As a part of its continuing measurement assurance program, the Mass and Volume Section of the National Bureau of Standards has tested the adequacy of the total correction, $D(V_1 - V_2)$, in various laboratories located at altitudes ranging from near sea level to approximately 2000 m. Several test objects have been used, including kilograms made from a variety of materials ranging in density from 2.7 to 16.6 g/cm^3. An analysis of the data from the comparison of selected objects in this test indicated that $(M_1 - M_2)$ was not constant with location.

Through the courtesy of the Naval Medical Research Institute, Bethesda, Maryland, and the 1099th Physiological Training Flight, U.S. Air Force, Andrews Air Force Base, Maryland, the comparisons have been repeated at barometric pressures up to approximately 2 atm (in a decompression chamber) and down to approximately 0.5 atm (in an altitude chamber). These limited experiments tend to confirm the results of the earlier tests in the various laboratories. Over the pressure range from 0.5 to 2 atm, the magnitude of the effect appears to be 1 mg in 1 kg for objects having a volume difference of approximately 200 cm^3.

In the generally accepted method of computing D, it is assumed that moist air behaves as an ideal gas. Although this assumption may be "almost" true under standard environmental conditions, over the range of the conditions in these tests the lack of ideality could introduce an error in D on the order of 0.06 percent of D. For V_1 and V_2 determined by the best generally accepted methods, the error in the differential volume $(V_1 - V_2)$ is on the order of 0.035 percent of $(V_1 - V_2)$. The combined effect of these two possible errors would indicate an upper bound to the expected mass discrepancy of about 0.2 mg, only one-fifth of that observed.

The implications from the above experimental evidence are as follows:

1) There is an uncertainty in the realization of the mass unit in material other than that of the defining artifact which exceeds the instrumental limitations.

2) The inconsistency in the realization of the unit depends upon the volume difference between the objects being measured and the barometric pressure (the air density). Surface effects do not appear to be significant.

3) With regard to commonly encountered secondary standard weights, the resolution of the apparent problem may require a slight shift in value but will not affect the consistency of the unit so embodied. The magnitude of such an offset is below the level of significance in trade and commerce.

4) The magnitude of the inconsistency may be of consequence in certain areas of scientific study that lie outside of the realm of mass measurement, for example, physical constants, precise force measurements, and meteorology.

Most experiments are conducted at, or near, normal atmospheric pressure, that is, in environments in which there is a limited range of variability in air density. In these cases, the nature of the discrepancy discussed above is essentially that of a systematic error in the unit which is not detectable in terms of inconsistencies in the results of the experiments. Since there are no independent ways of assigning mass values to objects of interest, one must resort to a comparison of the results of measurements in a variety of environments in order to verify the consistency of the results from current measurement methods (*1*).

PAUL E. PONTIUS

Mass and Volume Section, Optical
Physics Division, Institute for Basic
Standards, National Bureau of Standards,
Washington, D.C. 20234

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1. Experiments are under way to determine the exact nature of the anomaly; these data, together with a detailed analysis of past experiments, will be presented elsewhere (P. E. Pontius, in preparation). It is anticipated that a workshop to discuss the problem will be organized later in 1975.

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Chemical Fractionation of the Lunar Regolith by Impact Melting

Abstract. *Impact-produced agglutinitic glass in both lunar highland and mare soils is enriched in mafic elements, in potassium, phosphorus, and sulfur, and in most lithophile elements, whereas it is depleted in plagioclase components including europium. It is proposed that the chemical fractionation is the result of a multistage partial-melting mechanism that accompanies micrometeoroid impacts into soils. The process would be expected to occur on solar system bodies that have an impact-produced regolith.*

Soils returned by Apollo and Luna missions are the products of both destructive and constructive processes. Rock fragments are broken down into smaller particles by micrometeoroid impacts, and glassy agglutinates are created through cementation of grains by impact melts. The decrease in particle size and the construction of agglutinates in lunar soils are indicators of the cumulative amount of exposure at the lunar surface (*1, 2*). It has been widely assumed that the chemical composition of the soils is an expression of the composition of the source rocks, and that impact-melting does not affect the distribution of the nonvolatile elements. We have now found evidence that the impact-melting of lunar soils is accompanied by significant chemical fractionation (*3*).

Agglutinitic glass is enriched in ferromagnesian elements and in most lithophile elements. We suggest that this fractionation is caused by a multistage partial-melting process due to micrometeoroid impacts. The change in the chemistry of the soil with increased exposure at the surface must be considered in attempting to relate soil composition to bedrock composition.

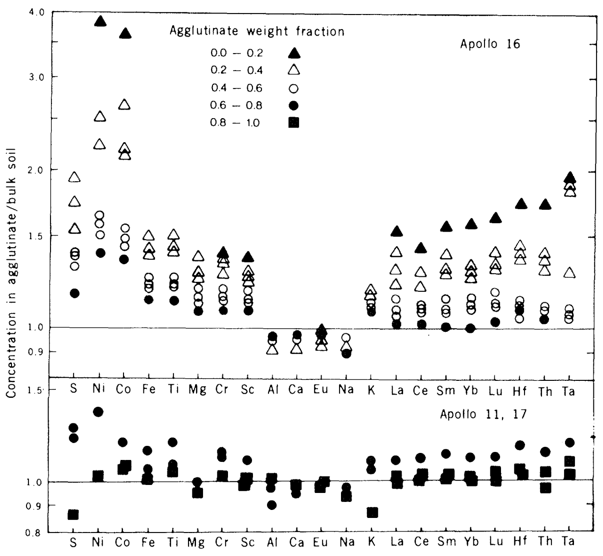

Fig. 1. Concentrations of elements in agglutinitic glass relative to the parent bulk soils. The Apollo 16 soils are from the lunar highlands, whereas the Apollo 11 and 17 soils are from mare regions. Different symbols represent different weight fractions of agglutinitic glass in the soils. The chemical differences between agglutinitic glass and the bulk soil are greatest for those soils containing small amounts of glass. When agglutinitic glass becomes dominant, its chemistry necessarily converges with that of the bulk soil. Agglutinitic glass is relatively enriched in mafic elements and in most lithophile elements but is depleted in the elements that are the components of plagioclase (Al, Ca, Na, and Eu).

