Heterogeneous agglutinitic glass and the fusion of the finest fraction (F³) model

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Abstract—Evidence in favor of the model fusion of the finest fraction (F³) for the origin of lunar agglutinitic glass has been accruing. They include (1) theoretical expectations that shock pulses should engulf and melt smaller grains more efficiently than larger grains, (2) experimental results of impact shock, albeit at lower than presumed hypervelocity impacts of micrometeorites on the lunar regolith, and (3) new analyses confirming previous results that average compositions of agglutinitic glass are biased towards that of the finest fraction of lunar soils from which they had formed. We add another reason in support of the F³ model. Finer grains of lunar soils are also much more abundant. Hence, electrostatic forces associated with the rotating terminator region bring the finest grains that are obviously much lighter than courser grains to the surface of the Moon. This further contributes to the preferential melting of the finest fraction upon micrometeorite impacts. New backscattered electron imaging shows that agglutinitic glass is inhomogeneous at submicron scale. Composition ranges of agglutinitic glass are extreme and deviate from that of the finest fraction, even by more than an order of magnitude for some components. Additionally, we show how an ilmenite grain upon impact would produce TiO₂-rich agglutinitic glass in complete disregard to the requirements of fusion of the finest fraction. We propose an addition to the F³ model to accommodate these observations (i.e., that micrometeorite impacts indiscriminately melt the immediate target regardless of grain size or grain composition). We, therefore, suggest that (1) agglutinitic glass is the sum of (a) the melt produced by the fusion of the finest fraction of lunar soils and (b) the microvolume of the indiscriminate target, which melts at high-shock pressures from micrometeorite impacts, and that (2) because of the small volume of the melt and incorporating cold soil grains, the melt quenched so rapidly that it did not mix and homogenize to represent any preferential composition, for example, that of the finest fraction.

INTRODUCTION

Micrometeoritic bombardment is the principal process of space weathering of the lunar regolith. The process produces melt and vapor. The melt bonds soil grains, forms agglutinates, and for convenience is called "agglutinitic melt", which is preserved as agglutinitic glass. The vapor, although extremely important in the context of space weathering, is not the concern of this paper, which is, instead, the melting process vis a vis the data gathered in recent years.

Our new nanoscale backscattered electron (BSE) imaging of agglutinitic glass, results obtained by Taylor et al. (2001), and results from modeling impacts on porous targets (Cintala, 1992), amend and enhance our understanding of lunar agglutinates and the agglutination process termed the F³ (fusion of the finest fraction) model (Papike, 1981). Taylor's is a set of micron-scale measurements showing that the proportion of agglutinitic glass (identified chemically) in lunar soils increases with decreasing grain size. Cintala quantifies melt and vapor products from porous targets. Based on these results, our previous work (Basu et al., 1975; McKay and Basu, 1983; Basu and McKay, 1985), and our current work we argue that (1) agglutinitic melts are inherently inhomogeneous; (2) the melts are the sum of an "indiscriminate melt" of a part of the target and preferential melting of the finest fraction in the target; (3) many, if not all, of the homogeneous domains in agglutinitic glass are extremely small volumes (<<10 μm³) of the total melt, which did not mix before quenching; and (4) multiple recycling events remobilize and amalgamate the micromelts into larger multiple domains of inhomogeneous glass.

We use "indiscriminate melting" to imply a melting process that is not controlled by any eutectic, peritectic, or cotectic properties of the target composition; rather, the production of a superheated melt of the volume of the target through which
high-intensity shockwaves travel before attenuation. We do not envisage this melt to have a necessarily single composition. Rather, we expect that compositional domains within the target will initially produce melts of different compositions that do not necessarily mix and homogenize before quenching. For example, feldspar-rich and pyroxene-rich domains within the melting volume will produce melts of feldspar-like and pyroxene-like compositions that may flow alongside collecting, incorporating, and entraining smaller dust grains. "Modal melting" in which the composition of the resultant melt is the same as that of the melted volume of the target, is different from our concept. The F³ model implies modal melting of the finest fraction of lunar soils. Inhomogeneous indiscriminate melting in addition to F³ is the concept that we support with our new data.

