

INTEGRATED INVESTIGATION OF THE MIXED ORIGIN OF LUNAR SAMPLE 72161,11*

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Abstract. Sample 72161,11 (dark mantle at LRV-3) has a graphic mean grain size (M_z) of 3.88 ϕ , inclusive graphic standard deviation (σ_I) of 1.29, and a total carbon content of 204 $\mu\text{g C g}^{-1}$ sample, and is, therefore, quite mature. However, the agglutinate content is only 30% in the 90–177 μm particles, indicating an apparent departure from steady state. Analyses of C, CH₄, and H₂ concentrations in size fractions larger than 149 μm show that the volume correlated component of these species increases with increasing grain size. In a homogeneous agglutinate population the volume correlated component is expected to be independent of grain size. The observed increase can be interpreted in terms of the mixing of a dominant local population of coarser agglutinates, with high carbon and hydrogen, with an imported population of finer agglutinates relatively poor in carbon and hydrogen. When analyses of size-fractions from the bulk sample are considered, these effects are apparently obliterated by the admixture of coarse-grained material low in agglutinates. It seems likely that this low agglutinate content is a consequence of the breakdown of the fragile, large agglutinates in the imported material during their movement to the sample site.

1. Introduction

The data accumulated in investigations of lunar samples have made it possible to construct steady state models for certain kinetic processes that are operative at the surface of the moon. Some of these models have defined the equilibria existing between particles of various sizes and solar wind derived elements in the lunar regolith. For this integrated petrographic and analytical investigation of a complex sample from the Taurus-Littrow region, we shall use the comminution-agglutination model proposed by McKay *et al.* (1974) and the solar wind implantation-retention model described by DesMarais *et al.* (1973b, 1974) and Hayes *et al.* (1975) to postulate the origins of the particulate components of lunar sample 72161, 11, a submillimeter fraction of a surface sample from the dark mantle regolith at LRV-3. The area sampled for 72161 is located near light mantle material at the base of the South Massif.

On the basis of Zn, Cd, and Ga content, Baedeker *et al.* (1974) estimate a high 16% orange glass component in 72161. High Fe and Mn values further suggest to them that South Massif contributions to this sample are small. Philpotts *et al.* (1974) come to a similar conclusion of mixed origin for this sample on the basis of Rb-Yb data. They further suggest that 72161 may represent “relatively recent ray material ejected from near or on North Massif.” Though Rhodes *et al.* (1974) classify 72161 as a ‘North Massif Type Soil’ (dominant in all dark mantle material), Miller *et al.* (1974) consider

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72161 to be intermediate in composition between dark and light mantle materials. In short, previous investigators have generally called for a mixed origin for 72161. On the basis of our integrated investigation we propose to characterize the admixed component.

2. Experimental

Grain size analysis was performed by wet sieving with liquid argon following the method described by DesMarais *et al.* (1973a). Wet sieving with boiling argon serves two purposes. It provides for the gentle agitation required to obtain complete size separations of the regolith particles, and it removes the dust layer from the particle surfaces. These effects facilitate the identification of particle types and allow production of homogeneous size fractions. Modal analyses (binocular microscope) for particle types were carried out on size fractions greater than 45 μm . Most of the comminuted basalt fragments were also brecciated, and are classified here as breccias. Agglutinates were identified on the basis of morphology, heterogeneity of included grains (both grain-type and grain size vary), and the presence of non-entire margins with re-entrant angles, etc.

Analyses for CO , CO_2 , CH_4 , and H_2 were carried out by stepwise pyrolysis in a helium atmosphere. Amounts of gases released were measured with a calibrated Hewlett-Packard 5700 A gas chromatograph fitted with a Varian, Inc. helium ionization detector (DesMarais *et al.*, 1973a). A least-squares fit to a third-order polynomial is now used to define the calibration curves. The bulk sample (72161, 11), ten bulk sieved fractions (down to 4.75 ϕ or 37 μm) were analyzed.

