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Water on the Moon and a New Nondimensional Number

Abstract. *A nondimensional number called the Jeffreys number, which represents the ratio of the Reynolds number to the Froude number, is useful in geophysical problems related to the motion of viscous masses under gravity. The Jeffreys number is used to show that it is impossible for the lunar maria to be underlain by a layer of material 1 kilometer thick having the plastic properties of ice.*

Urey (*1*) proposed that the lunar surface has been shaped by flowing water in some places, especially in the so-called sinuous rills. These are meandering channels, generally thought to be the work of some fluid, often regarded as the channels of flows of lava (*2*) or ash (*3*). Urey's main point is that, with a couple of minor exceptions, there are no signs of deltas at the lower ends of these channels. Since the amount of material which has been eroded away in forming the channel may be hundreds of cubic kilometers, the lack of evidence of deposition is certainly significant and is not due to any problem associated with observing the deposits, unless they are widely dispersed.

Urey agrees with suggestions by Gold that the maria are underlain with permafrost having the properties of "plastic ice" (*4*). In this case, the melting, evaporation, and eventual escape of the water would explain the lack of delta deposits.

This paper demonstrates that the dynamic behavior of ice is inconsistent with what is known about the maria. In particular, the viscosity of ice is so low that the maria, if composed of ice, should show no craters over a kilometer in diameter. Larger craters should have smoothed out as a result of gravitational action.

In problems which involve both gravitational and inertial forces, it is customary to consider the ratio of the Reynolds number to the Froude number. The Reynolds number is

$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho v L}{\mu} \qquad (1)$$

where ρ is the fluid density, v is the velocity of the fluid, L is a characteristic length, and μ is the fluid viscosity.

The Froude number is

$$\mathrm{Fr} = \frac{\text{inertial forces}}{\text{gravitational forces}} = \frac{v^2}{gL} \qquad (2)$$

where g is the gravitational acceleration. The ratio of the Reynolds number to the Froude number occurs so frequently in geophysical problems that it should perhaps be given a separate designation, such as the Jeffreys number

$$\mathrm{Je} = \frac{\text{gravitational forces}}{\text{viscous forces}} = \frac{\rho g L^2}{\mu v} \qquad (3)$$

or if we introduce a characteristic time $t = L/v$

$$\mathrm{Je} = \rho g L t/\mu \qquad (4)$$

For example, the equation of Jeffreys (*5*) for the flow of a viscous liquid of thickness L down an incline of angle A can be written

$$\mathrm{Je} = 3/\sin A \qquad (5)$$

The equation of Heiskanen and Vening Meinesz (*6*) for the rate of recovery of a continental area after the disappearance of a glacial ice sheet may be written

$$\mathrm{Je} = 2\pi S \qquad (6)$$

where S is a nondimensional shape factor, namely, the ratio of the width of the area to the depth of deformation. Even the application of the Stokes equation to the rise of a bubble of radius L, consisting of gas of negligible density, through a liquid of density ρ may be written

$$v = (-2/9)(L^2\rho g/\eta) \qquad (7a)$$

where v is the terminal velocity of the sphere and η is the coefficient of viscosity. Thus

$$\mathrm{Je} = -9/2 \qquad (7b)$$

In general, the Jeffreys number is of the order of the ratio of width to height in the collapsing structure.

Glacier ice behaves like a fluid of viscosity 10^{14} poise (*7*). Since the temperature of the moon's interior does not fall below $-33°C$, properties of ice in the interior of the moon would resemble those of glacial ice. For a crater 1 km in radius, with a depth-to-radius factor of ½, if $\mathrm{Je} = 2$ and $g = 162$ cm sec^{-2}, t is approximately 10^7 seconds. We would therefore expect a lifetime of the order of a few months, whether we regard it as the limiting case of a large bubble or as a problem in continental uplift, if we consider the rate at which the walls of the crater will slump inward. Since the maria do contain numerous craters of this size, it is not likely that they have a substantial layer of ice.

