competent cells. Hemopoietic tissue was successfully reconstituted in a significant number of animals. In all groups except those that received operation 1 and lethal x-irradiation, the animals that died after 8 days had *Brucella* agglutinin titers within the range achieved by the survivors of the respective group.

Extirpation of the appendix, sacculus rotundus, and Peyer's patches before x-irradiation and reconstitution, completely abolished the antibody response to *B. abortus* in 9 of 14 animals and markedly suppressed the response in the remaining five. When only the appendix, which represents 50 percent of this type of lymphoepithelial tissue of rabbits, was excised, the agglutinin response to *B. abortus* was delayed but not suppressed. By contrast, thymectomy or removal of the spleen and mesenteric lymph nodes did not interfere with the development of antibody responsiveness. We interpret these observations as reflecting the fact that although the thymus may play an important role in supplying antigen-sensitive cells during the afferent limb of the humoral immune response (*6*), it plays no role in the efferent limb of this response. Furthermore, removal of so-called peripheral lymphoid tissues (spleen and lymph nodes) does not interfere with recovery of humoral immunity after irradiation. Intestinal surgery of itself does not interfere with recovery; indeed, the response in the group of rabbits that received operation 3 was higher than that of the unoperated, irradiated control group. We believe that this finding probably reflects an adjuvant effect secondary to tissue injury.

In the absence of x-irradiation, removal of lymphoepithelial tissues of the intestine in 4-week-old rabbits is followed 4 weeks later by a humoral immune response to *Brucella* equal to that of normal nonirradiated rabbits. It would seem that by 4 weeks of age, rabbits have sufficient numbers of lymphoid plasma cell precursors that are differentiated but uncommitted and that retain the capacity to mount and participate in primary antibody responses 4 weeks later. Since the dose of x-irradiation probably was sufficient to destroy most of these cells we may conclude that we have prevented restitution of this cell line by operation 1. Under these circumstances, no primary antibody response can be mounted in spite of the antigenic potency of *Brucella*.

We reemphasize our postulate that stem cells originating in hemopoietic tissue and differentiating into immunoglobulin- and antibody-producing cells can develop and function normally without being directly or indirectly influenced by the thymus gland. Our results indicate that in rabbits, this differentiation occurs under the influence of lymphoepithelial tissues of the intestine. We believe that the data of Miller and associates (*6*) who used sheep erythrocytes as antigen in mice, support our general hypothesis that the thymus does not exert a differentiative influence upon antibody-producing cells. These investigators have clearly shown, however, that the thymus plays an important role in the development of antigen-sensitive cells operating on the afferent limb of the humoral immune response; this applies at least when the response to sheep erythrocytes is studied.

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Lunar Rivers

Abstract. *Mature meanders in lunar sinuous rills strongly suggests that the rills are features of surface erosion by water. Such erosion could occur under a pressurizing ice cover in the absence of a lunar atmosphere. Water, outgassed from the lunar interior and trapped beneath a layer of permafrost, could be released by a meteoritic impact and overflow the crater to form an ice-covered river. A sinuous rill could be eroded in about 100 years.*

Photographs obtained by the Lunar Orbiters show sinuous rills resembling meandrous channels of terrestrial streams; about 30 are visible from Earth and were first described in 1788 (*1*). The sinuous rills appear to originate in craters on relatively higher ground and to terminate on lower plains, their widths often decrease with distance from the crater, and they tend to occur in groups (*2*). Significant new features revealed by the Lunar Orbiter photographs are the smaller meandrous channel in the bottom of Rima Prinz I (Fig. 1) and the mature meanders in the smaller channel on the floor of Schroeter's Valley (Fig. 2), which require reexamination of theories of the origin of the rills.