3. Results and Discussion

The grain size distribution of 72161, 11 for the ten size fractions is described by the following parameters (Folk and Ward, 1957):

Graphic Mean (M_z) = 3.88 ϕ

Inclusive Graphic Standard Deviation (σ_I) = 1.29 ϕ

Inclusive Graphic Skewness (Sk_I) = -0.23, and,

Graphic Kurtosis (K_G) = 1.38

Modal analyses are given in Table I and are plotted in Figure 1. These results indicate that: (a) the maximum concentration of agglutinates occurs in the 2.5 ϕ (177 μm) to 3.5 ϕ (90 μm) size range, (b) agglutinate contents correlate negatively with dark vitric breccia contents for the various size fractions, and (c) except for light vitric breccias, there is no systematic size-dependent concentrational trend of the individual particle types.

The pyrolysis analyses of methane and total carbon concentrations in the bulk sample and in the agglutinates are presented in Table II. Our results show a total carbon concentration of 204 $\mu\text{g C g}^{-1}$ for 72161, 11. Such a high carbon content, together with the very fine mean grain size ($M_z = 3.88 \phi$) and a sorting (σ_I) of 1.29 ϕ , clearly indicate that the lunar sample 72161 is from a mature regolith. According to McKay *et al.*

TABLE I

Modal analysis data for 72161, 11 in different size classes (in number percent)

	0 ϕ -2 ϕ	2 ϕ -2.3 ϕ	2.5 ϕ -3 ϕ	3 ϕ -3.5 ϕ	3.5 ϕ -4 ϕ	4 ϕ -4.5 ϕ
Plagioclase	2.7	1.6	1.0	3.8	3.1	5.4
Pyroxenes, etc.	2.7	1.6	1.0	2.4	4.2	2.8
Rocks	5.4	3.1	3.1	2.4	3.1	1.3
Breccia						
Vitric, dark	40.5	50.0	39.8	34.5	34.8	44.9
Vitric, light	2.7	10.9	10.2	15.4	17.4	20.3
Recrystallized	2.7	1.6	2.5	2.0	4.2	1.9
Glass						
Spherules	8.1	4.7	4.1	1.0	3.5	2.8
Irregular	5.4	7.8	8.2	7.5	7.3	9.2
Agglutinates	29.7	18.8	30.1	31.1	22.3	11.4
Number of grains	37	64	196	293	287	316

(1974), such a mature sample should contain approximately 47% agglutinates in the 90–150 μm size range. However, Table I shows that the agglutinate content of 72161, 11 in this approximate size range is only about 30%. A departure from the steady state is indicated. Together with the workers cited in the introduction, we attribute this departure to the mixing of regoliths of different origins.

Lindsay (1974) views agglutinate content differently than does McKay *et al.* Lindsay (1974) proposes that agglutinate content may serve as an indicator of maturity only for samples in a small segment of the lunar ‘soil evolution path’ which is dominated by agglutinate formation, since crushed (comminuted) agglutinates appear to have a

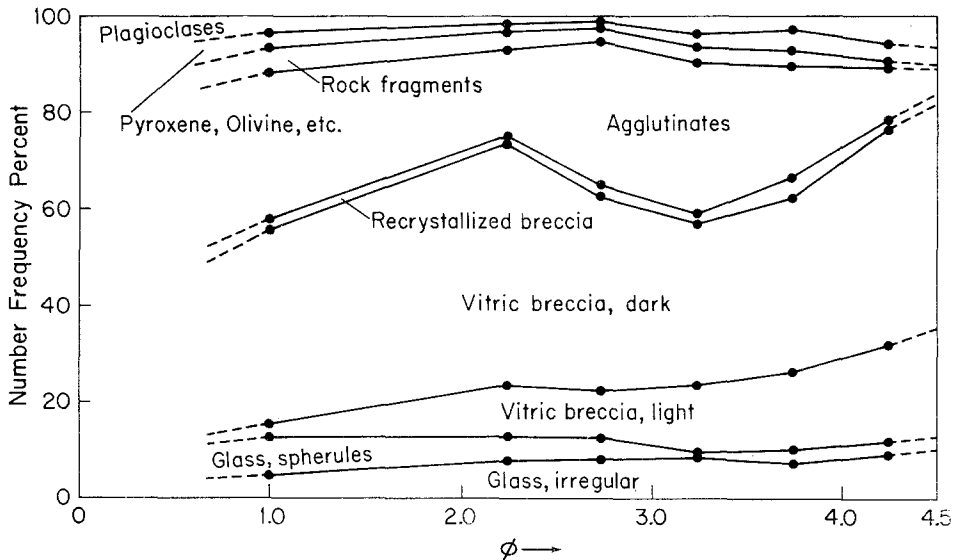


Fig. 1. Plot of number frequency percent particle type vs. grain size in ϕ units in lunar sample 72161, 11. Note general absence of size-dependent composition trends.

