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Some compositional aspects of lunar regolith evolution

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This paper discusses the compositional aspects of the lunar regolith in terms of regolith dynamics. Emphasis is placed on problems concerning lateral movement and mixing of soil components in response to meteoroid bombardment, and on the source of apparently exotic material in mare soils. In particular, it is shown that there are contradictory lines of evidence concerning the efficacy of impact-related lateral transportation of regolith components. Most of the compositional diversity of regolith in the lunar highlands and at the margins of mare basins can be accounted for by comminution and mixing of local rock types with relatively minor lateral transport. In contrast, the mare regolith contains substantial amounts of apparently exotic, highland-derived components in addition to the local basalts, implying efficient lateral transportation. In view of these contradictions, it is suggested that these so-called exotic components may be of local derivation, excavated by meteoroid impact from beneath thin mare basalt layers. A consequence of this model is that the mare basins are filled with impact breccias and melts and covered by a thin veneer of volumetrically insignificant mare basalt.

Introduction

It is widely recognized that the bulk composition of the lunar regolith results from complex meteoroid impact-related processes, including the comminution, mixing and transportation of various rock types, accompanied by the generation and addition of impact melted glasses. In this paper, an attempt is made to relate compositional characteristics of the bulk soil to regolith dynamics, and, particularly to problems concerning lateral movement of soil components in response to meteoroid bombardment, and to the source of apparently exotic material in mare soils.

Most studies to date dealing with the bulk composition of the lunar regolith have been largely concerned with the chemistry of the soils as a reflection of the composition, distribution and abundance of contributing rock types (e.g. Goles *et al.* 1970, 1971; Hubbard *et al.* 1971; Lindsay 1971; Lindstrom *et al.* 1972; Schonfeld & Meyer 1972; Wanke *et al.* 1972; Duncan *et al.* 1973; Rhodes *et al.* 1974; Duncan *et al.* 1975; Schonfeld 1975). A wide variety of techniques, of varying degrees of sophistication, have been used to identify and estimate the abundance of these rock types in the lunar soil, including variation diagrams, graphical analysis, linear least-squares mixing models, R- and Q-mode factor analysis, and cluster analysis. The main exercise of most of these studies has been to match the observed regolith composition with a mixture of locally sampled rock types and the compositions that reflect the authors' concepts of primary lunar rock types. The latter have multiplied with succeeding missions, but now that data is available from all lunar missions, it seems likely that most soil compositions can be derived from a surprisingly small number of possible primary rock types. These include:

(*a*) high titanium mare basalts (e.g. A-11, A-17 basalts),

(*b*) low titanium olivine and quartz normative mare basalts (e.g. A-12, A-15 basalts),

(*c*) 'KREEP' basalts and breccias (e.g. A-14 breccias),
(*d*) KREEP-like noritic breccias (e.g. A-16, A-17 noritic breccias),
(*e*) anorthositic gabbroic breccias (e.g. A-15, A-16, A-17 anorthositic gabbros),
(*f*) gabbroic anorthositic breccias and anorthositic breccias (e.g. A-15, A-16 anorthosites).
Some of these proposed rock types may not, in fact, be primary, but mixtures of other rock types (Schonfeld 1974). Rocks such as dunite, troctolite, granite, and anorthosite proper are of local significance, but appear to be minor (5 %) components of the lunar soils studied to date. Although using a different nomenclature, a similar, and also relatively limited number of primary rock types contributing to highland soils have been recognized on the basis of glass and lithic fragment analyses (Reid 1974).