The obvious similarities in appearance between the rills and terrestrial river channels early led to the suggestion that the rills were produced by erosion by water (*2, 3*). Since liquid cannot exist at pressures below the triple point, an atmosphere providing at least that pressure was considered essential if water was to flow on Moon's surface. The idea that aqueous erosion of a surface always requires an atmosphere has persisted hitherto, so that objections to the existence of such an atmosphere have also led to rejection of surface erosion by water as the mechanism forming sinuous rills (*4*).

Our main point is that the lunar surface may be eroded by water under vacuum conditions, since an overburden of ice can provide the pressure required to maintain the liquid phase. Thus we suggest that sinuous rills may indeed be features of water erosion of the surface by ice-covered rivers whose source is subsurface water released by meteoritic impacts.

Lunar subsurface water may be expected to result from outgassing from the interior. Because the subsurface temperature is below the freezing point of water, a layer of permafrost, about 1 km thick, would form and prevent subsequently outgassed water vapor and other volatiles from reaching the surface. This layer would be stable on a geologic time scale against loss through sublimation if it were covered by about 100 m of lunar material. Liquid water and other volatiles would be trapped below this layer (*5*).

A sufficiently great meteoritic impact would rupture the permafrost. From terrestrial craters we know that the brecciated region extends to a depth comparable to the crater's radius (*6*). Thus an impact producing a crater of the order of 1 km in diameter (or larger) would rupture the subsurface ice.

If the water pressure were sufficiently great, the water would overflow the crater and cut a rill. The pressure could be provided by the overburden, by trapped volatiles, or by a hydrostatic head. The weight per unit area of the overburden would provide an upper limit to this pressure. If the material above the water level were about 1 km in depth and had a specific gravity lower than 3, the water could not be raised higher than about 1 km above the surface. Crater-rim heights of this order are associated with crater radii of about 10 km (*6*), so that craters still larger would not be expected to originate rills. Schroeter's Valley, the largest sinuous rill, begins in a crater of 5-km radius; most rills begin in smaller craters of radii nearer 1 km. The decrease in the number of craters of increasing radius would lead us to expect most rills to emerge from impact craters just large enough to break the permafrost. The occurrence of rills in groups may indicate that only certain areas of Moon had sufficient subsurface water pressure to overflow threshold-size craters. The lack of rills associated with all craters of the proper size within a group may mean that impacts followed depletion of the excess pressure by prior ruptures of the permafrost. Even if the pressure were insufficient for overflow, flooding might lead to flat-bottomed craters (*5*).

As the water welled up within the crater, the exposure to near-vacuum would cause it to boil, the latent heat being supplied from the water—principally through the formation of surface ice. Boiling would continue in the liquid below until the weight of the ice layer was sufficient to maintain the triple-point pressure (37 g/cm^2 under lunar gravity). Sublimation would occur at the ice surface at a rate depending on how rapidly energy was supplied to the surface. Liquid would continue to freeze at the ice-water interface. The ice would thicken until an equilibrium was established in which the upper-surface mass-loss rate by sublimation ($\dot{m}_U$) balanced the rate of mass gain at the bottom by freezing ($\dot{m}_L$). The nature of the equilibrium would be determined by the depth-dependence of the absorption of radiant energy. The equilibrium conditions for an idealized model (*7*), under the limiting assumptions that the incident radiant energy is all absorbed either at the upper surface of the ice or in the water beneath, are shown in Fig. 3.

