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TITLE: Analytical, Experimental, and Modelling Studies of Lunar and Terrestrial Rocks

PRINCIPAL INVESTIGATOR: Larry A. Haskin
Department of Earth & Planetary Sciences
Campus Box 1169
Washington University
One Brookings Drive
St. Louis, MO 63130-4899

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Overview

The goal of our research has been to understand the paths and the processes of planetary evolution that produced planetary surface materials as we find them. Most of our work has been on lunar materials and processes. We have done studies that obtain geological knowledge from detailed examination of regolith materials and we have reported implications for future sample-collecting and on-surface robotic sensing missions. Our approach has been to study a suite of materials that we have chosen in order to answer specific geologic questions. We continue this work under NAG5-4172.

The foundation of our work has been the study of materials with precise chemical and petrographic analyses, emphasizing analysis for trace chemical elements. We have used quantitative models as tests to account for the chemical compositions and mineralogical properties of the materials in terms of regolith processes and igneous processes. We have done experiments as needed to provide values for geochemical parameters used in the models. Our models take explicitly into account the physical as well as the chemical processes that produced or modified the materials. Our approach to planetary geoscience owes much to our experience in terrestrial geoscience, where samples can be collected in field context and sampling sites revisited if necessary. Through studies of terrestrial analog materials, we have tested our ideas about the origins of lunar materials.

We have been mainly concerned with the materials of the lunar highland regolith – their properties, their modes of origin, their provenance, and how to extrapolate from their characteristics to learn about the origin and evolution of the Moon's early igneous crust. From this work a modified model for the Moon's structure and evolution is emerging, one of globally asymmetric differentiation of the crust and mantle to produce a crust consisting mainly of ferroan and magnesian igneous rocks containing on average 70–80% plagioclase, with a large, mafic, trace-element-rich geochemical province, and a regolith that globally contains trace-element-rich material distributed from this province by the Imbrium basin-forming impact. This contrasts with earlier models of a concentrically zoned Moon with a crust of ferroan anorthosite overlying a layer of urKREEP overlying ultramafic cumulates.

From this work, we have learned lessons useful for developing strategies for studying regolith materials that help to maximize the information available about both the evolution of the regolith and the igneous differentiation of the planet. We believe these lessons are useful in developing strategies for on-surface geological, mineralogical, and geochemical studies, as well.

The main results of our work are given in the following brief summaries of major tasks. Detailed accounts of these results have been submitted in the annual progress reports.

Geologic Implications of Cryptic Rock Components of Soils: Chemical Mass-balance Modelling

We can understand the formation and evolution of the Moon's crust only if we can identify and quantify its main igneous rock types. This information must be extracted through studies of the soils and breccias of the regolith, as bedrock sampling is not possible for most rock types. Once an igneous rock type has been identified as a regolith precursor, its provenance must be determined. Using chemical mass-balance (mixing) models, we have shown that lithologies not evident or prevalent in the collection of large rocks can constitute several percent or more of a soil. For example, Apollo 17 soils consist mainly of two kinds of mare components, high-Ti mare basalt and orange glass, and two types of highland components, melt breccia and feldspathic upper-crustal lithologies. Compositional trends in the soils typically extrapolate toward some mixture of the melt breccia and pre-basin components, indicating a physical association of those two highlands components before admixture of the basaltic components (Korotev and Kremser, 1992). The local high-Ti mare basalts are younger than the highland crustal materials, and the orange glass in the soils is readily observed, so these illustrative results are not surprising.

