Table 2. X-ray diffraction maxima of clays from Eocene chalk soils.

Soil	Relative intensity at various D-spacings		
	22 Å	16 Å	15 Å
Houston		13	
Houston		20	
Hunt			10
Hunt			12
Hunt		16	
Hunt		14	
Vaiden	8		

fering basal spacings that are a function of both particle size and depth.

X-ray diffraction maxima of a group of clays from other chalk soils are shown in Table 2. The 16-Å maximum is apparent, and anomalies such as 15- and 22-Å spacings are also present. These unusual spacings may be interpreted as random interstratifications. It should be mentioned that discrete 14- and 18-Å spacings are the rule in these clays, rather than anomalous spacings. Clays of the Houston, Hunt, and Vaiden soils derived from Eocene chalk show strong indications of interstratification. Diffraction maxima at 22, 16, and 15 Å indicate that the systems are complex. These maxima are usually thought to be indicative of vermiculite-montmorillonite interstratification, but the variable nature of low-angle diffraction maxima leaves one with doubt about the correct interpretation.

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Surface Material of the Moon

Abstract. *A skeletal fuzz that consists mostly of open space probably covers the moon to a depth of several millimeters or centimeters. The solid part of the fuzz probably consists of randomly oriented linear units, with or without enlarged nodes, which either anastomose in a mesh or are branching.*

Light is retrodirected from the surface material of the moon; that is, the moon's surface has the property of backscattering much more light in the direction of the light source than it scatters in other directions (*1*). This inference is the only possible explanation of three otherwise anomalous features of the brightness of the moon: the lack of limb darkening on the full moon, the steepness of the photometric curve for the moon as a whole, and the form of the photometric curves for individual points on the moon, which have maxima at full moon rather than, as theory predicts, when the sun is most nearly overhead, at local noon.

The most probable explanation of the retrodirected light is that it is a shadow effect due to roughness of the moon's surface. According to this hypothesis, already well known half a century ago (*2*), much of the moon's visible surface is in shadow at large phase angles; the individual shadows are much too small to distinguish with even the best telescope, but they darken the surface. As the phase angle decreases, less and less of the area is in shadow, until at 0°, at full moon, each shadow is covered by the object that casts it.

The difficulty with the shadow effect hypothesis has been that no materials familiar on the earth cast nearly enough shadow. Large amounts are required: the moon's light is estimated to decrease roughly 15 percent between phase angles 1½° and 4½° (*3*), and it decreases to less than one-twelfth the full-moon value by quadrature (*4*). Fragmental materials such as gravel, sand, or angular blocks can cast only a small fraction of the necessary shadow (*5*), and even scoria fragments, themselves rough and pitted, are insufficient (*6*). It would seem to follow that dust, too, cannot produce the observed retrodirected light. At best dust would be expected to produce no more shadow than the angular blocks, and the photometric curves would be less steep unless the particles were highly opaque; the great majority of minerals and rocks become lighter in color when powdered, as on the streak plate or in a hammer scar. Hapke has recently argued (*6*) that "fairy castles" of dust particles a few microns in diameter might produce the required shadows, but aside from the difficulty with the opacity of such small particles, the "castle" structures he describes depend on electrostatic charges that would presumably decay in a few thousand years, especially under monthly cycles of ionizing radiation from the sun. The structures would therefore lack stability and would collapse.

Other kinds of roughness have also been invoked. Barabashov supposes the moon's surface to be closely seamed with deep cracks and fissures (*7*). Bennett suggested that the surface is covered with hemispheric pits (*8*). Van Diggelen showed that hemi-ellipsoidal pits, with depths greater than their diameters, produce photometric curves more like those produced by the moon (*1*). However, all of these seem to fail at the limb. Consider a point on the moon's equator at 85°E (*9*). There our line of sight is nearly tangent to the surface, and we see only the areas between the cracks or the pits. At local noon, just after first quarter, all these areas should be in full sun, without shadows, and should look brighter than at full moon, not a mere fraction as bright.

The problem, therefore, is to find some kind of geometry that can satisfy the requirements better. These requirements are that the surface material of the moon (i) should provide at least 15 percent of dark shadow at a phase angle of only 4½°, and increasing amounts at increasing phase angles, and (ii) should look essentially the same when it is viewed nearly tangent to the surface, near the limb, as when it is viewed vertically down onto the surface, at the subterrestrial point.

