rivers" to 50 percent for "flash floods" in desert streams. The energy required to support small particles is directly proportional to the square of the gravitational acceleration (13). Therefore we would expect on Moon, where the gravitational acceleration is 0.16 times that on Earth, the load fraction to be increased by a factor of 36 above that of terrestrial rivers of the same velocity. Thus even "sluggish" lunar rivers could be expected to have a load fraction of 10 percent. The volumes of both Rima Prinz I and II are of the order of 10¹⁰ m³. With a specific gravity of about 3 for the eroded material and a load fraction of 10 percent, the volume of water required to excavate such a rill is 3×10^{11} m³. For the range of flow thus deduced, times of the order of 10 to 10³ years are required for excavation of these features.

It was implicit in the foregoing discussion that the lunar surface material is easily erodible, so that the time for the formation of the rills was simply the time required for carrying away of the material. Measurements by Surveyor and others indicate that at least the top several centimeters of the lunar surface is composed principally of particles finer than sand (finer than 100 μ) (14), and that these particles are bonded with cohesive forces of the order of 10^3 dyne cm⁻² (9), and loosely packed, with a void fraction greater than 50 percent (9, 11). Material of such strength and size would be easily disintegrated and transported. Moreover, since the walls of the rills have angles of repose of less than 35 deg (comparable to that of sand), such weakly bonded material may extend to depths of a few hundred meters, at least in regions where the rills have occurred.

Finally, because there is no abrupt change in gradient at the end of the rills, we would expect deposition of the stream load to be relatively thin and to cover a large area similar to deposition in the sinks of the Humboldt and Mojave rivers in the western United States. Collapse and filling of voids in the porous mare surface, and overall subsidence, also may be significant. The higher rims of the large craters in this region would prevent their being filled with sediment, whereas the higher influx of smaller meteorites could soon saturate the surface with small craters and obliterate any outline of the region. On a geologic time scale, the area of the deposits soon would be indistinguishable from the surrounding mare.

Thus the presence of sinuous rills on the lunar surface may be interpreted as evidence of the existence of a subsurface layer of permafrost which may still retain considerable amounts of other volatiles trapped water and beneath.

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- The equilibrium conditions are determined by the following equations. The mass-loss rate 7. through sublimation at the upper surface is in grams per square centimeter per second

 $\dot{m}_U = 6.12 \times 10^9 T_U^{-1/2} \exp(-6110/T_U)$

where T_U is the temperature (degrees Kelvin) at the upper surface. If the radiant energy is absorbed at the upper surface of the ice, the freezing rate at the lower surface

$$\dot{m}_L = k(T_L - T_U)(L_S d)^{-1}$$

whereas if the radiant energy is absorbed in the water

$$\dot{n}_L \equiv k(T_L - T_U)(L_S d)^{-1} - qL_S^{-1}$$

where T_L is the temperature of the lower surface $(273^{\circ}K)$, k is the thermal conductivity of ice $(0.006 \text{ cal cm}^{-1} \text{ deg}^{-1} \text{ sec}^{-1})$, d is the equilibrium depth (in centimeters) the ice layer, L_s is the latent heat of fusion (80 cal g^{-1}), and q is the incident flux of radiant energy (calories per square centimeter per second). For surface absorption, the sublimation rate at the top surface

$$\dot{m}_U = [k(T_L - T_U)d^{-1} + q - \sigma T_U^4]$$

and for absorption in the water

$$\dot{m}_U = [k(T_L - T_U)d^{-1} - \sigma T_U^4]$$

$$(L_S + L_V)^{-1}$$

where σ is the Stefan-Boltzmann constant (1.36 \times 10⁻¹² cal cm⁻² deg⁻⁴ sec⁻¹), and (1.36 \times 10⁻¹² cal cm⁻² deg⁻⁴ sec⁻¹), and L_V is the latent heat of vaporization (600 cal g⁻¹). From these expressions one can determine \dot{m}_U (equal to \dot{m}_L) and T_U as a

function of q. 8. The thermal-diffusion time, τ d^2/α , is approximately 1 year where α is the thermal diffusivity of ice (0.015 cm² sec⁻¹); since this time is longer by an order of magnitude

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- Only 20 cal is required to raise the temperature of 1 cm³ of lunar subsurface material (specific heat, 0.2 cal g⁻¹ deg⁻¹; density, 3 g cm⁻³) from --30° to 0°C. Thus the volume (a) cm⁻³) from -30° to 0°C. Thus the volume of ice produced by warming of 1 cm³ of the solid material is 0.03 cm³; if the void fraction exceeds about 3 percent, ice will not wholly fill the voids as water vapor permeates the cold lunar soil.
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Nitrogen-15: Microbiological

Alteration of Abundance

Abstract. The abundance of N^{15} relative to N¹⁴ is significantly altered during experiments in vitro in which nitrate and nitrite are microbiologically reduced to nitrogen gas. In all studies to date, $N^{14}O_3^{-}$ and $N^{14}O_2^{-}$ species have been preferentially reduced. This selectivity has a complex dependence on conditions in the medium. The results are not only relevant to natural variations in N^{15} relative to N^{14} but should be seriously considered during N¹⁵ tracer studies in soils.