The Jeffreys number can be used directly to study the analogy (*4*) between terrestrial pingos (craterlets a few tens of meters in diameter formed by the diapiric motion of ice) and certain lunar craters with large central peaks, such as Alpetragius, which are about three orders of magnitude larger. Pingos occur in regions that were once glaciated; hence, their lifetimes are under 10^4 years. Alpetragius, which is a rather sharp feature of the moon, may be only 10^8 years old. If these two structures are fundamentally analogous, they should have the same Jeffreys number. Using the second form of the Jeffreys number (Eq. 4), we find that the material in Alpetragius, which is analogous to the ice of the pingos, cannot be ice; it must have a viscosity of the order of 10^{20} poise or more, like the material of the upper mantle of the earth.

These principles can be applied to the problem raised by Urey. If a sinuous rill, such as Schröter's Valley, about 5 km wide and 1 km deep, were to be cut in ice, the Jeffreys number would probably be about 5. The corresponding value of t is about 10^7 seconds; it appears that Schröter's Valley would disappear within a year, even if the ice were protected from melting by an overburden of soil. These rates of movement are quite consistent with the observed movements of thick glaciers, which advance at rates up to 10 m per day.

The possibility of ice in the cavities of the rocks is not refuted by this argument, which applies only when there is enough ice to lubricate the contacts between rocks. However, if the maria are mostly soil and rock, then Urey's delta problem remains.

A possible solution to the delta problem is the suggestion (*8*) that dense ash flows may carve the sinuous rills and may then be transformed into a dilute phase in which they are essentially dust-laden gas clouds. In this phase they are capable of spreading widely and dropping their load as a thin layer on the maria. Jaffe (*9*) has postulated the existence of such a layer for quite different reasons.

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Fossil Mycelium with Clamp Connections from the Middle Pennsylvanian

Abstract. *A mycelium with clamp connections and chlamydospores has been discovered within the wood of a Middle Pennsylvanian fern. This suggests that forms extant in the middle of the Pennsylvanian had life cycles comparable to some modern Basidiomycetes.*

Hyphae found in the wood of a Middle Pennsylvanian coenopterid fern *Zygopteris illinoiensis* (Andrews) Baxter, have clamp connections, structures which immediately identify a mycelium as belonging to the class Basidiomycetes. The fossil hyphae are similar to extant saprophytic Basidiomycetes (Fig. 1, compare A to G with H to K).

The numerous clamp connections formed on the fossil hyphae (Fig. 1, A and B) resemble comparable structures formed by living Basidiomycetes (Fig. 1H). The best preserved clamp connections have two septa; one within the hypha at the base of the clamp, and the second closing the clamp connection hook. Infrequently, a hyphal branching occurs from the clamp connection itself (Fig. 1C). Similar wall orientation and branching occur in extant hyphae (Fig. 1H). In some fossil material there are hyphae having clamp connections in which the hook of the clamp does not form a complete union with the hypha (Fig. 1D). These structures resemble pseudoclamps (*1*) which are produced, under cytogenetic control, with common-B matings of extant basidiomycete mycelia (Fig. 1I). The fossil specimens have globose swellings which are short, unicellular portions of the hyphae characterized by rounded lateral walls which are noticeably thicker than those of the remaining mycelium. Often, septa without clamp connections occur adjacent to the area of swelling. These unicellular, swollen structures may be borne singly in a terminal position (Fig. 1G) and either singly or in chains in an intercalary position (Fig. 1, E and F). These struc-