RECENT WORK

Modal analysis of lunar and terrestrial material using an electron microprobe has been in practice for some time (e.g., Albee et al., 1973; Chodos et al., 1973; Dymek et al., 1975; Rooney and Basu, 1994). The technique has been recently refined and adapted to conduct modal analyses of lunar soils to determine the proportions of single phases in lunar mare soils (Taylor et al., 1996). Identification of specific phases is dependent on windows of chemical compositions set up by the operator. Once such windows are set up, phase-identification is automatically assigned based on the chemical composition of any pixel of the target as determined by an automated energy or wavelength dispersive x-ray analysis software. Automatic summation of analyzed spots of similar composition quantifies the abundance of each phase in the sample. Presumably, each analyzed spot is submicron in size although the excitation volume under the electron beam may be 3–5× larger. Thus, relative proportions of phase distributions in lunar soils are determined at least at 2–3 μm scales. Taylor et al. (2001) have found, by defining agglutinatic glass chemically, that in any "given soil with decrease in grain size, the abundances of the agglutinatic glasses always increase" from 45 μm to below 10 μm (unless specified otherwise the size of a grain is expressed as the size of the sieve opening through which the grain passed). The principle of this method of modal analysis of lunar soils is identical to that of the Gazzi–Dickinson method used for optical modal analysis of terrestrial clastic sediments (Gazzi, 1966; Dickinson, 1970; Gazzi et al., 1973; Ingersoll et al., 1984; Suttner and Basu, 1985; Zuffa, 1985; Rooney and Basu, 1994). The method renders the results independent of the size of soil grains (e.g., Ingersoll et al., 1984; Zuffa, 1985). This means that if the proportion of one or more phases changes in different grain-size fractions of the same material, and especially if the change is systematic, then there must be a systematic addition or removal of the phase from appropriate grain-size fractions.

Cintala et al. (1993) conducted comminution experiments on two terrestrial natural glasses (tephra and obsidian) and found that they are weaker than olivine, pyroxene, and feldspar. Therefore, preferential comminution of agglutinatic glass is a likely process to concentrate agglutinatic glass in finer sizes. Consequently, the new data (Taylor et al., 2001, 2002) are compatible with the results of apparently the only experimental study (Cintala et al., 1993). The data are also compatible with the less likely possibility that more agglutinatic glass is produced in <10 μm sizes than in larger sizes. Note that on recycling (i.e., as smaller fragments of previously formed agglutinates are incorporated in newer larger agglutinates) agglutinatic glass is added to larger sizes (McKay et al., 1974). This process acts in the opposite direction of preferential comminution. It is likely that agglutinatic melts form in the region of 10 μm, binding clasts including previously formed agglutinates, to form larger agglutinates. The latter, upon comminution, systematically adds to the population of agglutinatic glass in finer fractions.

It is reasonable to accept that hypervelocity impacts of micrometeorites on the lunar regolith produce melts that scavenge nearby grains, congeal rapidly (indigenous microcrystallites are extremely rare in agglutinatic glass), and form agglutinates (McKay et al., 1972). At the point of hypervelocity impact (i.e., at the peak shock stress the target vaporizes); however, it is likely that some of the impacts on the lunar regolith are made by projectiles that do not have sufficient velocity to create significant vapor, but may still produce a melt. Away from the point of impact, shock stress attenuates, melting occurs followed by fracturing of the target at lower shock stresses. Calculations and modeling based on physical properties of matter, as well as some experimental work (Cintala, 1992), show that impacts (e.g., at 15 km/s) into the lunar regolith generate ~7× as much liquid as vapor. The volume of liquid produced (i.e., the melt volume) may range from ~10 to 50× the volume of the projectile depending on the physical properties of the projectile (e.g., diabase or Fe-metal). Whereas these model-dependent numbers are not absolute for all atmosphere-free planetary bodies at different distances from the asteroid belt (and the Sun), production of significant amounts of impact vapor is a robust result. Part of this impact vapor possibly escapes the gravitational field of the Moon; part may be trapped in vesicles in agglutinatic glass; the rest must condense back on surfaces of exposed lunar material (e.g., Christofferson et al., 1996; Keller and McKay, 1993, 1997). Cintala (1992) additionally shows, as have many others (e.g., Kieffer, 1971, 1975; Schaal et al., 1979), that porous targets melt and vaporize at lower shock pressures than non-porous targets. A corollary: for identical impacts, porous targets (e.g., regolith) would produce more melt (and vapor) than a non-porous large target (e.g., a rock fragment). Porosity in this case has to be understood in terms of the size of the projectile relative to the target. For example, to a 10 μm projectile, a collection of loosely packed 10 μm grains as target is porous but a target of 10 cm rock fragment is non-porous.
CURRENT WORK

