of mean grain size for mature and immature soils (5) suggest that maturation roughly doubles the initial surface area, so that the geometrical surface areas measured for mature soils, about $200 \text{ cm}^2 \text{g}^{-1}$ (6), lead to values for A_0 and A of about $100 \text{ cm}^2 \text{g}^{-1}$.

y = fraction of material melted, and presumably decarbonised, during agglutination. Microscopic examination of agglutinates suggests a value of about 0.5.

P , K and B are constants describing the rate of agglutination, hydrogen stripping and maturation of surface area, respectively. Some tentative values are presented, pending more complete computer matching of coefficients based on additional experimental data. Values for K of $\sim 10^{-5} \text{y}^{-1}$ were found to give reasonable results. Achievement of a mature surface area represents equilibrium between impact comminution and growth by agglutination. Thus B is closely related to the rate of agglutination, P , and initially the two are equated. We suspect that agglutination operates at a somewhat slower rate than does H stripping on account of the observation that $\delta^{13}\text{C}$ appears to approach rapidly to a "saturation" value (3). A value of $5 \times 10^{-6} \text{y}^{-1}$ is thus assigned to both P and B .

Calculation of ^{13}C abundance, and hence $\delta^{13}\text{C}$, follows that for ^{12}C by adopting a value of $5 \times 10^{-7} \mu\text{g cm}^{-2} \text{y}^{-1}$ for F and a value for K which is related to that for ^{12}C by the reciprocal square roots of the isotope masses (in the form of methane), i.e. $0.97 \times K(^{12}\text{C})$. Delta values thus calculated are relative to the $^{13}\text{C}/^{12}\text{C}$ ratio arbitrarily assumed for the solar wind. The initial value of $\delta^{13}\text{C}$ for indigenous lunar C has a negligible effect on the values eventually achieved.

Figure 1 shows the relationship between C abundance and $\delta^{13}\text{C}$ predicted by the model, together with data for Apollo 16 samples (2,3). Because isotope results are measured relative to the PDB standard, calculated values have been translated onto the PDB scale. We have attempted this by assigning two alternative values to K and by constraining the model curves to pass through the point (180 ppmC; $+13^\circ/\text{ooPDB}$), representative of a mature soil. The data are better matched by $K = 10^{-5} \text{y}^{-1}$ but a value of $1.8 \times 10^{-5} \text{y}^{-1}$ yields a value for the initial isotopic composition of the solar wind which is in line with our recent estimate (3). The general shape of the theoretical curve is followed reasonably well by the experimental data, despite some scatter. Note that samples 61221 and 67461 are, for various reasons, considered to be anomalous (2,3). A tendency for the lunar samples to exhibit more isotopic fractionation than predicted may be due to some diffusional loss of C in addition to that resulting from H stripping, e.g. during agglutination. The time associated with the maximum C enrichments found in Apollo 16 soils, $5 \times 10^5 \text{y}$, is barely compatible with the age of the regolith and the turnover rates inferred from drill stem data. However, this derived time is governed by the value taken for the cosmic abundance of C, for which an uncertainty of a factor of four is probably realistic. Note that, during the period of evolution of regolith grain size towards its equilibrium value, our measure of sample "age" is not linearly related to others such as cosmic ray exposure age.

The model presented above is in general agreement with qualitative

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pictures suggested by Epstein and Taylor (2) and Moore et al (7). We have not yet attempted a rigorous comparison with the predictions of the model presented by DesMarais et al (8), in which the effect of agglutination on C accumulation is considered, but not the effect of H stripping or the isotopic consequences.

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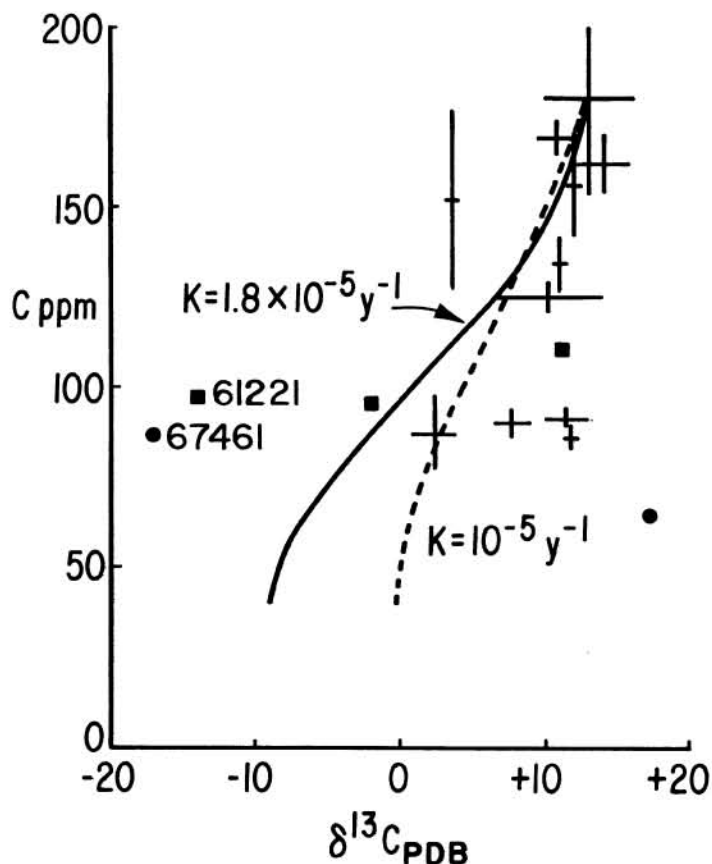


Figure 1. Comparison of theory and experiment. The predicted relationship between C abundance and $\delta^{13}\text{C}$ is matched reasonably well by the experimental data. Square symbols represent data from Ref 2, all other data from (3). A value of 40 ppm was taken for indigenous carbon, C_0 , at the Apollo 16 site (3).