Origin and Evolution of the Lunar Surface: The Major Questions Remaining

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Origin and evolution of the lunar surface: the major questions remaining

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The major factors in the evolution of the lunar surface have not been determined yet. Huge lava flows and lunar differentiation, though commonly assumed, is in discord with much of the evidence. The alternative is for most of the surface to represent the last stages of accretion of the Moon only, with the chemical differentiation having taken place previously in the source material. Radar, seismic, surface exposure, and mascon evidence can then be accounted for. A large-scale surface transport mechanism of soil must then have been present.

The Apollo programme is over. The problems and puzzles that remain about the construction and derivation of the Moon may be with us for a long time.

We have learned a lot of detail. But where do we stand with respect to the major questions? Most investigators appear to have regarded the major questions as settled before the programme started, and thought of the need only of filling in detail. The Moon was thought of as a differentiated body like the Earth. The maria were huge lava beds. Volcanism and impacts together had shaped the surface.

One searched hard for evidence to substantiate these basic concepts. Of course, had they been correct, this might have been a quick way to success. Thus, one searched for volcanic sites, for features related to volcanism, and one interpreted what was seen wherever possible in those terms. Much was built upon that conceptual structure, so that it has now become quite hard to distinguish these constructs from factual evidence. Reports were written presenting as fact what is pure conjecture. For example, in an official report of the Lunar Science Institute, Houston (1972), we read: 'The crust of the moon consists largely of anorthositic rock, a result that was almost totally unexpected.' It is conceivable that that is true, but in fact we have only seen scattered samples of the rocks and the inference that there is a crust of solid rock and that it is made of anorthosite is a very uncertain conjecture. Words like 'typical mare basalt' have become common parlance, although no one knows how this material is distributed and whether it is not just as common in some highland regions. This misrepresentation is a great disservice to lunar science and to the success of the costly lunar programmes.

The only firm evidence of volcanism we have obtained in all missions and all observations, concerns the material, not the moon as a body. Melting and differentiation from a melt undoubtedly played a major role in the manufacture of lunar rocks. But where and by what means this melting occurred we do not know.

In all six Apollo missions, directed strongly towards a search for bedrock, no such stuff has been obtained. No crystalline rock has been sampled that is now lying where it froze. All rocks collected were only scattered, thrown material. There has been no suggestion that any lava flow has been sampled – and this on a body whose surface is a desert scarred with innumerable impacts and heavily denuded in some areas. Would that have been expected for a surface largely created by volcanism?

But the evidence is much stronger than that against lava sheets underlying the surface dust. The radar evidence (Evans & Hagfors, 1968) and the seismic evidence (Latham *et al.* 1970; Gold & Soter 1970; Jones 1973) taken together make it quite impossible that solid rock is a major component at a depth of a few metres, or indeed shallower than about a hundred metres over most of the Moon.

Earth-based radar gives a clear indication that there is not a sudden transition from the top soil to broken-up bedrock at a shallow depth. Long-wave radar (at a wavelength of 7.5 m) (Thompson 1970) would penetrate through the material of the top soil and show subsurface reflections down to a depth of at least 100 m and quite possibly 200 or 300 m. (Lunar soil is much more radar transparent than any terrestrial soil or rock.) Jumbled up pieces of rock would scatter the radio waves back with an intensity several times greater than is observed. Moreover, this rough subsurface would make the Moon more or less equally reflecting over the whole disk, just as the rough optical surface makes the full Moon more or less equally bright. The long-wave radar, however, shows the edge to be more than 100 times fainter than areas closer to the middle. The radar Moon is enormously limb-darkened. It is therefore clear that there are no large areas on the Moon where a thin layer of the surface soil overlies coarsely broken-up bedrock.

On the other hand, the seismic signals clearly preclude any largely continuous rock sheet being present generally at a small depth, for then the enormously reverberant signal that is always observed would have no explanation, nor would the absence of the usual dominant point-to-point signal of a shear and a pressure wave. The seismology could be satisfied only with a sub-surface structure of a coarsely or finely broken up rock; but the radar denies the presence of any structure coarse on the scale of metres (i.e. the radar wavelenths used that penetrate deeply through the powdery soil). The combined evidence is for a deep soil, generally layered, with a compaction increasing with depth, but with only gentle transitions in density, or generally smooth interfaces where a sudden change of density does occur. Only then can the remarkable radar limb-darkening be understood.