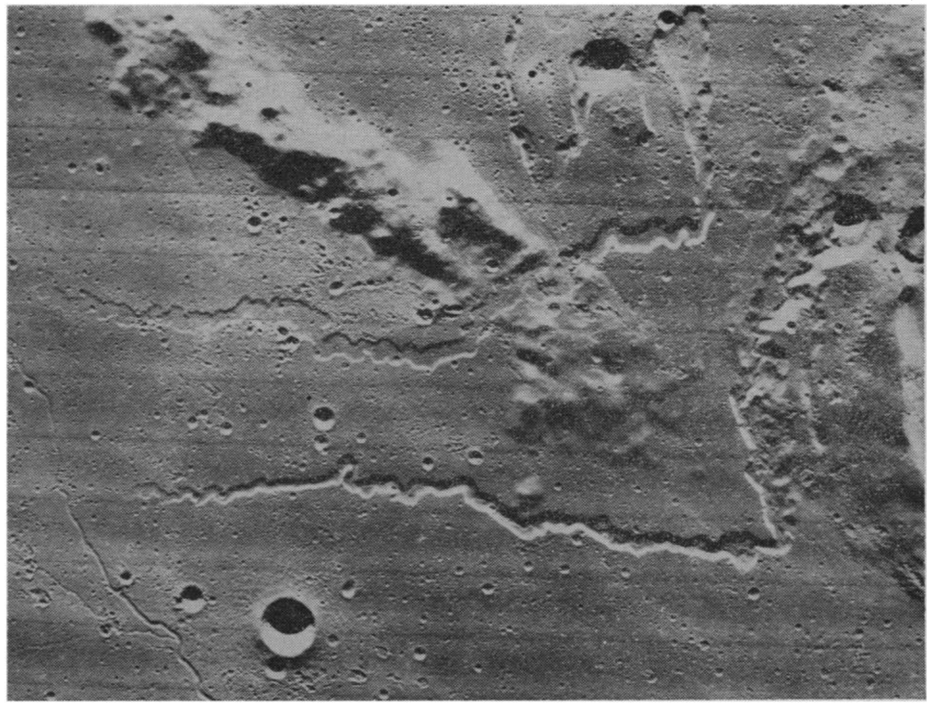


Fig. 1. The sinuous rills Rima Prinz I (bottom) and II. The width of the field is 67 km; Sun's elevation, 16 deg. [Lunar Orbiter V medium-resolution frame 191]

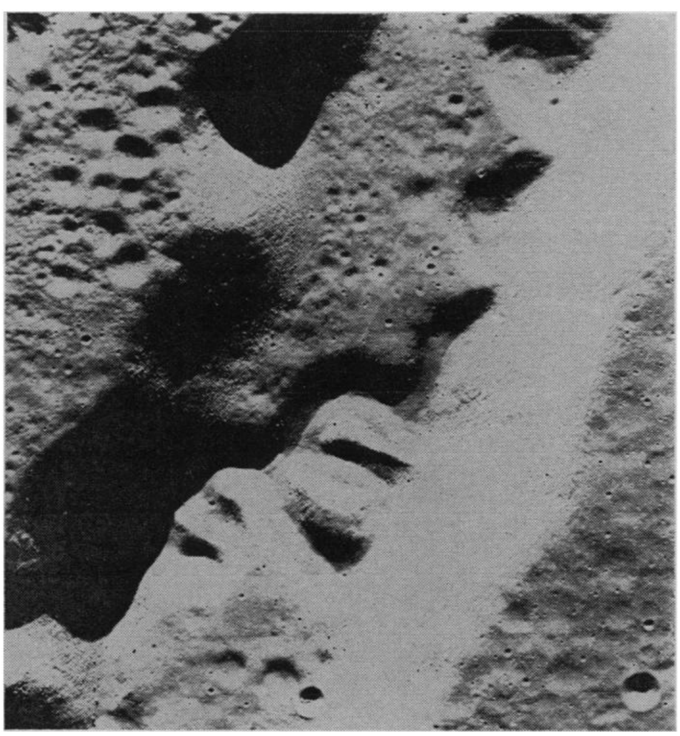
Several factors complicate this idealized treatment when applied to water on the lunar surface. The most important complication is the fact that we would expect the water to be a carbonated, muddy brine, so that the ice forming during the initial boiling-freezing phase would be foamy and dirty, with reduction in the transparency and thermal conductivity of the ice. Furthermore, as the ice sublimed, nonvolatiles accumulating on the surface would absorb most of the incident solar energy; the resultant equilibrium thickness of ice and rate of freezing would approach those for total surface absorption (Fig. 3). Because of the nearly linear dependence of the mass-loss rate on the incident flux of radiant energy and because the thermal-diffusion time (*8*) is long relative to a lunar day, we would expect lunar diurnal variations in the thickness of ice to be small perturbations of the equilibrium thickness determined by the time-averaged radiation flux of approximately $1/\pi$ of the solar constant. The uncertainties in the properties of the dirty ice (principally the thermal conductivity, density, and surface reflectivity), as well as the eventual insulating effect of accumulated nonvolatiles on the surface and the dependence of the incident radiation flux on latitude, all tend to reduce the mass-loss rate. Thus a freezing rate of 10^{-5} g cm^{-2} sec^{-1}, calculated (Fig. 3) for the time-averaged flux of solar radiation (0.01 cal cm^{-2} sec^{-1}), represents an upper limit.