TABLE II
Distribution of C, CH₄, and H₂ in the size fractions of 72161,
11 (in $\mu\text{g g}^{-1}$ sieved fraction)

Size fraction μm	H ₂		CH ₄		Total C	
	Bulk	Aggl.	Bulk	Aggl.	Bulk	Aggl.
420-1000	49	93	0.5	2.3	74	187
250-420	55	85	0.7	1.4	87	173
149-250	58	84	1.0	1.3	99	162
105-149	59	101	1.4	1.7	114	146
74-105	80	107	1.2	2.0	148	174
53-74	107	128	3.2	2.2	175	190
37-53	106	246 ^a	4.2	4.1	225	242
30-37	99		4.8		236	
20-30	121		7.0		332	
< 20	193		9.0		465	
Average-bulk sample		144		3.8		204 ^c
Intercept ($\mu\text{g g}^{-1}$ particle)	52	67	0.58	0.23	78	98
Slope ($\mu\text{g cm}^{-2}$)	98	194 ^b	6.6	8.1 ^b	287	319 ^b

^a Doubtful point; disregarded for regression analysis.

^b For the 4 finest size fraction only.

^c Moore *et al.* (1974) report 200 $\mu\text{g C g}^{-1}$ sample for 72161, 12.

mode at about 6ϕ . A comparative discussion of the McKay *et al.* and Lindsay models is beyond the scope and purpose of this paper, but it should be noted that Lindsay's proposal does not nullify our hypothesis concerning the mixing of regoliths in any way.

To further consider the distribution of carbon and hydrogen, we will follow the treatment introduced by DesMarais *et al.* (1973a), in which the relationship between particle size and, for example, total carbon content is expressed as an equation of the form

$$[\text{C}]_r = [\text{C}]_v + S_c/r,$$

in which $[\text{C}]_r$ is the concentration ($\mu\text{g C g}^{-1}$) of carbon in a size fraction of average radius r (cm), $[\text{C}]_v$ is the concentration ($\mu\text{g C g}^{-1}$) of the volume-correlated component, and S_c is the 'surface concentration' ($\mu\text{g C cm}^{-2}$) of carbon. The coefficients $[\text{C}]_v$ and S_c can be determined from regression analysis, or graphically, from a plot of $[\text{C}]_r$ vs $1/r$, and are useful parameters for the comparison of lunar soil samples. The 'surface concentration' is not genuine, however, because it is based on assumptions of particle sphericity and uniform particle density (3 g cm^{-3}). This treatment is not restricted in its applicability, and is useful with all solar wind-implanted or surface-correlated species.

Micrometeorite bombardment is the principal driving force for comminution, agglutination, and particle cycling (Heiken and McKay, 1974). The effect of cycling is

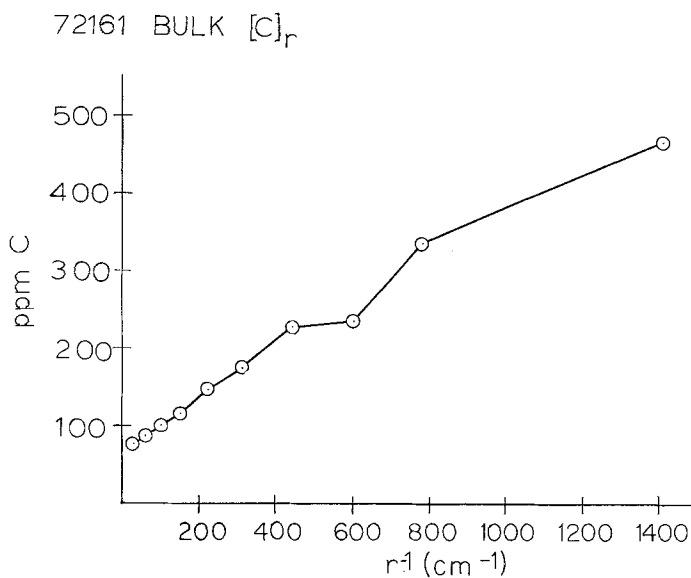


Fig. 2a.