Very strong evidence concerning the lunar soil, such as its exposure record, its state of deposition, as well as radar and seismic evidence mentioned, now appears to us to make the case that the surface material fell in more or less in its present form, rather than that it is the consequence of meteoritic grinding of a lunar endogenic crust. Further evidence concerning the Apollo 17 orange soil, the mascons and their absence on the back, and the many indications of surface denudation and deposition all speak for infall and surface transportation processes as having been the dominant effects (Gold 1971, 1973; Ronca 1971).

Many investigators believe that the chemical evidence has proved the opposite case, namely that a chemical differentiation history on the Moon must have preceded the production of the present soil. That these differentiation processes occurred in the material that came to form the lunar soil cannot be doubted. However, there is no way of knowing where this happened. So long as we have no clear understanding of the origin of the Moon, any assumption concerning the original nature of the material must be a weak and needlessly restrictive one.

It has been claimed that the lunar chemical analysis has shown the material to represent to some extent a closed chemical system. This claim can be doubted, but in any case it would not affect the present debate, since the same considerations of chemistry can be applied to a previous body whose surface material may have become the dominant contribution to the outer few kilometres of the Moon.

Nor can the regional distribution be taken to prove that case. It is clear that a large amount of vertical redistribution has taken place on the Moon, such as the deep excavations of the great basins and the deposition of that material to form the surrounding mountains. Therefore any vertical differences, resulting from a compositional change in the course of the accretion, will exhibit themselves as regional differences now. Denudation of high ground keeps exhibiting the lower material there (and crater profiles show that generally more than 2 km have been removed), while the last addition must dominate on the flat low ground. Thus differences among successive layers of the accreted material tend to show themselves as differences between high and low ground.

The lunar soil shows generally a remarkably high surface exposure, as judged by its cosmic ray tracks, by its implanted gases, and by its surface sputter or condensation deposited layer (Maurette & Price 1975; Lal, this volume). If this degree of surface exposure occurred during the entire age of the Moon at the present rate, only a thin layer could have been treated, however well the material was stirred or moved. The estimates of the maximum amount so treated range from a few tens of centimetres to a few metres. While this may perhaps seem adequate to account for the material investigated in the form of the 3 m drill cores, it is far from adequate when the stirring by larger crater forming events is taken into account. Much of the material now in the top few metres must have come from nearby craters that are many tens of metres deep. A substantial admixture of unexposed material should therefore be present almost everywhere in the soil.

Apart from the total amount of surface exposure, the distribution also cannot be accounted for. If random stirring were held responsible for bringing grains to the surface for exposure, then even the most vigorous stirring would still give a larger proportion of unexposed grains than is found. A computer simulation study (Gold & Williams 1974) demonstrates this clearly.

Furthermore, most of the core tubes investigated show many very distinctive layers, with differences of grain size, albedo and chemical composition. However these layers might be produced, their presence argues against the supposition that the soil has generally been stirred exceedingly thoroughly so that most grains could acquire their surface exposure.

If on the other hand direct infall were responsible for the soil, then the observed exposure record would refer to both the exposure suffered by a grain before and after landing on the Moon. Exposure of a tenuous cloud of grains would then be needed only for a short time, on account of the much greater surface area presented; each grain in the cloud may receive an exposure rate as high as only the uppermost layer does on the Moon. Infall of small grains onto a surface that is itself composed of loosely packed small grains will not eradicate either cosmic ray tracks by heat annealing or destroy surface deposits, so long as the infall speeds are only of the order of the escape speed of the Moon (2.4 km/s). In fact, planetary accretion processes may well supply grains out of gradually attenuating orbits, and the impact speed would then be as low as 1.7 km/s (the lunar orbital velocity), assuring the almost complete preservation of all details of the grains.