Unlike the orange glass, however, some major soil components cannot be directly identified petrographically because they are too fine grained, have been too well mixed with other materials, or have been converted to glass. Their presence in a soil or breccia can nevertheless be discovered and their proportions precisely determined by chemical mass-balance modelling. Thus, our results (Korotev and Kremser, 1992) showed that all Apollo 17 mare soils contain ~8% of very-low-Ti (VLT) mare basalt. To advance beyond demonstrating that VLT basalt *might* be present as a cryptic rock type to showing convincingly that it is present required mass-balance modelling at an improved, very high level of confidence. We achieved that level by two means: We analyzed hundreds of small rock fragments from the soils to determine what rock types are actually present and to establish their compositional ranges, and we tested thousands of possible model mixtures based on different combinations of these and other well determined rock compositions. The modelling results showed that the only acceptable mixtures of possible components were those including a VLT component, a number of fragments of which were found in the small rock fragments (Jolliff et al., 1996a). Establishing the widespread, well mixed occurrence of the VLT component is geologically important, because there is no known source of VLT basalt within the Taurus-Littrow valley (Korotev and Kremser, 1992). Lateral transport of enough basaltic material from Mare Serenitatis to add several percent of VLT basalt to the valley as a widespread component of mare soils would require nearby impact events producing craters >100 km in diameter, and these craters are not present. Possibly, the source is pyroclastic material from within the valley or flows that underlie the high-Ti basalts of the valley floor.

The presence of VLT basalt in the Apollo 17 mare regolith may be surprising, but it seems plausible given that there is a local mare source, at least for High-Ti basalt. We also showed by precise modelling, however, that the Apollo 16 regolith contains ~6% of a low-Ti mare component (Korotev, 1997c). The nearest known source of mare material near the Apollo 16 site is Mare Nectaris, but that mare has spectral characteristics of an intermediate-Ti basalt. Also, this low-Ti mare component is widespread and well mixed into the regolith to at least half a meter depth, so its presence is not a consequence of lateral transport by small impacts. It does not occur in the ancient regolith component of Apollo 16 (McKay et al., 1986), and may have been added when the Cayley plains formed. The identification of these mare components far distant from any obvious source requires a suitable geologic mechanism of emplacement and places a constraint on the origin of the regolith in which they now occur.

Thus, chemical compositions of regolith fines (the <1-mm particulate component) provide a record of aspects of geologic history that has not been found elsewhere. For definitive work of this type, many of the older chemical analyses of Apollo and Luna materials lack precision or contain too many systematic errors, and many of the materials analyzed early were not characterized petrographically so we cannot be certain what they were. New analyses of well-characterized materials were and in some cases still are required.

Characterizing Typical Lunar Highlands

The best picture of the overall characteristics of typical lunar highlands has come from the Apollo γ-ray data, the Clementine data, and the feldspathic lunar meteorites. The highlands are rich in feldspar (mostly in the range 70–80%), but contain at least several percent FeO nearly everywhere. Highlands of the Procellarum-Imbrium region are also rich in Th and presumably other incompatible trace elements. Of the Apollo and Luna landing sites, the Apollo 16 site is the most like typical highlands, but its regolith is richer than typical in incompatible trace elements and mafic components, judging from the lunar meteorites, remote sensing, and mass-balance modelling. These materials, however, turn out to be late additions to the Apollo 16 highlands.

The "extra" trace elements and highland mafic components are found in mafic impact-melt breccia, which is a significant component of the Apollo 16 regolith (~30%, Korotev, 1997c). We recently discovered that there are at least five compositionally distinct types of mafic impact-melt breccias at the Apollo 16 site, not two as previously believed (Korotev, 1994). Compared to otherwise similar melt breccias from other sites, all of these breccia types are unusual in containing a high abundance of an Fe-Ni metal of meteoritic origin, suggesting their origins are somehow connected. Two terrain units occur at the Apollo 16 site: the Cayley plains and the Descartes Formation; the populations of the mafic impact-melt breccias differ between these two units. Mixing trends in Apollo 16 ancient regolith breccias indicate that the mostly feldspathic components of the ancient highland regolith were well mixed and presumably fine grained before admixture of the trace-element-rich, mafic-impact-melt-breccia component; the mare-derived component of the present Apollo 16 soil was added even later (Korotev, 1996b). The widespread occurrence of the Cayley soils, all very similar in composition, and the behavior of the mafic melt breccias as a single mass-balance end member within them in nearly constant proportion (25–31%) indicates that the event that produced the mixture was a major, relatively late event such as a basin-forming impact, not a series of smaller events (Korotev, 1997c; Korotev et al., 1997). When the mafic impact-melt breccias are "removed" in the mathematical sense from the regolith of either the Descartes or the Cayley terrain, the residual compositions of the "prebasin" regoliths are similar to each other and similar to those of the feldspathic lunar meteorites but somewhat more feldspathic (Korotev, 1996b). Thus, the Apollo 16 regolith is anomalous compared to typical highlands only in containing a higher proportion of KREEP-bearing, mafic impact-melt breccia, a consequence of its proximity to one or more major basins.