These requirements indicate at least three general facts about the geometry of the material of the lunar surface. First, it must have much open space, because an object cannot cast much shadow at small phase angles on a surface on which it rests; it can do so only on a surface above which it is raised. For example, the maximum area of shadow that a cylinder of radius r can cast at phase angle 4½° on a plane surface on which it rests is $r(\tan 4°30')$, or $0.08r$; that is, 4 percent as much as the projected area of the cylinder (Fig. 1). Thus a series of such cylinders, laid parallel, cannot cast more than about 4 percent of shadow, and that only if they are spaced $2.08r$ apart. Most configurations of equidimensional objects will cast less than that, because in general the objects will be less than spherical, or less than ideally spaced, or on a rough surface on which they will tend to occupy the depressions. However, a series of evenly spaced cylinders 3 diameters apart in planes spaced 3½ diameters apart can show 16 or 17 percent of shadow at phase angle 4½° (Fig. 2), and if randomly spaced or farther apart they could show even more. We can conclude that the lunar material must consist of opaque elements isolated from each other both horizontally and vertically by distances that average several times their diam-

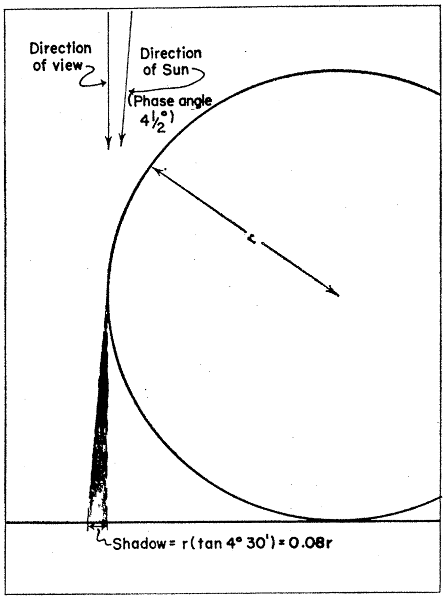

Fig. 1. East-west section through a cylinder (axis N-S) resting on a horizontal plane. At phase angle 4½°, the area of shadow visible from directly above is r(tan 4°30′), or 0.08r. This is 4 percent of the projected area of the cylinder.

eters, so that we can see well down into the lattice and so that the deeper elements may have large amounts of shadow cast on them even at relatively small phase angles.

Secondly, some or all of the units of this structure must apparently be linear, to be able to maintain this open texture. No aggregate of equidimensional units resting on each other would support itself with the open spacing indicated. The data on scoria show that even tabular units, such as the walls between the vesicles of a vesicular rock, would be unable to provide the required separations.

Thirdly, the orientation of the inferred linear units must be varied, and probably must be random, or the surface would not look so nearly the same whether it is viewed vertically, horizontally, or at intermediate angles. If, for example, vertical orientations were predominant, the area at the center of the apparent disk of the moon, where we would be looking along the linear elements, would look different from the areas to the north and south, and at quadrature the limb at the subsolar point, at the equator, would look different from the limb to the north and south.

The requirement for random orientation excludes not only vertical needles or pinnacles, such as velvet or spires of dust particles, but also such an apparently randomly oriented structure of needles as an opened-out pile of jackstraws, standing at all angles on a generally smooth surface, because the jackstraws that rise highest above the initial surface would be those most nearly normal to it, and the only elements visible at the moon's limb would be those oriented nearly vertically. Any felt of matted fibers would also be excluded, not only because the porosity might be too low, but also because the fibers in a felt would tend to have a predominantly horizontal orientation. Thus an accumulation of the volcanic threads known as Pele's hair would not explain the properties of the lunar surface. Even an unfelted tangle of threads, perhaps comparable to expanded steel wool, would probably not serve, because the elements rising highest, and therefore visible at the limb, would tend to be loops in which a nearly horizontal orientation would predominate.

