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A CONSTRAINT ON IMPACT THEORIES OF CHONDRULE FORMATION [1]

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The association between agglutinates and chondrule-like spherules, which characterizes the assemblage of impact-derived melt products in lunar regolith samples and some gas-rich achondrites, is not found in primitive chondrites. This observation suggests that impacts into a parent-body regolith are unlikely to have produced the chondrules. We believe that if chondrules were formed from impact melt, it was probably generated by jetting during particle-to-particle collisions, presumably in the nebula.

1. Introduction

Many, if not most, chondrules have clearly formed by solidification of melt droplets, and an origin for these droplets by hypervelocity impact melting is now commonly [1–3], though not unanimously [4–6], accepted. The term "droplet chondrule" has been advanced [7] to describe those objects for which a molten stage is incontrovertible and throughout this article the term "chondrule" will imply "droplet chondrule". Two types of impact process have been described for chondrule production, distinguished by the environment in which impacts occurred. On the one hand, the surfaces of massive parent bodies (conceptually of the asteroid size) are proposed as the impact site [3,8–11], whereas on the other hand, collisions between dispersed objects of comparable, small (conceptually centimeter) size have been suggested [2,7,12]. Kieffer [7] has called the first type of impact, in which one of the impacting bodies is much larger than the other, a "particle-to-parent" impact and the second type, in which they are of comparable size, a "particle-to-particle" impact. Implicit in the former category of theories is usually the identification of the target object with the parent body upon which the chondrites were eventually assembled following further impact brecciation and lithification (e.g. [11]). However, a sub-category of this one may be considered, in which chondrules were ejected from impacts on planetesimal surfaces, to be subsequently accreted by other planetesimals, or the same one. Distinctions between these different environments will be elaborated later.

The internal textures within chondrules closely resemble those developed during laboratory simulations involving crystallization after supercooling by 400–750°C below the equilibrium liquidus temperature, indicating comparable degrees of supercooling for chondrules [13]. Thus it appears that the melting event erased from the chondrules themselves any textural evidence concerning their ancestral environment, though Dodd and Teleky [14] have interpreted preferred orientations among olivine crystals in certain chondrules as resulting from fabrics developed within one or more extended magma bodies. However, apart from this

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possibility, intrinsic properties of the chondrules have failed to yield tests capable of distinguishing between the different theories. It has therefore been necessary to rely upon indirect evidence bearing upon this question.

We consider here the possibility that some petrographic evidence, apart from the chondrules themselves, may be present in chondrites, capable of shedding light on the nature of the chondrule-forming process. Note that this evidence does not necessarily bear upon the origin of the *chondrites*, which have been shown to be, in most if not all cases, brecciated rocks from near-surface regions of several, probably asteroid-sized parent bodies [11, 15–21].

Of the two impact processes described above, particle-to-parent and particle-to-particle, the former is by far the better studied as it is the dominant ongoing geological process on the lunar surface. Kieffer [7] has suggested that the products of particle-to-particle impacts are significantly different from the products of particle-to-parent impacts, and we are here particularly interested in the melt products. In general, the nature of these products may be influenced by the temperature, physical state, etc., of the impacting materials, and it is possible to imagine a large variety of parent body states, ranging from porous dirty snowballs to hot crystal/mush mixtures. However, it appears that early formed bodies, at least at the formation location of the chondrites, were relatively cool ($\lesssim$700 K), rocky objects [22,23]. We know from lunar studies that repeated impacts onto a parent body surface can indeed produce spherules * (which may or may not crystallize into chondrule-like structures depending upon their chemical composition and/or thermal history) [3,10,11,27], as well as comminuted rock fragments, high-pressure phases and various other forms of melt-derived glass. The most abundant form which such glass takes on the lunar surface is as agglutinates or glass-welded aggregates which "consist of comminuted lithic, mineral and glass fragments bonded by glass droplets" [28]. It is generally agreed that agglutinates form both by spatter of impact-melted droplets onto the regolith surface while still fluid and by injection of impact melt as stringers into the porous regolith immediately surrounding an impact crater [28]. The close association between spherules (using the term to include chondrule-like objects) and agglutinates in lunar regolith samples is thus not surprising and a similar association has been reported [29] for gas-rich achondrites (howardites) for which an origin as regolith breccias similar to those on the moon has been generally accepted [30–32].