Natural variations in the abundance of N^{15} have often been reported (1). It is well known that biological processes play a major role in the nitrogen cycle, but the extent to which the abundance of N^{15} relative to N^{14} may be altered by specific microorganisms has not been investigated. We have studied several microorganisms that participate in the nitrogen cycle; denitrification by different organisms has been examined from the standpoint of nitrogen-isotope fractionation.

Pennassay broth (Difco), modified with potassium nitrate or nitrite in the concentration range 10 to 30 μ mole/ml, was sterilized in a 2-liter vacuum flask. After inoculation, the reaction vessel was evacuated. The product, N_2 gas, was continuously collected in evacuated 1-liter sample bulbs. Checks revealed that contributions by atmo-

spheric N_a were negligible. Contaminants were removed with a liquidnitrogen trap before mass-spectrometric analyses. The amounts of nitrogen gas collected during periods of time were measured with a mercury manometer; nitrate concentration was determined by the standard phenoldisulfonic acid method (2). A magnetic-valve system was used to introduce alternately the sample and a N_2 standard into the mass spectrometer. Ion currents corresponding to masses 28 and 29 were simultaneously collected, and their ratios were digitally recorded (3). The N¹⁵: N¹⁴ compositions are expressed on a δN^{15} scale, with the initial nitrate (or nitrite) used as a reference, where

$$\delta N^{15} \text{ (per mille)} = \left[\frac{(N^{15}: N^{14}) \text{ (sample)}}{(N^{15}: N^{14}) \text{ (NO}_3^{-})} - 1 \right] \times 1000$$

The results of one study of reduction of nitrate by Pseudomonas stutzeri (NCIB 9040) appear in Figs. 1 and 2. The rate of production of N₂ maximized very sharply about 26 hours after inoculation and then declined rapidly (Fig. 1). The small plateau in the production rate between samples 7 and 8 is significant; we shall discuss it later. The isotope fractionation and percentage reaction of nitrate are plotted as a function of percentage production of N_2 (Fig. 2). Obviously the $N^{14}O_3^{-}$ is reduced preferentially to $N^{15}O_3^{-}$; this selectivity is expressed as the "instantaneous isotope-fractionation factor," defined as the N14: N15 composition of N₂ product at any instant, divided by the N^{14} : N^{15} composition of reservoir nitrogen at the same instant.

The behavior of this factor is very complex. Although N₂O collected during our experiment was negligible, it was abundant in some trials; in such instances, isotopic balance is difficult to achieve. In all denitrifying systems studied, the isotope fractionation has been smaller during the initial stages of the reduction (samples 1 and 2 of our study). This phenomenon apparently depends on variation in cell population. Behaviors have been analogous during microbiological reductions of SO4= and $SO_3^{=}$ to H_2S (4) in that the isotope fractionation is lower during population growth than during the stationary phase.

In our study, the instantaneous isotope-fractionation factor remained relatively constant at 1.02 for samples



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Fig. 1. Relative production rate (arbitrary units) of N_2 as a function of time during reduction of NO3by Pseudomonas stutzeri (NCIB 9040).

3 through 7 (Fig. 2). Then it decreased near the previously mentioned small plateau in the rate of production of N_2 . This plateau appeared near the point of total depletion of NO_3^{-} . The N_2 subsequently produced must have originated from an intermediate. The disappearance of NO_3^- also corresponds to a marked discontinuity in the isotopic composition of product N₂ (and instantaneous isotope-fractionation factor). This discontinuity further attests that a different metabolic process became dominant at 60-percent production of N_2 .

It is expected that a kinetic isotope effect should result during rupture of the N-O bond. In a different medium, instantaneous isotope fractionations up to 1.03 have been realized with Pseudomonas, but this value is still smaller





than the theoretical value for simple bond rupture (5). Thus the N-O scission step is not totally rate controlling, and the observation is consistent with the other observation that NO3was exhausted at 60-percent production of N_2 .

Preferential reduction of N14O3- and N¹⁴O₂- has also been demonstrated with other denitrifiers (a Bacillus and an Alcaligenes isolated from soils).

These results are relevant to studies of soils with N¹⁵ tracers. Cheng et al. (6) expressed concern that the N^{15} : N¹⁴ variations in different components of any one soil sample might introduce errors if the N15 tracer became significantly diluted. Our report suggests that greater errors may result from microbiological isotope fractionation during the course of the N¹⁵ tracer study. Our experiments suggest that, on average, $N^{14}O_3^-$ and $N^{14}O_2^-$ are utilized 2percent faster than the labeled species. Furthermore, during long-term experiments the alteration in abundance of N^{14} relative to N^{15} may be much greater because of reservoir effects.

Extension of these nitrogen-isotope studies should (i) clarify terrestrial variations in abundance of N¹⁵ relative to N^{14} , (ii) elucidate mechanisms in the nitrogen cycle, and (iii) provide a better assessment of errors in N15 tracer studies.

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