If the water breached the crater wall, it would flow down the slope (boiling and freezing where exposed to vacuum), quickly covering itself with a blanket of ice. Since the appearance of the rills indicates that the rivers were hundreds of meters wide—large relative to the equilibrium thickness of the ice blanket—we would not expect the ice to restrict the river's course or hinder the development of meanders; cracks in the ice would be rapidly repaired by the freezing of water exposed to the vacuum and the supercooled ice.

The boiling water, when it first encountered the very porous and weakly bonded material on the slope (*9*), would churn the surface and produce a slurry of mud and ice. As the water penetrated deeper into the ground, it would be preceded by vapor whose pressure would inhibit boiling beneath the surface. By forming frost, the vapor would also warm the subsurface material to 0°C. If the porosity were greater than a few percent, the frost thus formed could not fill all the voids and prevent further penetration (*10*). Since the Surveyor (*9*) and radiometric (*11*) experiments indicate that the top several centimeters of the lunar surface has a porosity of 50 to 70 percent, porosities greater than a few percent are likely to extend down to the permafrost. If meteoritic impacts have disintegrated the lunar material to a considerable depth, we would expect the material to be easily erodible down to the permafrost. In fact, the rills have an average depth of about 100 m, the estimated depth of the top of the permafrost layer (*5*).

The time required for erosion of a sinuous rill depends on the rate of flow and the load-carrying capacity of a lunar river. One estimate of the rate of flow of water in the rills follows from the fact that the rate must be sufficient to maintain flow against loss by freezing. Thus the product of the surface area of the channel and the freezing rate per unit area provides a lower estimate of the mass flow rate from the crater. For example, the two medium-sized rills Rima Prinz I and II (Fig. 1) both cover areas of the order of 10^{12} cm^2. With a freezing rate of 10^{-5} g cm^{-2} sec^{-1}, the rate of flow through these rills must have been at least 10 m^3 sec^{-1}. We can also estimate the rate of flow from correlation of the meander wavelength of the channel with the rate of flow for terrestrial rivers; the wavelength ranges from 1 to 3 km (Fig. 1). Data for suspended-load alluvial rivers in the western United States (*12*) show that such wavelengths are associated with flow rates of the order of 100 m^3 sec^{-1}. Finally the velocities of lunar rivers can be crudely estimated from comparison with turbid terrestrial rivers having velocities of the order of a few meters per second or less. Because of the increased frictional losses due to the ice cover and the lower gravitational acceleration, we would expect lunar rivers to flow at velocities less than 1 m sec^{-1}. Assuming that an upper bound on the cross-sectional area of the flowing water is given by the product of the width of the rill (about 1 km for Rima Prinz I and II) and a depth comparable to the thickness of the ice, we find that such velocities give flow rates of the order of 10^3 m^3 sec^{-1}. Thus in summary the freezing rate provides a lower estimate of 10 m^3 sec^{-1} for the flow rate through either Rima Prinz I or Rima Prinz II, comparison with terrestrial river velocities gives an upper estimate of 10^3 m^3 sec^{-1}, and the meander wavelengths of these rills are consistent with this range of rates.