Figs. 2a-c. (a) Plot of total C (a, b) and CH⁴ (c) concentrations in $\mu\text{g C g}^{-1}$ sieved fraction vs $1/r$, in bulk and agglutinate separates from sieved fractions of 72161, 11.

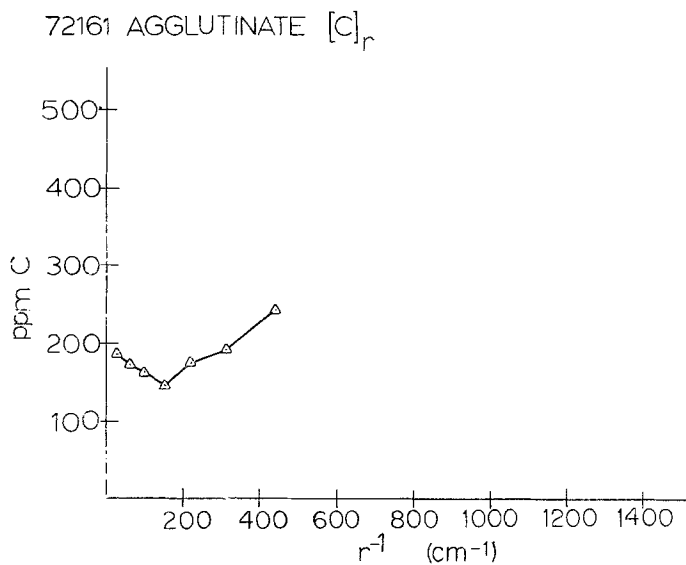


Fig. 2b.

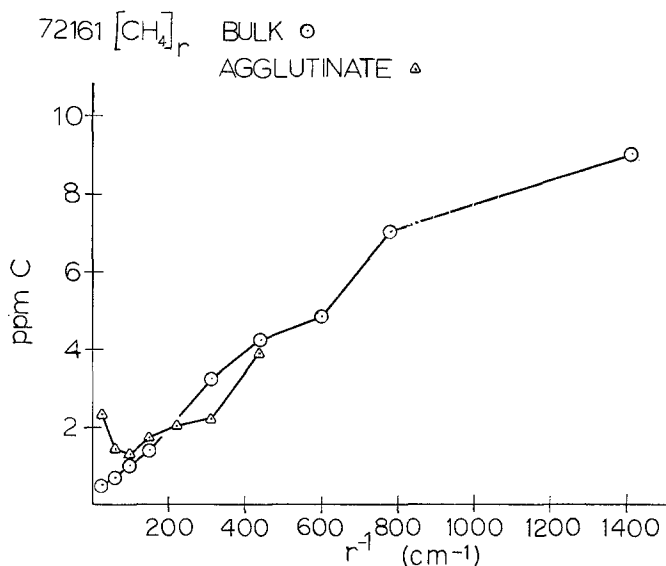


Fig. 2c.

manifest in a general increase in $[C]_v$. For a mature regolith sample in a steady state, an asymmetric V -shaped $[C]_v$ vs $1/r$ curve is expected (this curve appears in Figure 4 as the 'host' curve). With maturity and higher agglutinate content, an upswing of the curve occurs in the coarser grain sizes (greater than $50 \mu\text{m}$ radius) because of the increased agglutinate content in this size range. Examples of this upswing in samples 15012 and 15401 are reported in DesMarais *et al.* (1973b).