Many features of agglutinates are submicron in size. Resolution of optical microscopes with normal lenses stands at \(~1 \mu m\) at high magnification, which can be improved by a factor of 2 or 3 with oil-immersion lenses under favorable conditions. We have followed up our optical microscopic observations with BSE microscopy and imaging of agglutinates and their interiors at about 5–10 nm resolution. We have examined and collected \(\sim 1500\) BSE images of the interiors of \(~75\) agglutinates from 20 soils using a JEOL FEG-scanning electron microscope (SEM) at the Johnson Space Center. Observations and images provide higher resolution than that obtainable with optical microscopes or with older SEMs, which refine and add to our previous observation. Although new results do not lead us to fundamentally revoke our previous inferences, they provide direct evidence for non-F3 melting. We confirm that agglutinitic glass, in general, consists of small (\(<10 \mu m\)) domains of homogeneous entities. Margins of these domains commonly show concentrations of micron-scale clasts, vesicles, and FeO globules, which define flow lines (Figs. 1 and 2). Many vesicles and FeO globules tend to attach themselves to edges of larger clasts (e.g., around pyroxene in Fig. 1b, ilmenite in Fig. 2b) or larger vesicles (e.g., upper right in Fig. 1b).

DISCUSSION

Agglutinitic glass is a preserved product of shock melting by micrometeorite impacts. Recent work indicates that agglutinitic glass (defined chemically) is preferentially concentrated in sizes \(<10 \mu m\) (Taylor et al., 2001). Given Cintala’s model, one infers that the size of the majority of micrometeorites responsible for producing agglutinates must also be \(<10 \mu m\). From a study of impact pits on Gemini windows, Zook et al. (1970) estimated that the modal size of micrometeoroids at 1 AU to be \(~8 \mu m\). Whereas this is the mode of the numbers of micrometeorites, most of the mass of micrometeorites is carried by those that peak at \(~100 \mu m\) (Zook et al., 1970; Grun et al., 1985). If so, the major numerical flux of micrometeorites is responsible for producing agglutinitic melt on the Moon and the larger micrometeorites may be responsible for producing large glassy objects (See et al., 1983). However, note that a part of the melt produced on impact into soils will jet out in a spray, incorporating dust and then quench in flight. Botryoidal outer surfaces of most whole agglutinates (Figs. 3.8 and 3.9 in Taylor, 1975) attest to the availability of free space during quenching. Much of the melt may be injected into surrounding subsurface soils to produce clast-rich agglutinates or simply bond soil grains within the regolith. If so, domains of glass preserved in single agglutinates could be only a fraction of the total melt generated per impact. Regardless, the inference from current work is that micrometeoritic impacts produce agglutinitic melt in very small quantities accompanied by a significant proportion of vapor.

FIG. 1. Backscattered electron (BSE) images of compositional domains in agglutinates: (a) at least three domains of molten material (medium gray, light gray, and white) in vesicular agglutinitic glass; (sample 15221); (b) small (some \(<1 \mu m\)) domains of different glass compositions and partly melted to apparently unmelted mineral clasts, 75081; note the heterogeneity in the distribution of FeO globules within the glass.

Compositions of such small domains of melt provide clues to their origin. Electron probe microanalyses of 1–2 \(\mu m\) sized or smaller spots on agglutinitic glass range in composition from being feldspar-like to being pyroxene-like (Charette and Adams, 1975; Gibbons et al., 1976; Basu and Bower, 1976; Via and Taylor, 1976; Hu and Taylor, 1977, 1978; Basu and McKay, 1985). Optical and BSE microscopy shows that glass in any agglutinate is commonly comprised of compositional domains (Fig. 1). The domains are commonly \(<10 \mu m\) in size. Multiple analyses within small domains of glass in single agglutinates are similar to each other; however, the domains differ in composition from each other within a single agglutinate. In fact, the widths of domains analyzed by Basu and McKay (1985)
were of the order of 1 $\mu$m; analyses were done on a spot-mode at the highest magnification of an SEM in which the spot was no more than 100 nm in diameter (we note that the excitation volume is larger, perhaps up to a maximum of 10$\times$, than the actual spot size). Quantitative analysis at finer resolution requires transmission electron microscopic (TEM) techniques and much thinner sections.