Lunar impact-melt breccias. We have compiled a large database of high-precision chemical compositions for lunar impact-melt breccias from the highland landing sites. Using this database, we have characterized compositional groupings (e.g., Apollo 16 - Korotev, 1994), filled in gaps that show in some cases a continuous range of compositions, and discovered new groups (e.g., Apollo 17 - Jolliff et al., 1996a). This database is important because the impact-melt breccias are samples from very large or basin impacts and their compositions and relationships strongly constrain correlations to specific events and source regions. This database allows us to discern subtle differences even in the nature of KREEP components, which reflect deep crustal heterogeneity that relates to early crustal differentiation (Jolliff et al., 1995c; Jolliff and Haskin, 1995; Jolliff, 1997).

Lunar Meteorites. We have combined our ability to analyze small samples and our knowledge of Apollo samples to characterize most of the lunar meteorites and to relate them to the Apollo samples. We have shown that several of the highland meteorites have important ferroan, mafic components as clasts and as cryptic components in matrix and glasses (e.g., Korotev et al., 1996b). In a mixed mare-highlands breccia, QUE94281, we reported on the geochemistry and petrology of VLT crystalline and volcanic-glass components (Jolliff et al., 1997).

Igneous-metamorphic Petrogenetic Modelling

Our early mass-balance modelling showed that a ferroan, highland rock type containing 10% or more mafic-minerals is a significant cryptic component of Apollo 16 soils and was probably an important prebasin highland rock type. This rock type, more mafic than ferroan anorthosite, is almost absent from the Apollo collection as an igneous rock. As part of the prebasin Apollo 16 regolith, by extension it must be present in typical highland soils generally. Lunar highland regolith breccias such as MAC88105 and QUE93069 consist largely of components derived from ferroan noritic anorthosite, a plagioclase-rich rock type, but containing as much as 10–25% pyroxene (Korotev et al., 1996b).

The Pre-basin Highland Crust. We found an example of the anticipated ferroan plagioclase-rich, mafic highland rock we knew form mass-balance modelling had to be present. Among the soils from North Ray Crater, Apollo 16, the one richest in non-Cayley components and richest in Descartes components contains a large suite of fragments of such a rock, a type called ferroan noritic anorthosite (Jolliff and Haskin, 1995). The lunar magma ocean hypothesis suggests accumulation of the mineral plagioclase feldspar by crystallization of that mineral and its separation by flotation from co-crystallizing mafic minerals such as olivine and pyroxene. Individual igneous fragments from the suite contain, in addition to accumulated plagioclase, products of crystallization of interstitial melt. By considering the set of 148 fragments as a whole, we were able to model quantitatively how a noritic anorthosite pluton with those characteristics could have originated, starting as a perched layer of plagioclase-rich mush within a magma ocean or similar setting (Jolliff and Haskin, 1995). The chemical compositions of the fragments and their constituent minerals showed that the process of formation of the rock was complex. Even the accumulated plagioclase, expected to be the simplest component of the rocks, shows evidence of several stages of growth and possible metamorphic recrystallization. This plagioclase made a "framework" of crystals buoyed by magma beneath and within. Part of this magma crystallized within the plagioclase framework, and its crystallization path, constrained by the compositions of the individual fragments, could be matched by combined trace- and major-element geochemical and petrologic modelling.