When particles are welded into agglutinates, some of the carbon implanted on the surfaces of these particles by the solar wind becomes incorporated into the volume correlated carbon component. Because the size of an agglutinate increases with the number of particles that are welded to form it, the ratio of volume to surface correlated carbon should increase as the size of an agglutinate increases. Thus, if agglutinates are separately analyzed, the smaller grain sizes with larger surface to volume ratios should display (as do other particle types) a linear correlation of carbon concentration versus $1/r$, whereas the larger agglutinates with relatively small surface to volume ratios should display a nearly horizontal curve independent of $1/r$.

Results for the bulk sieved fractions, the agglutinate separates from other sieved fractions, and the total bulk sample are given in Table II and plotted in Figures 2 and 3. In the different bulk size fractions, analyses for total C (Figure 2a), CH_4 (Figure 2c), and H_2 (Figure 3a) show that the concentrations of these species increase linearly with $1/r$. In the absence of the expected upswing in the curves in grain sizes larger than approximately $100 \mu\text{m}$ diam, this could have meant that only surface implantation of these species due to solar wind irradiation has taken place without any significant cycling or any significant agglutinate production. However, the effects of prolonged exposure of the sample to solar wind remain manifest in the high carbon and hydrogen

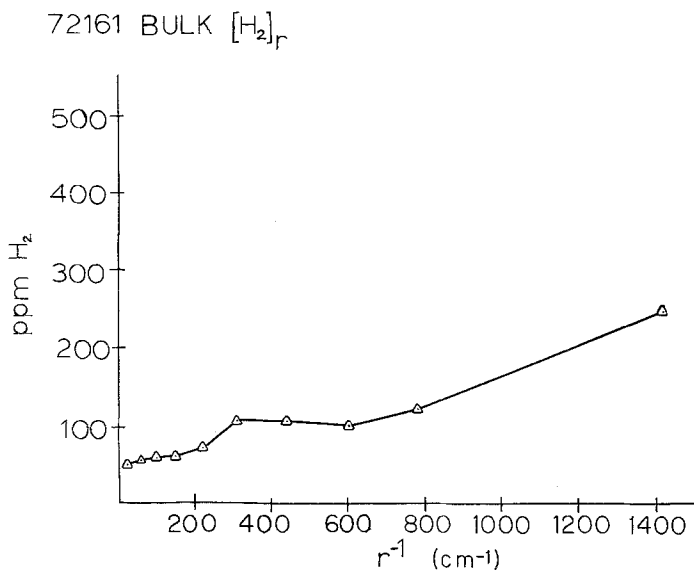


Fig. 3a.

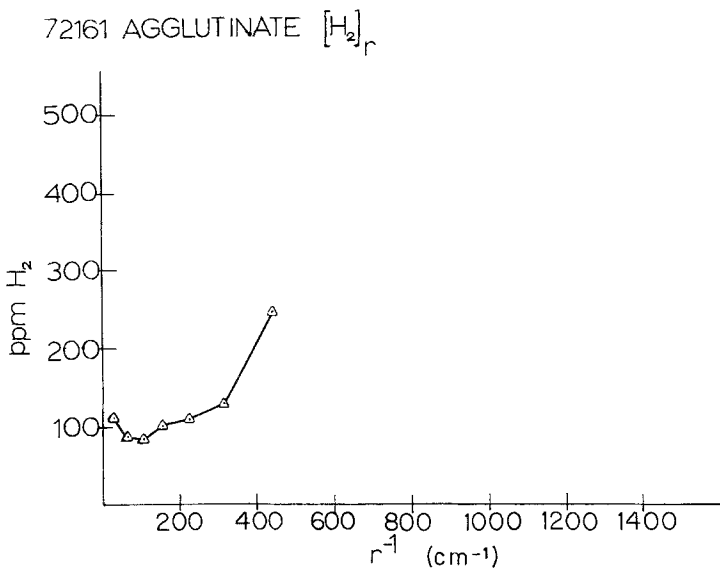


Fig. 3b.

Figs. 3a-b. Plot of H₂ concentrations in $\mu\text{g H}_2 \text{ g}^{-1}$ sieved fraction vs $1/r$, in bulk (a) and agglutinate separates (b) from sieved fractions of 72161, 11.

contents, particularly in the finer grain sizes. For such a mature sample it is difficult to explain an absence of cycling and the depleted concentration of agglutinates. As a matter of fact, a departure from the expected steady state is indicated.