Only two general types of structure appear to be able to produce the observed shadow effects on the moon. Firstly, the lunar surface material might have a three-dimensional mesh structure. A variant of this would be what we may call a Tinker-Toy structure, in which opaque units (nodes) are spaced apart by thinner rods; the material might resemble the models that crystallographers make with cork balls and toothpicks, provided the lattices occurred in various orientations, as in a polycrystalline solid.

Alternatively, the surface material might consist of linear units with a branching habit such that elements in all orientations could occur even at the top of the pile. A loose accumulation of lacy snowflakes would get around the difficulty that arises with jackstraws. Van Diggelen measured the photometric curves of another material with a structure that falls in this class; his curves for the lichen *Cladonia rangiferina*, commonly known as reindeer moss, were closer to those he obtained for the moon than were his curves for the pitted surface he favored (*1*). There can be neither snow nor reindeer moss on the moon, for snow would sublimate in the lunar vacuum (*10*) and no organic life could survive unshielded exposure on the surface. However, the geometry of the snow or the reindeer moss might perhaps be matched by some other kind of material that is stable on the moon, and is of inorganic origin.

The scale of the inferred meshwork or branching maze is not indicated by the optical effects: retrodirected light could be produced equally well by a mesh of steel girders with dimensions measured in feet, or by one of units more appropriately measured in microns, provided the material were opaque enough to cast the required dark shadows. However, comparison of the thermal emission data at different

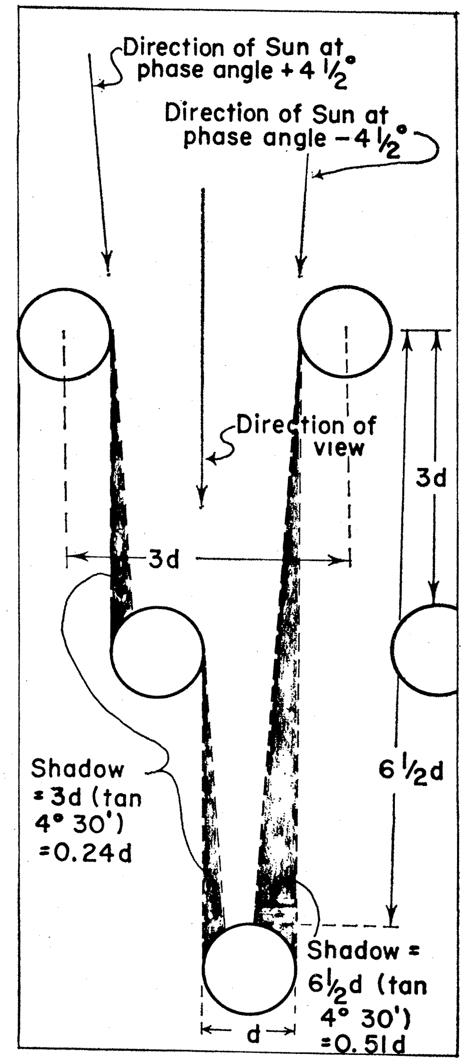

Fig. 2. East-west section through a series of horizontal cylinders (axes N-S) spaced 3 diameters apart in planes that are 3½ diameters apart. At phase angle −4½°, 51 percent of the projected area of each cylinder in the bottom layer, or 17 percent of the entire projected surface, would be in shadow as seen from directly above. At phase angle +4½°, 24 percent of each cylinder in the second layer and 24 percent of each in the third layer, or 16 percent of the entire projected area, would be in a shadow. If the cylinders were randomly arranged at distances that averaged 3½ diameters, the total area of shadow would be greater, as there would be overlap of some cylinders so that we could see farther below the top surface to surfaces more completely shaded.

wavelengths gives us limits on the scale. During a total eclipse, the emission temperature of the moon's surface, as measured at infrared wavelengths, drops some 175°C during the period of less than 1¼ hours that the moon is in the earth's penumbra; but at a wavelength of 8.6 mm, as Gibson has shown (*11*), it varies less than 1°C. This evidence indicates that the sun cannot strike more than a few centimeters, at most, below the topmost elements of the skeletal structure. A lower limit to the scale is also suggested by Gibson's work (*11*); the depth to which we can see into the material probably corresponds either to his upper layer, 0.5 cm thick, or to his upper and intermediate layers, totaling several centimeters.