In recent, precise analysis and modelling of Apollo 17 materials, we determined that the highland component of the North Massif soils was mainly granulitic breccia and mafic impact-melt breccia in roughly equal proportions. We also found, however, that there must be in addition a more mafic Mg-suite component in North Massif soils that is not a significant component of South Massif light mantle soils (Korotev and Kremser, 1992). We then sought the identity of this component by analysis of 2–4 mm soil fragments, and found it to be magnesian troctolitic anorthosite (Jolliff et al., 1996a). The South Massif light mantle soils, which do not require this additional magnesian component, derive mainly from the top of the massif, are >70% mafic impact-melt breccia (Jolliff et al., 1996a). This difference between North Massif soils and South Massif light mantle soils is consistent with a stratigraphy that concentrates pre-basin, upper-crustal material into the lower parts of the massifs. This implies different origins for the upper and lower massif deposits.

The Most Evolved Crustal Igneous Rocks: INAA and Ion-microprobe Studies, New Theory, Experiment, and Quantitative Modelling. Among the 2–4 mm soil fragments from Apollo 14, we discovered a suite of some of the most petrologically and geochemically evolved lunar rocks known (quartz monzogabbro, granite, and an impact-melt rock with REE concentrations three times those of KREEP). This led us to study the mechanisms of chemical evolution of lunar residual melts and to discover the unusual effects of phosphate crystallization, especially whitlockite, on trace-element distributions. Whitlockite grains contained in these samples are rich in REE and within a single rock show grain-to-grain differences in REE concentrations. Previous workers had noted similar high REE concentrations and concentration differences and had concluded that the whitlockite was out of equilibrium with surrounding major minerals; they suggested crustal metasomatism would be required to produce those properties. We showed by modelling that the whitlockite REE concentrations in these rocks could be produced by igneous fractional crystallization (Jolliff et al., 1993a).

Demonstrating the above required development of a new fundamental understanding of the nature of REE partitioning into minerals such as whitlockite. We used a combination of detailed analytical measurements by INAA and by electron and ion microprobes, experiments to determine distribution coefficients, and theoretical modelling to determine the distribution (uptake) of REEs in whitlockite and apatite as a complex function of composition and crystallization timing (Jolliff et al., 1993a; Colson and Jolliff, 1993). We developed a concept of a special feature of late-stage fractional crystallization, that of melt-pocket equilibrium, in which the concentration-dependent partition coefficients come into play only after solidification has progressed to the point of isolating pockets of highly evolved melt. Finally, we used the new theory to model the phosphate REE concentrations observed within the actual lunar rocks.

In the course of this work, we also found the first and only clear example of an immiscible felsic liquid preserved in a plutonic rock, postulated by others to occur when fractional crystallization was extensive and believed important in the genesis of lunar granite (Jolliff and Floss, 1997). We showed that the unusual REE fractionation of lunar granites resulted from the crystallization of whitlockite prior to immiscible-liquid separation, and that the high REE contents of some lunar samples can be related to normal late-stage igneous processes.

Modification of the Pre-basin Highland Crust: The Hypothetical High-Th Oval Region and the Imbrium Impact Event

The highland soils at the Apollos 14–17 sites all contain mafic impact-melt breccia of one or more chemical compositions at each site. All contain meteoritic metal, and the metal found in Apollos 14 and 15 mafic impact-melt breccias, although in lower concentration, has the same composition as that found in the Apollo 16 mafic impact-melt breccias. In order to account for this and other characteristics of lunar surface materials, we have tested and re-evaluated the hypothesis that most or all of the mafic impact-melt breccias are "contamination" from the large Imbrium impact event. We have suggested (1) that the Imbrium event produced thicker, Moon-wide ejecta deposits than previously estimated, (2) that the Imbrium basin was excavated into an apparently unique, Th-rich geochemical province (we call it the High-Th Oval Region), so that the ejected Imbrium material in these deposits would be Th-rich like the mafic impact-melt breccias, and (3) that the distribution of Th concentrations in the highlands could result largely from Imbrium ejecta of material from that region. This work required us to extend previous models for ejecta deposit formation and to re-examine the Apollo gamma-ray Th data. It also set up testable hypotheses for the Lunar Prospector mission: that the High-Th Oval Region is a unique feature of the Moon, and that the Th in the lunar highlands comes largely from that region.