* The category of spherule considered here does not include material such as the orange and green glasses for which an endogenic origin, e.g., by fire fountaining, is generally accepted [24–26].

The preceding considerations lead us to the following hypothesis: by analogy with spherule-agglutinate associations observed in lunar samples and howardites, if chondrules sensu strictu were formed by impacts into parent body regoliths, there should be a corresponding association between chondrules and agglutinates in chondrites. This letter describes a search for such an association. Although we have no quantitative information about the ratio of agglutinates to spherules formed under a variety of impact conditions and regolith textures, we believe that large deviations from the ratios observed in lunar samples (about 1 in breccias (this work) to 10 in soils [33]) and howardites (about 1 [34]) would indicate an environment quite different from a lunar type of regolith. Two assumptions underlying this hypothesis are that if agglutinates were formed simultaneously with chondrules they would have been preserved with them; and that they would still be recognizable. It is known that recognizable agglutinate fragments survived induration into howardites, which are not noticeably less well compacted than many primitive chondrites, and glass-welded aggregates have been reported in some lunar microbreccias [35]. Nonetheless it seemed useful to investigate not only the possible presence of agglutinates in chondrites but also the survivability and recognizability of agglutinate fragments in similarly coherent lunar regolith breccias. An examination of such material is therefore also described.

2. Observations

Although glass is not uncommon in unrecrystallized chondrites, apparently the only description of "agglutinate-like" material in the literature is for two inclusions in the Weston chondrite [21]. From the published description and micrograph it is not clear how well the Weston material satisfies the observational criteria listed below. In addition to "agglutinates", Weston is described as containing thetomorphic silica and other evidence of high-pressure shock, suggestive of a parent body regolith [21].

Observational characteristics of agglutinates which serve as diagnostic criteria, at least on the basis of lunar experience, include a pronounced flow structure accentuated by abundant submicroscopic opaque grains; envelopment and, frequently, partial melting of a variety of lithic and mineral fragments; marked vesicularity; and a generally rounded outline, often incomplete due to fracture. With these criteria in mind, polished thin sections of a number of chondrites were examined in the petrographic microscope using both transmitted and reflected light. Representative chondrites were chosen from a number of categories deemed likely to have an unaltered regolith breccia structure. These categories included gas-rich ordinary chondrites (Fayetteville, Tysnes Island and Weston), unequilibrated ordinary chondrites (Hallingeberg and Khohar) and carbonaceous chondrites (Murchison and Santa Cruz).

Sections were scanned at 250 X magnification. The only possible, but by no means certain, agglutinate-like fragment was found in the Fayetteville gas-rich ordinary chondrite and is illustrated in Fig. 1. None