**Indiscriminate Melting**

In view of recent results, we consider the initial agglutinitic melt to be intrinsically inhomogeneous (i.e., does not necessarily represent only the finest fraction in the target). In this scenario, indiscriminate melting of a very small target, be it a collection of micron-scale grains or the surface of a single large mineral grain, produces a melt the compositional variability of which is ideally identical to that of the target. If the target is homogeneous, the melt is homogeneous; if the target is inhomogeneous, the melt is inhomogeneous. If there is sufficient turbulence in the melt and if there is sufficient time before quenching, the melt or some of its initial domains may homogenize. If melting is accompanied by differential volatilization or fractional vaporization, the composition of the melt will be rendered different from that of the target (e.g., Nancy *et al.*, 1976; Delano *et al.*, 1981), which may not directly affect the degree of homogeneity but may contribute to turbulence. Whereas impact melts may be produced instantaneously, the melt takes some finite time to quench into glass. During this time, the melt may flow and penetrate between cold soil grains. Clasts of random compositions and random sizes are incorporated into or attached to the melt. These clasts aid in quenching the melt in its heterogeneous state. Many observations show that heterogeneous glass at micron and smaller scale is common in most agglutinates (Figs. 1 and 2). The scenario given above is compatible with such observation. However, many agglutinates contain glassy segments that are larger than 10 $\mu$m. This observation needs an explanation.
Reycling

Recycling of lunar soils and soil grains is a well-documented process (e.g., McKay et al., 1974, 1977; Mendell and McKay, 1975; Basu and Meinschein, 1976; Basu, 1990). Not only can fragments of older agglutinates be incorporated into newer agglutinates (Fig. 3), older agglutinative glass can also be remobilized to mix, but not necessarily homogenize with new melts (Simon et al., 1986b). The process of recycling, thus, not only alters the degree of homogeneity of agglutinative glass, but also increases the total quantity (and proportion) of glass in agglutinates (Basu, 1977; McKay and Basu, 1983). Our observations indicate that most of the whole agglutinates we see in lunar soils, especially in mature ones, are products of recycling. The glass in these agglutinates is heterogeneous in composition, occurs in regions >>1 \mu m, and commonly comprises >10% of the whole grain.

Fusion of the Finest Fraction (F^3)

Papike (1981) proposed the F^3 model. The model invokes a mechanism of preferential melting of the finest fraction of lunar soils upon micrometeoritic impact. Walker and Papike (1981) stated that "finer size fractions ... melt more efficiently because of their higher surface area: volume ratios". Their absolute small sizes also contribute to preferential melting. Cintala (pers. comm., 2001) cites three reasons: first, "a given heat pulse would engulf a smaller fragment much more quickly and thoroughly than a larger one", second, "the smaller the particle, the less [is] the distance the shock pulse has to decay", and third, smaller grains being products of comminution have already suffered shock damage that has "depressed [the] heat of fusion for such small particles". Relatively low-shock-pressure experiments appear to indicate that such is the case (Hörz et al., 1984; Simon et al., 1985, 1986b). All contribute to "a greater ease in melting" of the finest fraction. Additionally, the modal size of micrometeorites (about 8–10 \mu m; Zook et al., 1970; Zook, 1975) is smaller by orders of magnitude relative to the clasts in the lunar regolith. Large clasts, say >1 cm, would not behave as a porous target even if a layer of submicron dust covers them; however, a collection of smaller grains, say <50 \mu m, would behave as a porous target that would likely contribute to preferential melting (Kieffer, 1975; Kieffer et al., 1976; O'Keefe and Ahrens, 1977; Hörz and Schaal, 1981; Cintala, 1992). Lunar soils, (<1 cm fractions of the lunar regolith) are very fine grained with a mean grain size between 40 and 50 \mu m and most are finely skewed (i.e., the median is finer than the mean) (Graf, 1993). This implies that finer grains of lunar soils are more readily available as targets of micrometeoritic impacts than larger grains. Additionally, the Rossiwall principle requires that the topmost layer (only a few grains in thickness) of the lunar regolith have an excess of the finest grains (Chayes, 1956; Criswell, 1975). Electrostatic forces that accompany the terminator region of the Moon would also elevate and deposit the finest fraction of lunar soils at the very surface of the Moon (Criswell, 1972, 1975; Rennilson and Criswell, 1974; Criswell and De, 1977). Thus, any micrometeoritic impact on the lunar regolith would melt the finest grains because they are more abundant in general and especially so in the topmost layer of the lunar regolith.

The Prediction—Given the above arguments, "The F^3 model predicts that the composition of agglutinate glass will fall on a mixing line between the composition of the <10 \mu m fraction and the bulk composition of the soil in which it formed" (Papike, 1981, p. 806; Papike et al., 1981, p. 412). This implies that the composition of agglutinative glass in any given soil should vary, with a few exceptions, only within a short range.