The Apollo 17 orange soil demonstrates a history of having been frozen from melt in space, and then, as completely hard particles – mainly small spheres or spheroids – having impacted the surface. Electron microscopy studies, performed in our laboratories, on a large number of beads show them to exhibit a very uniform degree of damage; the large beads have mostly one large area of damage on them, and the small ones have a small area of damage. In contrast with most rock chips there appear no hypervelocity impact craters on any of this material. Detailed statistics show that the damage observed must be almost entirely the one resulting from the infall of the material itself, not from any subsequent bombardment. Measurements of the breaking strength of the beads indicate that a high speed of impact into the soft lunar soil would have been required to cause the observed degree of damage. Pending experimental results with glass beads of similar strength, shot into lunar surface type of material, one can only make approximate calculations to define the speed these objects must have had. If that speed turns out to be above the orbital speed, this material must have been part of an infall, and not merely distributed from another location on the Moon. In any case the fall must have covered a large area, possibly the entire Moon, and the small patch found is the consequence of other processes having preserved it unmixed and having brought it to the surface in this location (as well as many others, perhaps, that the astronauts did not happen to visit). The material, though chemically distinctive from most of the lunar material, is nevertheless of a lunar type of composition so far as many abundance ratios are concerned. If it came into the Moon at more than orbital speed and hence from a non-lunar source, the presumption must be that the rest of the soil, being chemically similar, also came from that source. The orange soil thus provides an extremely useful sample of lunar soil for the deduction whether it all is of lunar or extralunar origin.

Within this simple cold accumulation model of the history of the Moon the age differences that are observed have a simple explanation. The age of the powder dates back to the protoplanets, on which it was differentiated. The only age we have then for the Moon is given by the oldest crystalline rocks that are found, of such size that they could not have been preserved in an infall from space. These crystalline rocks are then thought to be scattered by later impacts from the lavas produced in large earlier impacts, such as the ones that created the major basins. Each basin would then possess a supply of crystalline rock underneath its later dust cover, and a regional chemical similarity, but not identity, of dust and rocks can then be understood. On this basis the Moon may be no older than 3.5 Ga or so.

The striking differences between the front and the back of the Moon can be understood if indeed large scale surface migration of the powder has taken place through electrical effects, which are certainly quite different on the two sides (Gold 1959, 1973). The presence of the Earth, as we know very clearly, makes a profound difference to the electrical environment and particle bombardment that the Moon receives. In all other respects the front and the back are treated so nearly alike that no external influence could be suggested to change the surface evolution so completely. We have strong evidence of large scale surface transportation having taken place on the Moon, and flow boundaries that many thought of as lava flows must indeed be boundaries between different masses of powder, since otherwise bedrock at a very shallow depth would be implied which is not admissible on the radar evidence.

The lunar gravity anomalies called 'mascons' have a ready explanation if surface flows have tended to raise the floor level of low areas previously hydrostatically balanced. Where no such surface flows occurred there should be no mascons. Where a large impact had left a pattern of concentric rings and valleys the gravity map should merely reflect these remaining departures from equilibrium – just as is the case in Mare Orientale – while any subsequent addition of material by surface flow would generate a positive gravity anomaly. On this basis the depressions on the back of the Moon, being unfilled, should represent no gravity anomalies. This appears now to have been observed (Sjogren, this volume).

The cold accumulation discussion of the Moon fits well with a number of other data. There is no difficulty in supposing the interior to have always been cool enough to have upheld the stress differences that are seen. The complete absence of volcanism at the present time is then not too surprising. The absence of hydration in the soil can be understood if this is infallen material that had previously been anhydrous, while it is difficult to understand it if it is material differentiated from the interior of the Moon, since it would then have become associated with the water that would equally have become concentrated on the surface by the same differentiation process. If water is now seen to be escaping from the Moon, or if had ever escaped from the entire body, it would have been concentrated in the surface layers and hydrated the lavas just as on the Earth. Even if the total quantity of water escaping from the deep interior had been a very small fraction of the amount that came from the interior of the Earth, it is hard to avoid this conclusion. (The absence of an atmosphere hardly affects this process.) On the other hand, water could be escaping through cracks and fissures of the outer crust, if this is solid, without leaving any signs of hydration except in small regions.

Surface movements of powder, or large-scale lava flows, these are the alternatives for the shaping of the lunar surface. The evidence does not fit the lava flows, but most investigators will not believe the large-scale migration of the powder. This is the impasse at which we are at the end of the Apollo programme.

Lastly, the extreme similarity of the surface of Mercury to that of the Moon suggests that no complex interplay of internal and external activity should be involked, for it would be most unlikely to have been so similar for two bodies that are internally so different. There is no problem if this is the appearance of a surface generated by infall and the common external effects.

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