These rates of flow and an estimate of the volume of water necessary to excavate a rill determine the erosion time scale. The mass of water required equals the mass of material transported divided by the load fraction (the mass of material carried per unit mass of water). For rivers in the western United States the load fraction ranges from tenths of 1 percent in "sluggish



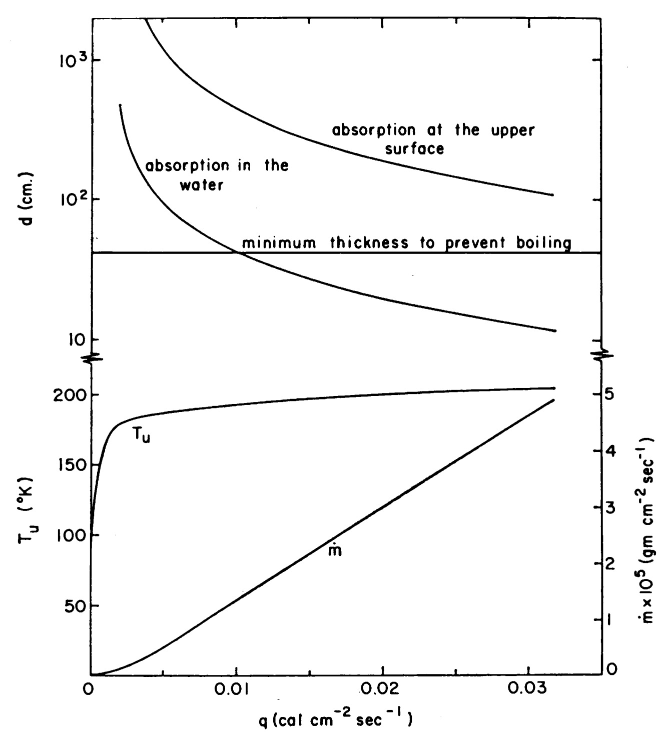


Fig. 2 (left). A section of the rill Schroeter's Valley, showing mature meanders of the channel on the bottom. The width of the field is 6 km; Sun's elevation, 15 deg. [Lunar Orbiter V high-resolution frame 204] Fig. 3 (right). Mass-loss rate, surface temperature, and equilibrium ice thickness versus incident radiation flux for the limiting conditions of absorption at the upper ice surface or in the liquid beneath. Only the ice thickness depends on the absorption model. Over a wide range of *q*, where upper-surface reradiation is unimportant, $\dot{m}_U$ is directly proportional and *d* is inversely proportional to *q*, and T_U is nearly constant. For values of *q* greater than 0.01 cal cm^{-2} sec^{-1}, the lower bound on the equilibrium thickness is the minimum thickness (40 cm) that prevents boiling. The ice thickness for any other absorption model is bounded by these extremes.

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 10^{10} m^3. 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} m^3. For the range of flow thus deduced, times of the order of 10 to 10^3 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 water and other volatiles trapped beneath.

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7. The equilibrium conditions are determined by the following equations. The mass-loss rate 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

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

where T_L is the temperature of the lower surface (273°K), k is the thermal conductivity of ice (0.006 cal cm^{-1} deg^{-1} sec^{-1}), d is the equilibrium depth (in centimeters) of 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

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

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 (1.36×10^{-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, $\tau = d^2/\alpha$, is approximately 1 year where α is the thermal diffusivity of ice (0.015 cm^2 sec^{-1}); since this time is longer by an order of magnitude than the lunar day, the neglect of the diurnal variations seems justified.
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Nitrogen-15: Microbiological Alteration of Abundance

Abstract. *The abundance of N^{15} relative to N^{14} 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 N^{15} 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 μmole/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-