The analyses of agglutinate separates from the different size fractions for grain sizes larger than $149 \mu\text{m}$ show an upswing in total carbon (Figure 2b), methane (Figure 2c), and hydrogen (Figure 3b). Theoretically, as discussed earlier, the concentrations of total C, CH_4 , and H_2 in agglutinate separates in that size range should have virtually no slope. Also noteworthy are the facts that (a) such upswings are absent in the bulk size fractions, (b) the lowest concentrations of these species occur in the size range of maximum agglutinate concentrations, and (c) the slopes of the curves are much higher than those observed for other steady-state samples. Again a departure from the models is indicated.

As suggested previously by Baedeker *et al.* (1974), and by Philpotts *et al.* (1974), the presence in 72161 of a mixture of soils provides the most satisfactory explanation. On the assumption that the host material was fully matured prior to mixing, we can now further characterize the admixed component on the basis of the present work.

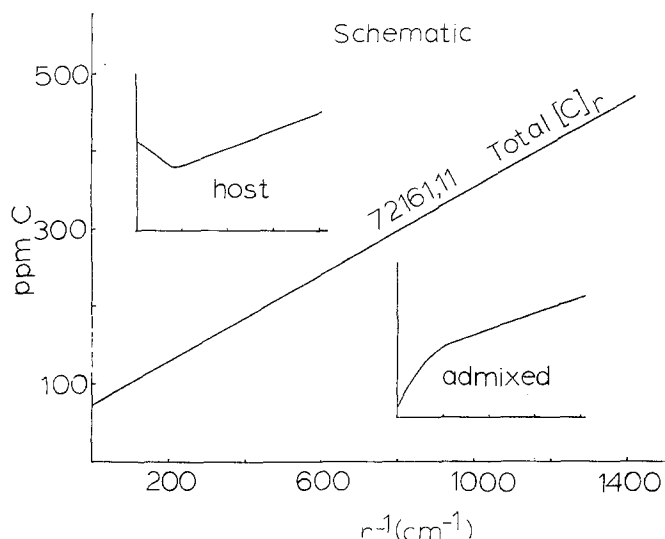


Fig. 4. A schematic representation of the distribution of total C concentrations with respect to grain size in the 'host' and the 'admixed' components of the experimentally derived plot for 72161, 11.

We begin with an *in situ* mature host regolith presumably in a steady state with respect to both its petrographic characteristics and the distribution of solar wind-implanted carbon and hydrogen. The imported component has the following effects on the modified mixed product: (a) dilutes the modal concentration of agglutinates in the product, particularly in sizes greater than $100 \mu\text{m}$ diam, (b) reduces the expected enrichment of total C, CH_4 , and H_2 , in the larger size fractions, (c) probably increases

the enrichment of these species in the finer sizes of the product thus increasing the slopes of the curves which, therefore, provide only an apparent surface concentration, and (d) reduces the expected abundance of these species in the agglutinate fraction in the 2.5ϕ ($177 \mu\text{m}$) to 3.5ϕ ($90 \mu\text{m}$) size range of maximum agglutinate concentration.

Therefore, the added component must have the following characteristics: (1) a very low agglutinate content in the coarser sizes and relatively higher concentrations in finer sizes, thereby accounting for (a), (b) and (c) above; this is because the agglutinates have much higher concentrations of volume-correlated C, CH₄, and H₂ and are consequently richer in these species than other particle types making up the regolith material – this could happen if the process of transportation of the added component was so energetic that the agglutinates, being very fragile, were preferentially comminuted, and, (2) the agglutinates of the imported component must be poorer in total C, CH₄, and H₂ than is the host, thus explaining (d) above – this could happen if the added component was an old buried regolith in which the old agglutinates also suffered greater loss of the implanted species.

A schematic representation of the above concept with respect to solar wind-implanted species (specifically for carbon) is shown in Figure 4. We can speculate, but certainly not substantiate any further, that the added component could have been an old regolith buried under a thin cover elsewhere, ejected relatively recently due to some small (?) meteoritic impact, and spread (as a ray?) on the site of 72161. Subsequent reworking by micrometeoritic bombardment completed the mixing process.

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