The role of lateral transportation

Most soil studies have been concerned with individual landing sites. They have shown that the broad chemical characteristics of the regolith can be largely related to comminution and mixing of prevailing rock types, in response to meteoroid bombardment, with introduction of varying amounts of exotic components. The nature and amounts of these foreign materials vary from site to site, ranging from about 10 % of mostly glassy mare basaltic material at the Apollo 16 site (Duncan *et al.* 1974; Delano 1975), to about 25 % of predominantly anorthositic gabbroic material at the Apollo 11 and Luna 16 sites (Wood 1970; Schonfeld & Meyer 1972), and as much as 30–70 % of a KREEP component at the Apollo 12 site (e.g. Goles *et al.* 1971; Hubbard *et al.* 1971; Schnetzler & Philpotts 1971; Wanke *et al.* 1972). In many cases, the proposed source of the foreign component is at considerable distance from the sampling site, implying either very efficient lateral transportation of the regolith associated with successive meteoroid bombardment, or the introduction of ray material from a single large impact event.

Soil samples collected at the Apollo 15 and 17 sites are particularly useful in evaluating the effectiveness of lateral movement of components of the regolith, since both sites provide the opportunity to examine the compositional consequences of lateral transportation from a well defined mare–highland boundary.

The Apollo 17 site is most informative in this respect because of the varied nature of the geology, which was studied in greater detail than at any previous site, and because of the greater compositional diversity of these soils as compared to soils from other landing sites. Within this wide compositional range, three compositional soil groups have been recognized, each one corresponding broadly with a major geological and physiographic unit (Rhodes *et al.* 1974). These are the Valley Floor, South Massif and North Massif type soils. Each of these soil types can be derived by comminution and mixing of the prevailing local rock types, which include high-titanium mare basalts and orange glass, KREEP-like noritic breccias and anorthositic gabbroic breccias. The Valley Floor type soils are derived primarily from the underlying titaniferous mare basalts and associated orange glass, with lesser amounts of massif derived components such as noritic breccias and anorthositic gabbros. The South Massif type soils, sampled at the foot of the South Massif and from the light mantle, can be generated by mixing locally sampled noritic breccias and anorthositic gabbros in roughly equal proportions, with only minor (10 %) contributions of mare basalt and orange glass. The North Massif type soils, collected along the base of the North Massif, also have compositions consistent with mixing noritic breccias with anorthositic gabbro, but with the latter dominant, and with moderate amounts (20–30 %) of mare basalt and orange glass components.

Several important conclusions concerning lateral transport and mixing of soil components can be made from these observations at the Apollo 17 site.

(1) The chemical homogeneity of the South Massif type soils is particularly striking, in view of the substantial compositional difference between the noritic breccias and anorthositic gabbros, the two major contributing massif rock types, and is in marked contrast to the wide compositional range generated by mixing massif material with local mare basalt. Homogenization thus clearly pre-dates the emplacement of the sub-floor basalts. In addition the compositions of the Valley Floor type soils reflect a mixing trend between mare components and a well-homogenized massif soil, not the prevailing massif rock types. Similarly, at the Apollo 16 site there is a wide scatter of rock compositions, which contrasts with the relative uniformity of the Apollo 16 soils, suggesting that this disparity between rock and soil variance may be characteristic of the lunar highlands. It is unlikely that the apparent chemical homogeneity of highland soils relative to mare soils is a consequence of more extensive gardening of the highland soils, since recent theoretical studies (Gault *et al.* 1974; Quaide & Oberbeck 1975) indicate that only the upper surface of the regolith is extensively mixed, and that inhomogeneities will persist below this surface mixing zone. These predictions are supported by trench and drill hole observations at the Apollo 16 site, as well as other sites, indicating that the soils are layered and heterogeneous. Consequently it seems necessary to suggest that the highland soils are derived from diverse rock types that have themselves been intimately mixed during periods of extensive large and small scale impact and brecciation, during the early history of the Moon.

(2) Lateral transport and mixing of soil components does not appear to have been an efficient process since the emplacement of mare basalts 3.7 Ga ago. Evidence for this is offered by the progressive decrease in massif-derived components in the soils, over a distance of only 4 km, with increasing distance from the North Massif sampling stations (figure 1). Similarly, if the light mantle was derived relatively recently by avalanching from the upper slopes of the South Massif (Howard 1973), then only minor amounts (10 %) of mare components, mostly orange glass, were thrown onto the upper slopes, a distance of less than 5 km, prior to avalanching. If some of this mare component was introduced after avalanching then even less was thrown onto the upper slopes.