Thus it is inferred that the surface of the moon is probably covered by an open-textured, highly porous maze or meshwork of randomly oriented linear units with or without nodes. The structure could be a mesh or a Tinker-Toy structure, or it might resemble that of snowflakes or reindeer moss. The scale is such that one can see several millimeters or centimeters into the structure, but not several decimeters. At this scale, the average diameters of its constituent units cannot be more than a very few millimeters, and the material can appropriately be described as a skeletal fuzz.

Such a skeletal fuzz can reasonably be expected to have most of the known physical properties of the surface material of the moon. In thermal properties, it would be an excellent thermal insulator, because it consists mostly of vacuum, yet is broken up enough to reduce heat loss by radiation. It would also have a low heat capacity, because there is not much matter there to hold the heat. Moreover, it would explain the observation (*12*) that at full moon the infrared temperature of the subsolar point, at the center of the apparent disk, is higher than that of the limb. Again, the temperature of the subsolar point measured by a bolometer would vary with the phase, as it is observed to do (*13*), because it would depend on the angle at which the surface was viewed. The fuzz would also explain the observation that during the penumbral stage of a total eclipse the limb areas lose a much larger fraction of their total heat than the central regions (*14*).

Other physical properties that would be explained include the observed low electrical conductivity of the surface layer; the surface of the matter that is present is much broken up, so that path lengths would be great. Radar experts who study the moon appear to agree that a skeletal fuzz of this character would account for their observations at least as well as dust. And I believe it would account for the optical effects it was invented to explain—the lack of limb darkening on the full moon and the photometric function curves.

The remaining known physical properties of the surface material of the moon do not appear to be necessarily inherent in the skeletal structure of the inferred fuzz. For example, a fuzz could as easily be light colored as black. However, none of the known physical properties appear to be incompatible with the inferred fuzz.

The presence on the moon of a material unlike anything we know on the earth should not surprise us, because the lunar environment is so very different from our own. A possible genesis of a skeletal fuzz that would have the inferred properties is the sputtering of vesicular rocks by protons of the solar wind (*15, 16*).

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References and Notes

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10. This statement is certainly true for the visible parts of the surface of the moon, although ice may be present in "cold traps" in certain craters near the poles that never receive any solar radiation and never rise above a temperature of about −200°C.
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13. F. E. Wright, "Lunar radiation," in Carnegie Institution of Washington, *Year Book 28* (1929), p. 399.
14. W. M. Sinton, in *Planets and Satellites* (see *3*), p. 439.
15. A paper setting forth this hypothesis more fully is in press (*U.S. Geol. Surv. Profess. Papers* **475-B**, art. 39).
16. This paper is published by permission of the director, U.S. Geological Survey.

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Atmospheric Iodine Abates Smog Ozone

Abstract. Traces of iodine in test samples of irradiated photochemical smog atmospheres either inhibit ozone formation or lower its concentration. Eye and respiratory irritation are reduced qualitatively. Iodine is more effective in suppressing ozone in a photochemical smog atmosphere than it is in purified air.

The relatively large concentrations of ozone encountered at high altitudes must be reduced when the rarefied atmosphere is compressed for use inside aircraft cabins.

As part of a study of problems that are associated with supersonic transports, we investigated catalytic methods for decomposing ozone in the air of pressurized cabins. Since ozone is also present in smog—indeed, the quantity of ozone is the usual index of smog severity—these methods seem relevant to the problem of smog abatement.

The ideal method for smog abatement is to prevent pollution of the atmosphere with its precursors, hydrocarbons and oxides of nitrogen. However, many years of effort have failed to provide practical means for reducing the nuisance. Since smog is a vital local problem, we studied the possibilities of using a trace material in the atmosphere to reduce the concentration of smog-generated ozone. Iodine proved to be unexpectedly effective in sunlight chamber studies.

The principal evaluations of the effect of iodine in smog-forming atmospheres were conducted in a portable 500-cubic-foot transparent enclosure with sunlight irradiation. One mil Mylar polyester film sheeted three walls and the top, and the frames, floor and end wall were constructed of aluminum alloy. Ozone was measured with an ultraviolet photometer in which a pair of matched photoelectric cells compares light transmission at 2537 Å through