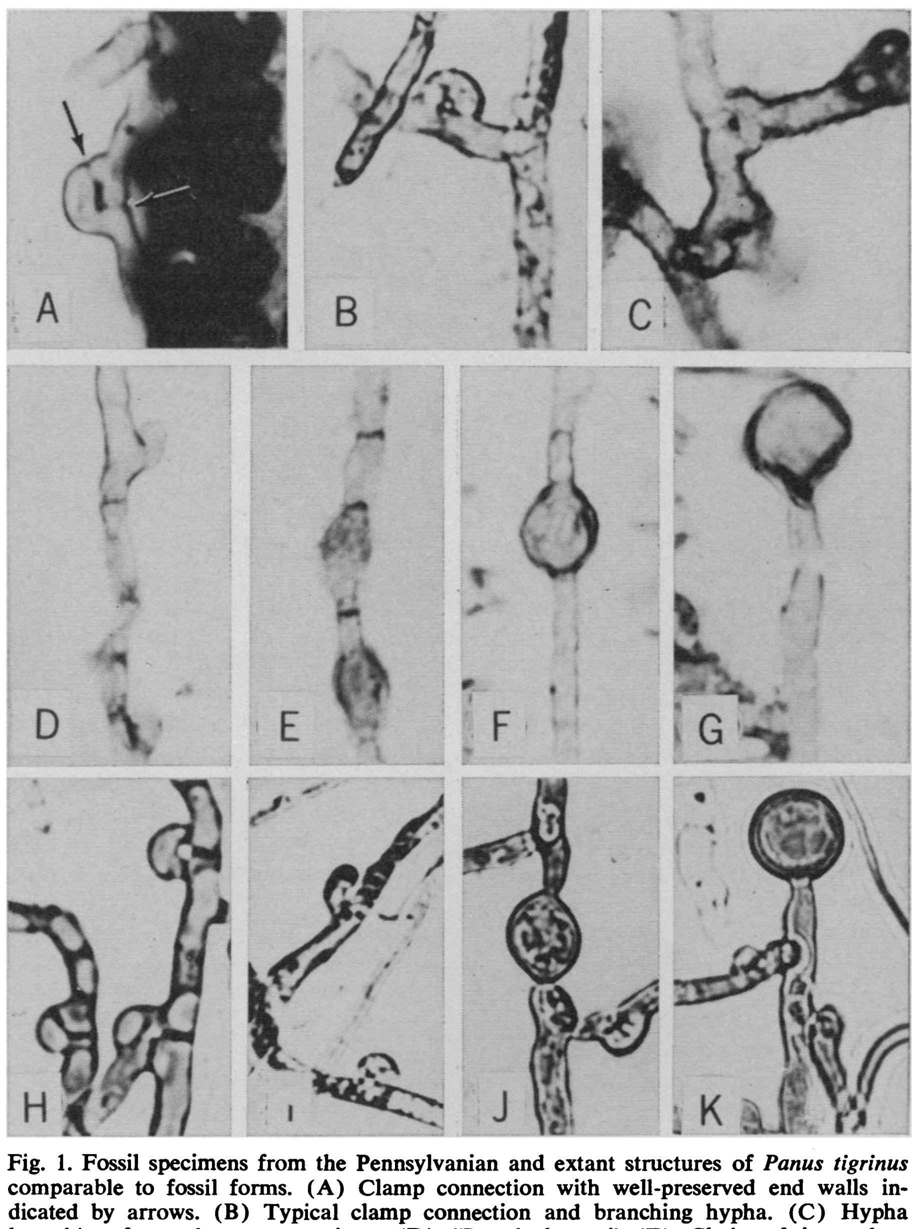

Fig. 1. Fossil specimens from the Pennsylvanian and extant structures of *Panus tigrinus* comparable to fossil forms. (A) Clamp connection with well-preserved end walls indicated by arrows. (B) Typical clamp connection and branching hypha. (C) Hypha branching from clamp connections. (D) "Pseudoclamps." (E) Chain of intercalary chlamydospores. (F) Solitary intercalary chlamydospore. (G) Solitary terminal chlamydospore. (H) *Panus tigrinus*, typical clamp connections and hypha branching from clamp connection. (I) *Panus tigrinus*, pseudoclamps. (J) *Panus tigrinus*, intercalary chlamydospore. (K) *Panus tigrinus*, terminal chlamydospore.