A New View of the Moon

As a result in large measure of the work described above, our current ideas of the Moon's igneous differentiation differ from the paradigm that produces a concentrically and symmetrically differentiated Moon with a highland crust that initially consisted of ferroan plagioclase-rich rocks, then was intruded by more magnesian magmas, and onto which melts form a global urKREEP layer extruded. Instead, we see an asymmetric differentiation to produce a crust consisting mainly of somewhat mafic ferroan plagioclase-rich plutonic rocks and somewhat mafic, magnesian plagioclase-rich plutonic rocks. The differentiation left a unique mafic geochemical province rich in trace elements beneath the Imbrium-Procellarum region (the High-Th Oval Region). The early igneous crust was constantly pounded by impacting planetary debris, the last and most spectacular impact events left the major basins and rearranged crustal materials substantially, in each instance mixing large amounts of material ejected from each basin with many times its volume of material on which the ejecta fell. The next to last of the major, basin-forming events, the Imbrium event, excavated Th-rich material from the High-Th Oval Region and spread it Moon-wide as mafic impact-melt breccia, leaving the pattern of Th observed in the highland regolith by the Apollo γ-ray experiment. All of this early history (and more) is recorded in the chemical compositions of the lunar regolith samples.

Toward Future Planetary Studies

The lessons we have learned from studies of lunar samples can help us design missions for robotic planetary exploration. We have learned that it is essential to understand the origins and provenances of the materials in planetary regoliths. All lunar samples came from regolith, and spectral measurements on the Moon, Mars, and most other planetary objects have been and will be made on regolith. We must now apply our expertise derived from working with lunar and terrestrial materials to prepare for on-surface mineralogy and geochemistry of many planetary objects, at this time mainly the Moon and Mars. We must use the lessons gained from studies of lunar regolith materials in the design of sample returns from those objects. The problem will be significantly different on Mars, given the atmosphere that winnows materials and displaces fines from their origins, and given the reactions with atmosphere and hydrosphere that have occurred. Much of Mars remains heavily cratered, however, so we may expect that many of the regolith materials are of impact origin, although they may have been displaced by later sedimentary processes.

From Soil Ground Truth to Remotely Sensed Terrain. Our extensive analyses of <1 mm soil fines have provided us with a soil compositional map in geological context for each of the Apollo sites, highland and mare. We are using these maps to determine how well spectral data (e.g., ground-based, Clementine, future Prospector) can be used to distinguish among known highland materials and provide several kilometer-scale geological insight. We have shown that Clementine spectra allow us to distinguish among the main soil types sampled at the Taurus-Littrow valley (Jolliff, 1997). Our extensive work on compositions of highland regolith materials caused Korotev et al., 1996 to question early estimates of global Fe concentrations derived from Clementine UV-VIS data (Lucey et al., 1995). Our discussions with the Lucey group about the discrepancy between our estimates and theirs was a factor in their recent revision of their Fe calibration, and has led to collaboration with them to help refine their new method of estimating Ti concentrations (Blewett et al., 1997c). The new calibration based on landing site soil data leads to estimates of highland surface compositions that are consistent with estimates based both on data from the lunar meteorites and the Apollo and Luna sites.

Assessing the Promise of On-Surface-Sensing Methods. We applied our knowledge of Apollo site geochemistry and geology and of analytical instrumentation to determine how well we could expect a particular instrument, an alpha-proton-X-ray spectrometer for major element analysis, to determine rock and soil characteristics that we knew to be present from observing them in Apollo samples. That work has also led to the development of new modelling approaches for such evaluations (Korotev et al., 1995a). One result of that study was to recognize that supplementing the data on chemical compositions with mineral identification and proportions on a small sample scale would greatly enhance our understanding of the materials encountered.

In response, we are currently developing a Raman spectrometer suitable for planetary on-surface sensing (Wang et al., 1997). Raman spectroscopy offers unambiguous identification of most minerals and can be used on a microscopic scale. We are learning how best to apply it to on-surface determination of rock and soil mineralogy (Wang et al., 1995; Haskin et al., 1997). Using it, we can expect to obtain mineral identification, constraints on mineral compositions, and mineral proportions in rocks and soils.

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