THE ACCRETION OF THE MOON. T. Gold, Center for Radiophysics & Space Res., Cornell University, Ithaca, N.Y., 14853.

Evidence of infall is abundant on the Moon. Craters of a range of size from a few microns to hundreds of kilometers bear clear evidence of impact generation. The bulk of the material that covers the surface in all areas is in the form of small particles, as must be expected for any surface subject to cold accretion. The small proportion of rocks of more substantial size, that could not have survived even the lowest possible speed of infall (1.7 km/sec, the orbital speed) are for the most part impact breccias, i.e., rocks whose origin appears to be the compaction of a more finely divided material by powerful pressure pulses, generally thought to be due to the explosive nature of high speed impacts. A very small fraction of the material is in the form of crystalline rocks or lavas, i.e. rocks that have frozen from a melt. Whether the heat that caused melting had its origin in a general lunar heat source or also in impact phenomena cannot be determined directly. Large impacts are understood to result in widespread melting, and if major basins on the Moon are indeed impact created, then some impact melts must in any case have been present. (Terrestrial impact formations have been identified demonstrating the formation of impact breccias <u>and</u> impact lavas (1).) A body formed by the cold accretion of rock objects of a wide range of size would therefore possess all those features: craters, powdered rock as chief constituent, and a small admixture of solid rock pieces formed by impacts. Mercury has surface features closely resembling those of the Moon, and its entire range of optical and radio reflection properties are also closely similar. Its surface and subsurface down to a depth of a few meters must be physically and probably even chemically rather similar. (The interior, with its density indicating a composition of 50% iron, is very different.) Both surfaces might therefore be thought of as having resulted from the last stages of the accretion process that built up these bodies in the first place. In that case the observations of the nature of the materials would reflect in an important manner on the circumstances in the early solar system, and give a type of information that is totally obscured on the Earth, and that is available from meteorites only in a form biassed by the chance events that were responsible for providing the samples of the present epoch.

Most investigators do not take this view. Rather they appear to believe that both the Moon and Mercury once possessed a surface of this general type, but that this earlier surface was replaced by internal action with magmas, and that the rocks so formed had their surface pulverized by later impacts. A second episode of widespread melting is then thought to have filled the large basins on the front side of the Moon and the large number of crater floors and low areas both on the front and back of the Moon and on Mercury. Finally, on both bodies this was to have been superseded by a further bombardment resulting in craters within the last lava filled areas, and the pulverization of the crystalline rocks, to generate that ubiquitous rock powder to a depth of some meters at least, without, however, adding more than a few percent of fresh material to the surface mix in the process.

Do the data really require this complex explanation? And would this picture indeed fit the detailed facts? The reason why it is thought to be

required is the presence of the flat fill in the basins, the maria, which is considered to have resulted from lava flooding; and the chemical and petrological evidence that shows the material to be similar to products of magmatic differentiation. Neither of these points are compelling: processes can and did transport pulverized materials to produce flat deposits on the Moon, and the entire mare fill may be of that nature. The prevalence of differentiated materials does not specify that the process occurred on the Moon; there are independant reasons for believing that the final accretion occurred from the debris of collisions of earlier bodies on which any of the processes now attributed to the Moon could already have occurred.

There are very serious questions as to whether the lunar differentiation picture can fit the known facts. Can as much powder as now covers the Moon be generated by impacts that have added no more than a few percent of fresh material? Most small impacts will only add to the powder, and mix it up. They do not contribute to the grinding up of rock. Can the locally differentiated material be the major component, and can it at the same time be as sharply layered as is found in the core tubes? Can one account for the presence of a far greater number of 10-200 meter craters on the mare ground than on the neighboring hillsides, and for the characteristic hillside patterns (elephant hide) being maintained (2)? Can one understand the long wave radar result of a strong limb darkening of the radar Moon (3) (by a factor of more than 100) when an impact shattered bedrock underneath a few meters of surface powder would give a more reflecting and almost uniformly bright radar Moon? Yet the supposed grinding up process and the nature of the seismic transmission would require the bedrock to be coarsely broken up and therefore a diffuse radar scatterer. Can one understand why all the long-range mixing that is implied by the ray patterns of young craters would not have resulted in a chemically homogeneous surface layer? Can one understand the degree of uniformity of the observed surface exposure effects in the lunar soil and the paucity of underexposed material? Can one understand the long-term rigidity implied by the mascons and the brittle interior implied by the deep focus Moonquakes? Lastly, can one understand why the interplay between internal and external effects should have been complex, yet so similar on Mercury as on the Moon?

The interpretation of these surfaces as resulting merely from the last stages of the accretion process requires certain assumptions, some of which have independent evidence to support them. That the present bodies of the solar system formed from the debris of earlier planetary bodies and not directly from the primitive condensate of the early solar system, is made probable firstly by the wide separation of the planetary orbits, not expected in a first round of formation, and secondly by the density differences between the planetary bodies. Many satellites are, like the Moon, made of materials evidently quite different from those of the parent planet. In a multi-stage process of smash-up and accretion, there will necessarily be a time variable supply in the type of material available for the accretion on any one body, depending on the details of previous collisions. The final accretion of the Moon must have had a supply rich in plagioclase and then one rich in pyroxene and ilmenite. Next one has to suppose that large-scale surface transportation

of powder has taken place on the lunar surface. There is strong evidence for that. The appearance of heavily degraded hillsides that show a patterned texture, but a low density of small craters, implies a degradation process that acts much faster than meteoritic impact. The characteristic shorelines between highland and mare ground indicate a general downhill transportation, even on slopes as small as 3 degrees (4). Such surface transportation will expose underlying material on high ground, which is in the process of denudation, while it will concentrate the last accreted material on the depositing low ground, and thus re-exhibit regional chemical differences, despite the Moon-wide mixing by meteoritic impacts. Surface flow filling an initially isostatic basin would indeed create the mass excess observed as mascons, and allow brittle fracture at great depth where Moonquakes appear to be generated. The deep powder fill of the maria, greatly compacted at depth, would result in the low radar reflectivity, as well as the great amount of radar limb darkening, and is at the same time in accord with the seismic results (5, 6).

The age of the powder grains may date the solidification of the material on the earlier bodies; their infall from a near orbit onto the Moon would not necessarily cause much heating, and even some of the cosmic ray tracks could survive. The ages of the crystalline rocks would merely reflect the times of impacts of sufficiently large objects to cause melting. These may be the large basin-forming events, or any impacts causing craters of more than a few kilometers diameter. The oldest dates would certify that the Moon of present size existed at that time; younger ages would merely indicate the stragglers in the accretion process.

The virtual absence of water in lunar rocks, and the low concentration of volatiles is easier to understand if the Moon had not heated enough to drive volatiles to the crustal layers and concentrate them there in the liquid magmas. If we are seeing material collected in powder form from space, subjected only to local impact melting, the absence of the volatiles is not surprising.

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