(3) There are severe discrepancies in the calculated abundances of certain rock types, based on soil compositions, compared with what one would deduce from the returned sample collection. This is particularly so for the anorthositic gabbro component, and can be attributed to preferential sampling of hornfels-like noritic breccias with respect to the less-coherent anorthositic gabbros. However, in contrast with many other landing sites, the soils at the Apollo 17 landing site can be derived entirely by mixing locally sampled rock types. There is no need to postulate the introduction of any foreign component to account for the soil chemistry, as has been suggested by Evensen *et al.* (1974).

Preliminary studies at the Apollo 15 site (LSPET 1972) showed that the soils become progressively more iron-rich and less aluminous with increasing distance from the Appenine Front, reflecting larger contributions of mare basalt and less of the feldspathic Front components. More comprehensive studies (Duncan *et al.* 1975; Schonfeld 1975) confirm this interpretation and show that the two major Front, or highland components, low-K Fra Mauro basalt and anorthositic gabbro, decrease systematically as the mare basalt contribution increases with increasing distance from the Front–Mare boundary. The LM soils are conspicuous exceptions to this general trend. They contain higher lithophile element concentrations than other soils from the mare surface, and have closer chemical affinities with the Front soils than with the mare soils. Both Duncan *et al.* (1975) and Schonfeld (1975) attribute the distinctive composition of this soil to a high exotic KREEP component introduced by a ray from the craters Aristarchus or Autolycus.

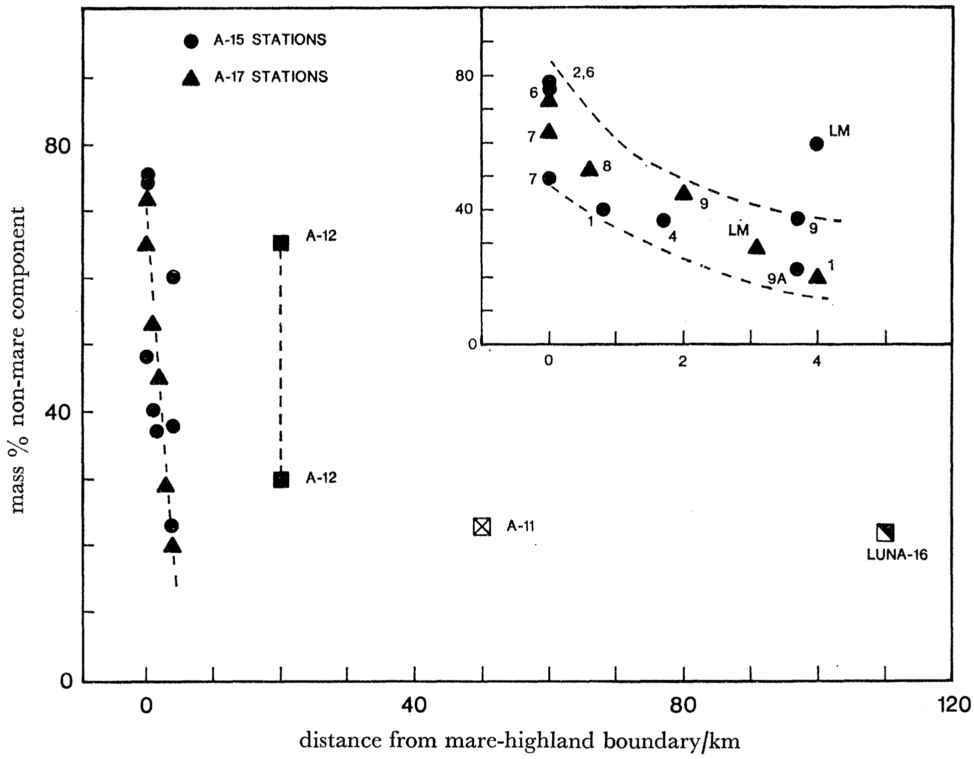

FIGURE 1. Percentage of chemically estimated non-mare components in lunar soil versus distance from a mare-highland boundary. Data for individual sampling stations at the Apollo 15 and 17 landing sites are shown in greater detail in the inset. Component estimates were obtained from Schonfeld & Meyer (1972), Rhodes *et al.* (1974), Duncan *et al.* (1975).