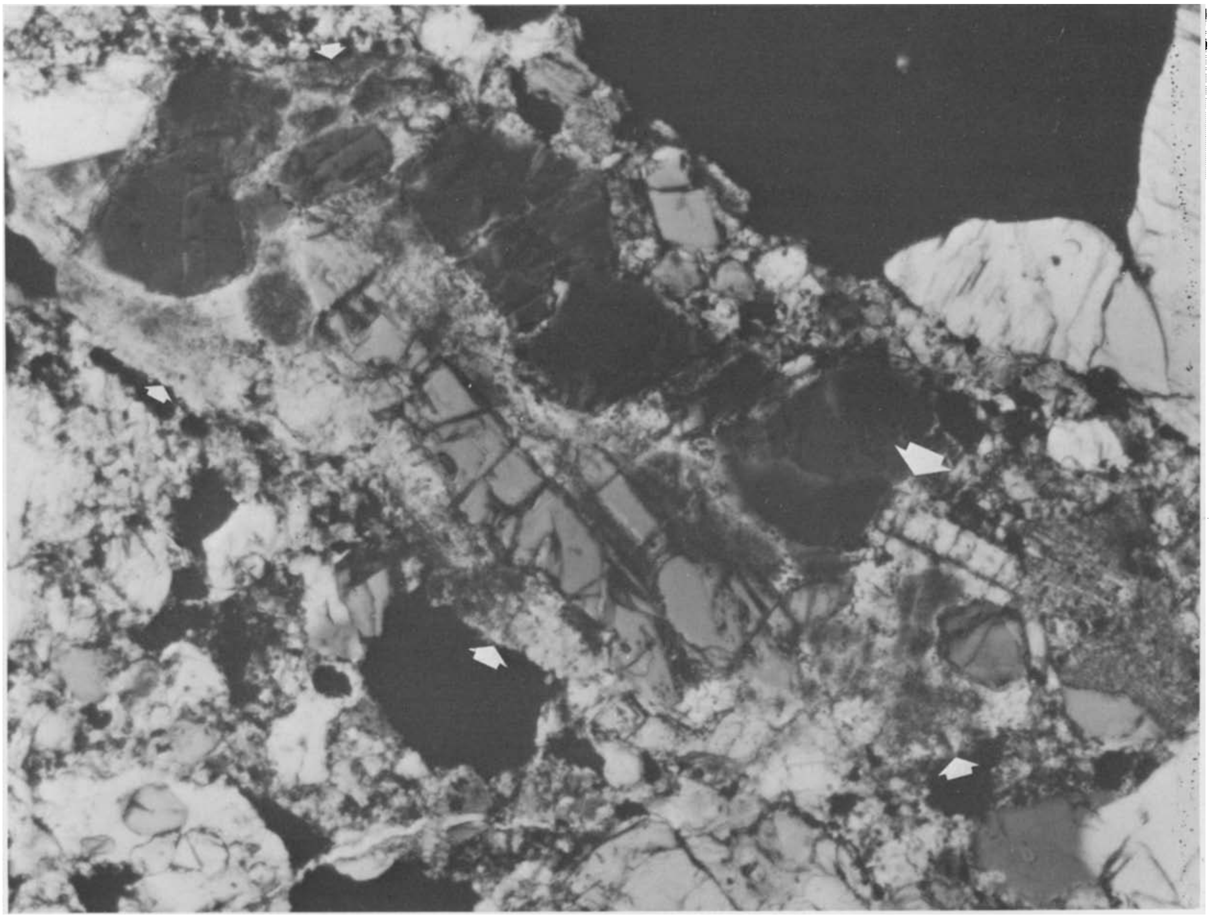

Fig. 1. Possible agglutinate fragment in the Fayetteville gas-rich ordinary chondrite. Note that, of the diagnostic criteria listed in the text, only the envelopment of mineral grains by glass is convincingly satisfied. A weak flow pattern may be detected in the glassy matrix but vesiculation and a rounded outline are missing. Boundary of the fragment is indicated by arrows. Polarized light, field of view 350 μm X 450 μm.

TABLE I

Agglutinate fragments were identified in those lunar breccias marked with an asterisk

10021,48 *	15459,13 *
10044	15466,13 *
10060,28 *	70019,96 *
10061,27 *	72395,80
12034,33 *	79035,63 *
14047,53 *	79135,24 *
14063	
14301,81 *	
14318,45 *	
15086,32 *	
15298,6 *	
15299,56 *	

were observed in the other meteorites. This result obviously cannot yield a quantitatively meaningful ratio for the proportion of agglutinates to spherules in chondrites but qualitatively it is clear that this value, if in fact sensibly different from zero, must be much less than 1 : 1 and therefore less than the values characteristic of lunar regolith or howardites.

In the second part of the observational study, polished thin sections of 18 lunar breccias, from all Apollo sites except 16, were examined microscopically under identical conditions to those employed for chondrites (Table 1). A regolith origin for the breccias chosen was inferred from literature analyses for carbon, nitrogen or ^{36}Ar. A few breccias for which high carbon contents were quoted turned out to have no other regolith characteristics, suggesting possible carbon contamination. Recognizable agglutinate fragments were observed in most breccias examined; quantities ranged over several orders of magnitude from "rare" to "abundant". Cohesiveness of these breccias ranged from "friable" to "tough" [36]. Agglutinates were generally of comparable or greater abundance relative to spherules, but no obvious relationship between agglutinate content, either absolute or relative to spherules, and grade of cohesiveness was apparent. It is particularly noteworthy that agglutinates were found in breccia 14318, a spherule-rich microbreccia whose densely welded structure has been interpreted as resulting from final compaction, after a number of impact episodes, at very high temperatures [11].

