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Comment on: "New" lunar meteorites: Impact melt and regolith breccias and large-scale heterogeneities of the upper lunar crust, by P. H. Warren, F. Ulff-Møller, and G. W. Kallemeyn

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Abstract–We described lunar meteorite Dhofar 026 (Cohen et al. 2004) and interpreted this rock as a strongly shocked granulitic breccia (or fragmental breccia consisting almost entirely of granulitic-breccia clasts) that was partially melted by post-shock heating. Warren et al. (2005) objected to many aspects of our interpretation: they were uncertain whether or not the bulk rock had been shocked; they disputed our identification of the precursor as granulitic breccia; and they suggested that mafic, igneous-textured globules within the breccia, which we proposed were melted by post-shock heating, are clasts with relict textures. The major evidence for shock of the bulk rock is the fact that the plagioclase in the lithologic domains that make up 80–90% of the rock is devitrified maskelynite. The major evidence for a granulitic-breccia precursor is the texture of the olivine-plagioclase domain that constitutes 40–45% of the rock; Warren et al. apparently overlooked or ignored this lithology. Textures of the mafic, igneous-textured globules, and especially of the vesicles they contain, demonstrate that these bodies were melted and crystallized in situ. Warren et al. suggested that the rock might have originally been a regolith breccia, but the textural homogeneity of the rock and the absence of solar wind–derived noble gases preclude a regolith-breccia precursor. Warren et al. classified the rock as an impact-melt breccia, but they did not identify any fraction that was impact melt.

In a recent paper, Warren et al. (2005) questioned our interpretation of the origin and history of lunar meteorite Dhofar 026 (Cohen et al. 2004). Herein we respond to the Warren et al. discussion of Dhofar 026; we will not address any other aspects of their paper.

In our paper, we demonstrated that Dhofar 026 is best interpreted as a strongly shocked granulitic breccia, or a strongly shocked fragmental breccia consisting almost entirely of granulitic-breccia clasts. Shock converted all the plagioclase to maskelynite. After the shock, the rock was heated to temperatures above its solidus; as a result, the maskelynite devitrified, and there was extensive partial melting (all pyroxene melted). As the rock subsequently cooled, the partial melts crystallized.

Warren et al. objected to many aspects of our interpretation. They were uncertain whether or not the bulk rock had been shocked. They appeared to disagree with our interpretation that the rock was heated above its solidus, partially melted, and subsequently rapidly cooled. They disputed our interpretation that most of the rock was originally granulitic breccia. They presented no clearly defined alternative interpretation for the origin and history of the breccia, however. They suggested that if the bulk rock had been shocked, it might have originally been a regolith breccia. They concluded, however, by classifying the rock as an impact-melt breccia, but they did not identify any fraction of the rock that had been impact melt. Moreover, they appeared to be using a definition of the term "impact melt" that is broader than the original definition (Dence 1971) and broader than the definition used subsequently by other workers who elucidated the process of impact-melt formation (see below). Below, we briefly describe the relevant aspects of rock texture and address each point of disagreement.

Four textural domains within Dhofar 026 are critical to this discussion: 1) monomineralic plagioclase patches (areas of very fine-grained acicular plagioclase), 2) olivine-plagioclase intergrowths (masses of very fine-grained acicular plagioclase enveloping sparse, small, equant olivine grains), 3) pyroxene-plagioclase intergrowths (very fine-grained subophitic-poikilitic intergrowths of plagioclase, olivine, and pyroxene), and 4) globules (small, sharply bounded, rounded bodies that consist of very fine-grained subophitic intergrowths of plagioclase, olivine, and pyroxene) ("very fine-grained" is defined for lunar rocks by Stöffler et al. 1980 as <0.03 mm). The first three domains make up the bulk of the rock, forming ~40–45%, ~40–45%, and ~10–20% of the rock volume, respectively. The globules form ~0.5% of the rock volume. We interpreted the acicular plagioclase in the first two domains as devitrified maskelynite (strongly shocked plagioclase). Warren et al. agreed with our interpretation of the monomineralic plagioclase patches, but they offered no opinion on the olivine-plagioclase intergrowths. We interpreted the pyroxene-plagioclase intergrowths and the globules as crystallized from melts that formed in situ, during post-shock partial melting; Warren et al. agreed that these domains crystallized from melts but did not agree on the cause, locus, or timing of the melting.

Although Warren et al. interpreted much of the plagioclase in the rock as devitrified maskelynite, they were uncertain whether the bulk rock was shocked. In the two domains that make up 80–90% of the rock (monomineralic plagioclase patches and olivine-plagioclase intergrowths), all the plagioclase is devitrified maskelynite; this observation indicates unequivocally that the bulk rock was shocked. Figure 4e of Warren et al. presents additional evidence for bulk-rock shock. The image shows short, lenticular, open tension fractures, several arranged en echelon; such fractures are diagnostic of bulk-rock shock (Chao 1967).

Warren et al. objected to the thermal history we proposed for Dhofar 026. We proposed that soon after the rock was shocked, it was juxtaposed with hotter material (perhaps enveloped by impact melt) and heated above its solidus by thermal conduction. As a result, the rock partially melted, and, during subsequent cooling, the melt crystallized rapidly. Warren et al. suggested that, under our scenario, crystallization of the partial melt should have been much slower than indicated by the observed texture. The final cooling rate, however, would depend upon the mass of the Dhofar 026 material, the mass of juxtaposed hotter material, and the subsequent history of these materials. We have so little information on these parameters that speculation as to cooling rates is virtually unconstrained.