These relations between the content of Massif and Appenine Front components in soils with increasing distance from the mare-highland boundary at the Apollo 15 and 17 sites are shown in figure 1. It is clear from this diagram and preceeding observations that, at these two sites, impact-related lateral transportation and mixing of the regolith is not a particularly efficient process. Most of the components in the soil have been derived locally, and mixing of substantial amounts of highland derived components with mare material is confined to a narrow zone of only a few kilometres. Substantial changes in albedo measurements (Pohn & Wildey 1970) and in surface Al/Si ratios measured by orbiting X-ray experiments (Adler *et al.* 1974; Trombka *et al.* 1974) at mare-highland boundaries, suggest that these observations may be generally applicable over the lunar surface. These conclusions are qualitatively consistent with the regolith evolution models of Shoemaker *et al.* (1970) and Oberbeck *et al.* (1973), which require that the bulk of the soil at a given site is of local derivation.

The problem of exotic components in mare soils

Almost all the mare soils that have been analysed are substantially more aluminous than the contributing local basalts. Similarly, data from the orbital X-ray experiments, summarized by Trombka *et al.* (1974), indicate that the Al/Si concentration ratios for most mare surfaces are more closely comparable with ratios obtained for analysed mare soil than with those for the basaltic rocks. These ratios appear to be relatively uniform over wide areas and similar for several different maria (e.g. Imbrium, Serenitatis, Tranquillitatis and Fecunditatis). Thus, it appears from these observations, that many mare soils contain significant quantities of apparently foreign, more feldspathic material, and that the contamination of comminuted mare basalt with this material is probably a mare-wide phenomenon and not simply restricted to the mare margins or to the few sites from which samples have been returned.

These observations and inferences are clearly in conflict with the conclusions of the preceding section. On the one-hand are the observations at the Apollo 15 and 17 sites, and the steep decline of albedo and Al/Si values at mare-highland boundaries, all of which are indicative of inefficient lateral movement of highland material across the mare surface. On the other hand, are the observations that several sampled mare soils, located from 20 to 120 km from the nearest highland source region, contain substantial amounts of foreign, presumably highland, components, pointing to an apparent efficacy of impact-related lateral movement. This dilemma is illustrated in figure 1. The Apollo 15 and 17 soils show a dramatic reduction in non-mare components, from about 70–20 %, within only 4 km from the highland-mare contact, whereas the Apollo 11, Luna 16 soils, and the Apollo 12 'dark' soils, which are located at distances of 50, 110 and 20 km respectively from the nearest possible highland source area contain comparable amounts of exotic components, as do the Apollo 15 and 17 soils collected from within 3–4 km of the mare-highland contact. The Apollo 12 'light' soils contain even more (about 50–70 %) of an exotic KREEP component, and have some chemical similarities with Apollo 15 Front soils collected at the actual mare-highland boundary.

In view of these conflicting lines of evidence it is appropriate to re-evaluate the source of non-mare components in the mare soils. O'Hara *et al.* (1974) have drawn attention to the discrepancy between abundances of petrographically observed non-mare components in the Apollo 11 soil and the larger amounts deduced from chemical data. They suggest that this anomaly may reflect the prevalence of poorly sampled feldspathic mare basalt fragments in the mare soil. If this is correct, not only will these basalts be more aluminous than most mare basalts, but they must also contain higher lithophile element concentrations. Basalts of this type, although rare, have been found as clasts at the Apollo 14 site and in a single sample (12038) at the Apollo 12 site. Alternatively, the discrepancy in petrographically and chemically estimated highland components may merely reflect a tendency for the exotic material to be concentrated in glasses and in the finer fractions of the soil. Resolution of this problem will require detailed petrographic and chemical studies of a large number of basaltic soil fragments.