3. Discussion

Before interpreting the observed lack of significant agglutinate-spherule association in chondrites in terms of the chondrule production environment, we should consider other possible explanations for the rarity, or even absence, of agglutinates in chondrites.

First, it has been suggested [37] that agglutinate-like material with chondritic composition, significantly more mafic than lunar crustal composition, would readily crystallize, eliminating the glassy matrix characteristic of lunar agglutinates. Although it is undoubtedly correct that material with chondritic chemistry crystallizes more readily than lunar material, we do not believe that such crystallization would necessarily destroy the criteria listed earlier for identification of agglutinates. In primitive chondrites, such as were studied here, evidence of a formerly molten state survives in the form of glass and delicate devitrification structures in chondrules and it is reasonable to suppose that agglutinates would behave in the same way. Thus, it seems unlikely that the degree of crystallization permitted by present petrographic evidence would have eradicated the flow structure which is the most conspicuous feature of sectioned agglutinates.

In addition, although vesicularity is not omnipresent among lunar agglutinates, it is extremely common [28] and is generally attributed to release of solar wind-implanted gas, mostly hydrogen and helium [38]. It could be argued that the irradiation history of chondritic material may have been less intense than that of the lunar regolith and that vesicularity therefore never developed. However, hydrogen and helium are heavily saturated on the lunar surface and only a few years of present solar wind flux at 1 AU serves to saturate, for example, hydrogen [39]. From the present concentration of solar ^{36}Ar in Fayetteville, $\sim 10^{-6}$ cm^3 STP/g [40], we may calculate a minimum dose of solar hydrogen which would have been associated with the argon implantation, 9×10^{18} H/g, using Cameron's cosmic abundance tabulation [41]. In view of the probability that some of the original implanted rare gas in Fayetteville has been lost, it is likely that the actual hydrogen concentration would have been closer to the values found in the lunar regolith, $\sim 5 \times 10^{19}$ H/g [39] and therefore presumably adequate to generate vesicularity comparable to that in lunar agglutinates.

Recrystallized agglutinates may, in fact, be found in lunar samples, still preserving many of their distinguishing features ([42] and unpublished work by J.F.K.). We conclude that agglutinates, if made from chondritic material, would probably have survived recognizably.

Secondly, if the parent body has a gravitational field which was smaller than that of, say, the moon, the ballistic time-of-flight of impact ejecta would have been longer on average than for lunar ejecta, allowing a larger proportion of melt to solidify in flight, thus decreasing the proportion available for production of spatter-agglutinates [43]. However, the requirement that a substantial quantity of the chondrules were retained for incorporation into chondrites imposes a lower, but presently undefined, limit to the gravitational field and hence an upper limit to the time-of-flight. Thus it seems unlikely that this effect would produce order-of-magnitude variations in agglutinate/spherule ratios, especially as agglutinates formed by injection of melt directly from the crater into surrounding regolith would not have been affected.

Finally, the possibility should be considered that sorting may have concentrated spherules preferentially over agglutinates before final compaction of the chondrites. Preferential accretion of chondrules over matrix particles has, in fact, been proposed as a process acting to increase the chondrule/matrix ratio following chondrule production in the nebula [44] and some observational evidence in support of such sorting has been advanced [45]. In order to reconcile the present observations with a regolith origin for chondrules, however, a sorting mechanism operative on the parent body, not during its accretion, must be postulated, and we can find no basis in theory or observation for such a process.

4. Conclusions

Because the proportion of agglutinates to spherules in chondrites is very much lower than that in lunar samples or howardites, we conclude that the hypothesis that chondrules were formed on a planetesimal with a lunar-like regolith is not supported by the evidence. Given the reasonable proposition that large-scale melt production is not a necessary condition for breccia formation, because impact breccias may be formed at substantially lower velocities than impact melt, our conclusion does not contradict the prevailing idea that many, or all, chondrites constitute such breccias, assembled in the surface regions of their parent bodies. The conclusion of this study applies only to the manufacture of the chondrules themselves, which must clearly have predated final compaction of the chondrites.