In the interpretation of remote-sensing data, in particular, the chemical processes occurring at the surface of the regolith must be taken into account.

Agglutinitic glass was separated from 1-g samples of highland and mare soils from the Apollo 11, 16, and 17 landing sites (*4, 5*). The soils were dry-sieved to < 250 μm and dispersed in a methanol column, and we separated them with an electromagnet by using the high magnetic susceptibility of Fe metal in the agglutinitic glass (*3, 4*). As determined by microscopic examination, the bulk of the ilmenite, pyroxene, olivine, plagioclase, and other mineral and lithic particles remained in the nonagglutinate fraction.

X-ray fluorescence analyses for major elements (*3*) were carried out on aliquants (200 to 280 mg) of the agglutinate and nonagglutinate fractions of 12 soils (*5*). Additional aliquants (20 to 30 mg) of the same samples were used for determining Na, rare-earth elements, and trace elements by instrumental neutron activation analysis (*3*). Analyses of the fractions compared with analyses of the bulk soils (*3*) show that the agglutinitic fractions of both highland and mare soils are enriched in Fe, Ti, Mg, Mn, Cr, Sc, S (*6*), P, K, La, Ce, Sm, Yb, Lu, Hf, Th, and Ta. The agglutinitic fractions are depleted, however, in Al, Ca, Na, and Eu, whereas the nonagglutinitic fractions are enriched in these same elements (Fig. 1). The agglutinitic glass thus is depleted in the components of plagioclase feldspar.

The observed chemical changes are not those expected from vapor-fractionation, and rapid cooling of melt to form glass precludes gravitational crystal-liquid fractionation. Warner *et al.* (*7*) and Simonds *et al.* (*8*) have suggested that chemical fractionation due to impact-induced partial melting may account for different lithologies in highland breccias. Grieve and Plant (*9*) argued that fractionation will not occur in a single impact as there is no mechanism to physically separate the first melt from the residue. They explained fractionation in some Apollo 16 breccias in terms of a two-stage mechanism in which the impact-produced total melt is splashed onto the rock surface and causes partial melting of the ferromagnesian constituents, which are then selectively incorporated into the original melt. We suggest that a similar multistage process may operate on the lunar soil with the following steps: (i) The heat energy released by an impacting projectile completely melts a portion of the soil. The melt is then splashed onto the adjacent, crystalline soil particles. (ii) The hot liquid preferentially melts and assimilates the grains with lower melting temperatures [for example, ilmenite, pyroxene, mesostasis (*10*)]. Rapid quenching of the melt to form glass leads to incomplete assimilation, and high-temperature minerals such as plagioclase tend to remain in crystalline form. The glass thus becomes enriched in ferromagnesian elements, in K, P, S, and in most trace elements, and depleted in the plagioclase components. (iii) Repeated impacts break up old glassy agglutinates (thereby releasing plagioclase inclusions) and continually concentrate ferromagnesian constituents into new glass. Plagioclase remains crystalline longer than the other phases.

The proposed partial-melting mechanism is supported by our observation that ilmenite and pyroxene inclusions are rare in agglutinates from the Apollo 16 soils, whereas these minerals typically occur in the nonagglutinate fraction. The mechanism also is consistent with our conclusion (*2*), based on separations of agglutinitic particles from 80 Apollo soils, that the soils in the maria have higher agglutinate contents (up to 90 percent) than highland soils (up to 75 percent). Highland soils, being rich in the relatively refractory plagioclase, appear to be less vitrified during impact-melting than the mare soils. This finding suggests that, if the percentage of agglutinates in a soil is used as an index of maturity, slightly different scales may have to be applied to the highlands and to the maria as a result of the differences in composition.

A similar fractionation mechanism may have operated to a limited extent on the scale of rocks and boulders in regional ejecta deposits during the very high impact fluxes early in lunar history. It is difficult to demonstrate the process on the scale of rock samples because the sampling of rocks in the regolith is statistically poor and few large (> 1 cm) agglutinates (*11*) are left on the lunar surface because they are rapidly destroyed by subsequent impacts (*12*). The petrographic evidence for multiple stages of brecciation (*7, 8*), however, indicates repeated construction and destruction of particles, and we suggest that remnants of agglutinitic glass may occur in breccias as finely crystalline or glassy intergranular material rich in Fe, Mg, Ti, Mn, and KREEP (K, rare-earth elements, and P) components.

The lunar example suggests that repeated impact-melting of any polymineralic surface should lead to agglutination and thereby to a fractionation of elements. Chemical fractionation of feldspar from mafics in lithic fragments of chondrites (*13*) and the discovery of glassy agglutinates in the Bununu howardite (*14*) are evidence of such a process occurring on a meteorite parent body. Spectral reflectance measurements of Mercury (*15*) indicate the presence of a glassy lunarlike soil layer on the surface, which may also be subject to the proposed partial-melting process. The chemical fractionation that occurs at the lunar surface may, therefore, have occurred on other objects in the solar system that have developed an impact-derived regolith.

JOHN B. ADAMS
MICHAEL P. CHARETTE
*Department of Geological Sciences,
University of Washington, Seattle 98195*
J. MICHAEL RHODES
*Lockheed Electronics Company,
Houston, Texas 77058*

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