Most authors are agreed that this non-mare material, which consists predominantly of KREEP and anorthositic gabbro in varying proportions, is ultimately derived from the lunar highlands. In this case, the question that needs resolving is, whether they were transported large distances on to the mare surfaces following the extrusion of mare basalts, involving either repetitive small-scale cratering events or large-scale deposition from a single large crater ray, or whether they were transported in thick, basin-filling ejecta blankets and impact melts, prior to extrusion of mare basalt, and then subsequently excavated from beneath thin basaltic flows?

Models of regolith evolution proposed by Shoemaker *et al.* (1970) and more recently by Gault *et al.* (1974) and Oberbeck *et al.* (1973), do not favour large scale lateral transport of material, but suggest that the bulk of the regolith is of local derivation. Evidence from the Apollo 15 and 17 sites supporting these models has been presented in the previous section. Additionally, if successive cratering and lateral transportation is an effective process, one would expect to find amounts of mare components in highland soils comparable to those of highland components in mare soils. This does not appear to be the case. For example, although mare components have been identified both chemically (Duncan *et al.* 1973) and petrographically (Delano 1975) in soils at the Apollo 16 site, they account for no more than 10% of the regolith. Similarly it has been argued above that transport of mare components at the Apollo 17 site on to the nearby South Massif was not an effective process.

In order to achieve the comparatively large quantities of exotic highland components in mare soils, many authors have appealed to single massive impacts, and suggested that the foreign material is introduced in rays from large, relatively recent, cratering events. Thus rays from Theophyllus, Copernicus, Aristarchus or Autolycus, and Langrunus or Taruntius have frequently been proposed as the sources for the highland components at the Apollo 11, 12, 15 and Luna 16 sites respectively. There are several difficulties associated with these suggestions:

(*a*) Oberbeck (1971) has shown that the characteristic high albedo of rays is not due entirely to the influx of freshly excavated material, but that it is largely a consequence of many small secondary or tertiary bright-haloed impact craters that have excavated the local regolith. Consequently, the rays are unlikely to have added substantial amounts of ejecta to the local regolith.

(*b*) In the specific case of the Apollo 12 site, Quaide *et al.* (1971) argue that the mapped ray crossing the site is not from Copernicus, but from a Copernican secondary crater only 45 km north of the site.

(*c*) At both the Apollo 12 and 15 sites bore core data indicate that there are layers of KREEP-rich soil beneath the surface. Layering such as this is more compatible with successive sampling of local material than it is with repeated infalls of ray material, which would of necessity have to be derived from different impact events and sources.

(*d*) It is perhaps stretching coincidence too far to require a specific ray at each site sampled to introduce the necessary foreign components. The difficulties with this model become enormous when attempting to expand from a single site to account for the high Al/Si ratio, and inferred feldspathic components, of large areas of the mare surfaces.

In view of the many difficulties discussed above, it is instructive to examine another alternative, namely the derivation of the exotic highland components in the mare soil by excavation from beneath thin mare basalt flows. Wasson & Baedecker (1972) argue convincingly for this alternative in the specific case of the Apollo 12 site. They point to the relatively close proximity of outcrops of Fra Mauro Formation within 20 km of the site, and suggest that KREEP breccias were excavated from beneath the mare flows by Middle Crescent Crater and subsequent cratering events. If this model is correct it implies that the thickness of the mare basalts is of the order of 150 m, which is in reasonable agreement with an extrapolated value of 170 m suggested by Pohn (1971).