Although the extreme scarcity, or even possible absence, of agglutinates in chondrites casts severe doubt on the production of chondrules within a regolith, it does not explicitly define the environment in which they actually were produced. Some plausible inferences may, however, be made.

The observations probably rule out the chondrule production by impact into a substantial parent body of normal rocky texture. This conclusion involves two reasonable assumptions. The first is that bombardment capable of generating the chondrules would also have produced abundant fragmental material, i.e., regolith particles. This assumption is consistent with results from hypervelocity impact experiments in the laboratory, in which fragmental ejecta outweigh melt material by factors of $\gtrsim 100$ [46,47]. The second assumption is that for the chondrules to have been retained on the parent body, its gravitational field must have been significant, i.e., capable also of retaining a regolith. Thus, it appears that an agglutinate-rich, regolith type of environment is likely to result from any kind of crystalline parent body environment which may be proposed for impact production of chondrules.

It is also unlikely that significant impact production of chondrules occurred during an *accretional* stage of parent body development. This follows from the necessity for inter-particle velocities to have been low (probably $<<1$ km/s) during accretion [48,49]. Inter-particle velocities high enough for substantial melt production (>2 km/s) [7] would have resulted in net *erosion* of the growing planetesimal. By the time that planetesimal gravitation became strong enough to overcome this erosional effect, the arguments of the previous paragraph would have become relevant.

The foregoing arguments are less effective in dealing with the third possibility mentioned in the Introduction, namely that chondrules may have formed as impact ejecta expelled from a planetesimal and subsequently reaccreted onto another planetesimal, or even possibly the same one. However, one of us (S.W.K.) has pointed out elsewhere [7] that such particle-to-parent impacts would also have produced a characteristic assemblage of shocked and unshocked fragments with a range of sizes and relative proportions. We do not believe that such assemblages are typically found in chondrites [7], although Dodd [1] has interpreted the components of the Sharps chondrite as a shock-produced assemblage.

It appears, therefore, that if chondrules were produced by impact melting, these impacts did not take place on a parent body. Formation of chondrules by jetting during small body, particle-to-particle, collisions, as postulated earlier [7], constitutes an alternative mechanism which satisfies the present observations, as do a number of other, non-impact-based processes. Because hypervelocity jetting is an observed phenomenon (e.g. [50,51]), we regard it as a somewhat more plausible chondrule production mechanism than more speculative processes such as nebular lightning discharges [52,53], T Tauri shock wave heating [54], metastable condensation [4] or condensation within massive protoplanetary atmospheres [5]. However, we reiterate that the present observations do not constitute a test between these possibilities but merely serve as a constraint on one aspect of impact-based theories.

We note at this point that evidence in support of such a collisional origin for chondrules was presented by Lange and Larimer [55] in the form of a chondrule in Krymka which had apparently been remelted by a second high-velocity collision. However, this interpretation was challenged by Vedder and Gault [56] who pointed out that the energy required for remelting would have been many times greater than sufficient for complete disruption of the chondrule. The argument of Vedder and Gault, with which we concur, does not apply to the collisional mechanism or evidence discussed here.

Production of chondrules by collisions between small objects dispersed in the primitive nebula has been proposed by a number of other workers [2,12], and is consistent with the scanty data on chondrule ages vis-à-vis the ages of chondrites [57–59], though these do not currently constitute an exacting test. Whipple [44] has pointed out that chondrules produced in the nebula may well be preferentially accreted by growing planetesimals because of aerodynamic effects and some evidence in support of this view has been presented by Dodd [45]. We have observed [7,60] that chondrule production by means of collisions required a high-velocity "spike" during an epoch characterized in general by interparticle velocities which were low enough to permit accretion ($\ll 1$ km/s). It is tempting to speculate that such a spike could have resulted from dissipation of residual nebular gas by a T Tauri event. Prior particle growth, via condensation and accretion would have taken place in a gas of density sufficient to moderate inter-particle velocities and, subsequent to the high-velocity spike, velocities would have declined through collisional viscosity until an accretional regime was again achieved.

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