The Test—The model was explained and defended in a series of papers (Walker and Papike, 1981; Simon et al., 1981; Laul
et al., 1981; Papike et al., 1981). Walker and Papike (1981) and several others (see the bibliography in Simon et al., 1986a,b for a complete list) have shown, statistical protestations notwithstanding, that the average composition of agglutinitic glass in several agglutinates in a given soil is biased towards that of the finest fraction relative to the bulk composition of the soil. Our analyses of some 600 submicron spots on several agglutinates bear out the above (Basu and McKay, 1985). Based on finding a depletion of ilmenite in the finest fractions of lunar mare soils and a concomitant depletion of TiO$_2$ in agglutinitic glass, Taylor et al. (2001, 2002) have also supported the model. Note that it is the average composition of glass in several agglutinates in a soil that shows this bias. If the proportion of agglutinitic glass (defined chemically) increases with decreasing grain size (Taylor et al., 2001), it is only expected that the composition of agglutinitic glass in any size fraction would be biased towards that of finer sizes. Thus, the evidence put up in favor of the F$^3$ model is somewhat compromised. For example, if a size fraction (say "x") of a soil were to consist of only agglutinitic glass, the composition of agglutinitic glass in any size fraction in that soil would mimic the composition of size fraction "x". Yet, given the theoretical considerations listed above and experimental studies by Cintala et al. (1993), Hörz et al. (1984) and Simon et al. (1985, 1986b), there should be overwhelming support for F$^3$.

Exceptions—The range of agglutinitic glass composition is extremely large within single agglutinates, agglutinates in any single soil, and in general (see plots in Gibbons et al., 1976; Via and Taylor, 1976; Hu and Taylor, 1977, 1978; Basu and McKay, 1985). For example, Hu and Taylor (1977) find that MgO varies from ~0% to ~12%, FeO from ~0% to ~14%, and Al$_2$O$_3$ from ~14% to ~34% in agglutinitic glass in soil 61241. Analyses of agglutinitic glass in four different agglutinates in soil 12033 show different ranges and different averages (Fig. 3 of Basu and McKay, 1985). In the literal sense of the F$^3$ model, the range and averages of agglutinitic glass compositions in different agglutinates in the same soil should be similar, if not identical, to each other and to that of the finest fraction of the
soil. That is not the case. Rather, compositional differences between glass domains in and between single agglutinates are common.

Modification—We propose an addition to the concept of the F3 model, which we believe brings our understanding of agglutinatic glass closer to reality. We envisage that indiscriminate melting of the target will take place in the zone of peak shock pressure from a hypervelocity impact, irrespective of the composition and the size of the target grain(s). Preferential melting of the finest fraction will occur principally in the volume of the target where shock pressures are lower and for reasons mentioned above, especially because of their preponderance at the lunar surface. Additionally, not all grains will melt fully, especially if the target is orders of magnitude larger than the micrometeorite. The inhomogeneity of the target is likely to persist in the melt that may not have the time to mix completely before quenching. Thus the total melt produced by a micrometeoritic impact is not only that of the finest fraction nor is it a product of modal melting. It is a combination of both indiscriminate melting and preferential melting.

We illustrate the above with an image of an agglutinate in the 90–150 μm fraction of soil 76321 (Fig. 4a,b). We see an ilmenite grain melted in part to produce Fe-Ti-rich agglutinatic glass, the entity of which is distinct in the otherwise Si-Al-rich glass of the agglutinate (Figs. 4c,d are energy dispersive spectra of the two phases). The Fe-Ti-rich glass contains a string of FeO globules and is clearly agglutinatic in origin. The average composition of all agglutinatic glass in this grain may well be on a mixing line between those of the bulk composition soil 76321 and its <10 μm fraction. However, the glass is heterogeneous and some, specifically the one illustrated in Fig. 4, can be easily traced to its primary parent mineral clast. We infer that an impact on an ilmenite grain with a veneer of dust resulted in a total indiscriminate melt of the dust and a part of the ilmenite grain to produce the Fe-Ti-rich agglutinatic glass.

SUMMARY

Agglutinatic glass is the quenched melt produced by the impact of micrometeorites on lunar soils. The melt is, on average, a product of the fusion of the finest fraction (F3), a la the model proposed by Papke (1981). Agglutic agglutinatic glass, however, is intrinsically inhomogeneous in composition even at submicron scale. We, therefore, recommend an addition to the F3 model suggesting that agglutinatic glass is an incomplete mixture of the indiscriminate total melt of the target in the zone of peak pressure and fusion of the finest fraction in the immediate surrounding.

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