There are also problems associated with deriving the KREEP component at the Apollo 15 LM site from an Aristarchus or Autolycus ray (Duncan *et al.* 1973; Schonfeld 1975). First, although situated on a mapped ray area, this area is also one of high bright-haloed crater density, indicating that local re-working may account for much of the higher albedo. Secondly, KREEP-rich material was sampled at the bottom of the drill stem as well as at the surface, thus making a unique source for this KREEP component, such as Aristarchus or Autolycus, extremely unlikely. Thirdly, both Schonfeld (1975) and Duncan *et al.* (1975) infer the presence of substantial amounts of a KREEP component, as well as low-K Fra Mauro basalt, in brown-glass matrix breccias, the dominant sample type at the Apenine Front. It is improbable that the KREEP component in these breccias could also be derived from the Aristarchus or Autolycus ray. In view of these difficulties, it seems possible that this, too, may be of local derivation, either from beneath the basalt flows, or from outcrops of the pre-mare surface such as the nearby North Complex, where high albedo breccias have been identified in photographs.

For this model to have anything but local applicability, the thickness of mare basalt layers must of necessity be much less than has been generally supposed. Furthermore, it requires that the mare basins are filled, not with mare basalt, but more probably with thick blankets of impact melts and breccias, as has been suggested by Head (1974), and overlain by a thin layer of volumetrically relatively insignificant mare basalt.

Although it is known that individual mare basalt flows can be very thin and yet cover large areas, there is little direct evidence concerning the thickness of mare basalt piles. De Hohn (1974) has recently attempted to estimate this in Mare Tranquillitatis, using pre-mare crater rim heights as a guide. On this basis, which will tend to exaggerate basalt thickness, he estimates that the average basalt thickness for Tranquillitatis is of the order of 500–600 m. There are many areas, particularly in marginal regions, where the estimated thickness is 200–300 m or less. The Apollo 11 site is in one of these areas.

In contrast with these measurements, and the inferences of this paper, most geophysical interpretations favour thick basalt piles in the mare basins. For example, the seismic velocity profiles in the Apollo 12–14 area have been interpreted in terms of a 25 km thick upper layer of mare basalt (Toksoz *et al.* 1973). Similarly, the presence of mascons has been widely accepted as requiring substantial basalt thickness. Sjogren *et al.* (1973) show that near-surface mare basalt discs with a depth of 2.5–2.7 km can explain the gravity anomalies of the circular maria. Although there are severe discrepancies in these estimates, they are clearly incompatible with the requirements for excavating highland-derived material from beneath basalt flows.

Conclusions

This paper has emphasized some of the contradictory lines of evidence concerning the effectiveness of impact-related lateral transportation of regolith components. On the one hand detailed studies of specific landing sites at mare-highland boundaries indicate that lateral transportation is an inefficient process and that most of the soil is of local derivation. On the other hand, many mare soils contain substantial amounts of feldspathic, apparently highland-derived components, implying an effective transport mechanism. In view of the striking variance of these conclusions, it is appropriate to re-examine hypotheses concerning the source of feldspathic non-mare components in mare soils and the transportation mechanisms that have been proposed. A model in which the non-mare components are locally derived by excavation from beneath thin mare basalt layers is believed to be capable of accounting for many of the anomalies. Although there are specific examples that provide support for this hypothesis, the geophysical evidence is largely contradictory, but is itself subject to alternative explanations.

Detailed evaluation of remotely sensed compositional data may be capable of resolving some of these problems. For example, it would be useful to know whether the mare regolith is relatively uniform in composition over wide areas as currently available data seems to suggest, or whether there are compositional gradients reflecting varying amounts of exotic highland components. If the latter are found, this could be indicative of either lateral transportation gradients or varying thicknesses of the mare basalt layer. It would also be useful to compare the composition of regoliths from the circular maria with those from the irregular mare areas, since, if the mascons are produced by thick mare basalt fill it is inconceivable that the non-mare material can be derived by excavation, whereas this may be a potential source of this material in the mascon-free irregular maria.

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