Another basis of the Warren et al. objection to our interpretation that the bulk rock partially melted was their interpretation of the globules: they interpreted these bodies as clasts with relict textures. In our paper, we presented evidence for in situ melting and crystallization of the globules, which we will not repeat here. Textures shown in the Warren et al. Fig. 4 provide additional evidence for in situ melting of the globules, as follows. The vesicles are smooth-walled and thus formed when the globules were wholly melted. Many vesicles intersect globule margins (Figs. 4a–c); in fact, one globule (top of Fig. 4a) consists almost entirely of a vesicle. If a vesicle formed within a molten globule that was enclosed by vacuum or an atmosphere of impact-derived volatiles (as proposed by Warren et al.), the vesicle would have disappeared once it pierced the globule surface: surface tension would have acted to minimize the surface area of the molten particle, causing it rapidly to develop a spherical outline. Such open vesicles could have been retained within molten globules only if vesiculation took place while the globules were enclosed within a plastic medium, one that could flow to accommodate vesicle formation but that would not permit escape of the volatiles within the vesicles. Thus, melting, vesiculation, and subsequent crystallization of the globules must have taken place while the globule precursors were within the breccia. Warren et al. interpreted the vesicles as relicts partly because they believed that the breccia could not have yielded enough by plastic flow to have accommodated vesicle growth. Their Figs. 4a and 4c, however, show vesicles 50–100 μm across formed within devitrified maskelynite, clearly demonstrating that the rock was capable of considerable plastic flow.

Warren et al. concluded that "the degree to which Dhofar 026 was ever granulitic is very unclear." The olivine-plagioclase intergrowths, which make up ~40–45% of the rock, show a texture that is diagnostic of lunar granulitic breccias: rounded equant grains of olivine enclosed in a mass of plagioclase. Warren et al. did not contradict our interpretation of this domain; they appear to have simply ignored its existence.

Most of the Warren et al. discussion of Dhofar 026 focused on the globules (and did not address the bulk of the rock). Indeed, the globules are enigmatic, and we do not claim we understand their origin. Warren et al. implied that we viewed the globules and pyroxene-plagioclase intergrowths as a continuum, but we do not. Both crystallized in situ from mafic melts after the partial melting; before this melting, the pyroxene-plagioclase intergrowths were mafic areas in the granulitic breccia, but we do not know what the protoliths of the globules were. We proposed that the globule precursors might have been clots of mafic minerals in the granulitic breccia, or, if the rock was originally a fragmental breccia, they might have been rounded clasts of mafic rock or glass (Apollo breccia 66055, described in our paper, is a possible analogue). Warren et al. pointed out that the globules appear to be more ferroan than the bulk of Dhofar 026. Such a difference in bulk composition would favor interpretation of the rock as a fragmental breccia, but there are such large uncertainties in the globule compositions that the compositional differences cannot be viewed as proven (globule bulk compositions were determined by defocused-beam EMP analysis, a method that has large errors). Some textural details, however, do suggest that the breccia was a fragmental breccia (e.g., the presence of local swirls of highly feldspathic devitrified glass possibly formed by shock melting of an original very fine-grained matrix). In fact, we do favor the interpretation that the rock, prior to the shock event, was a fragmental breccia, but, as the evidence is not conclusive, we classified the breccia on the basis of conclusions that could be clearly drawn from its texture: >>90% of the rock consists of strongly shocked, partially melted, granulitic breccia.

Although Warren et al. assembled an assortment of objections to our interpretation, they did not present a clearly defined alternative. Because Warren et al. interpreted the globules as relict droplets of crystallized melt, and quenched melt droplets characterize regolith breccias, they suggested that Dhofar 026 might be a shocked immature regolith breccia. The lack of lithologic diversity within the breccia argues against its precursor having been a regolith breccia. Regolith breccias, even immature ones, contain a diverse suite of clasts (e.g., agglutinates, granulitic breccias, and melt rocks, in addition to glassy spherules). Dhofar 026 is extremely homogeneous in texture, with the bulk of the sample consisting of shocked granulitic breccia. Moreover, regolith breccias generally contain solar wind–derived noble gases; as Warren et al. admitted, "noble gas concentrations are lower in Dhofar 026 than in even immature regolith samples...by a factor of more than 10." Before the rock was shocked, it may have been a fragmental breccia containing small clasts of mafic rock or glass, but its lithologic homogeneity and lack of noble gases rule out a regolith-breccia precursor.

Although Warren et al. did not present a scenario for the history of Dhofar 026 and suggested that the rock might be a shocked regolith breccia, they concluded by classifying it as an impact-melt breccia. They did so, "considering the evidence for an important melt component." They did not, however, identify that melt component. None of the three major domains, which make up >90% of the rock, can have been impact melt. Warren et al. agreed that the monomineralic plagioclase patches are devitrified maskelynite, so this domain cannot be the impact melt. As discussed above, the olivine-plagioclase intergrowths represent strongly shocked granulitic breccia and cannot be the impact melt. The olivine-plagioclase intergrowths were interpreted as impact melt in the earliest work on the rock (Cohen et al. 2001; Warren et al. 2001), but texture of the intergrowths indicates that this interpretation was incorrect: rapidly crystallized melt of this bulk composition would have precipitated aluminous spinel as one of the earliest phases, and its olivine grains would be interstitial to the plagioclase. The only major domain with a texture suitable for impact melt is the pyroxene-plagioclase intergrowth. In our paper, we discussed at length why this domain is not impact melt. Briefly, the argument is as follows: 1) pervasive, uniform, strong shock effects throughout the rock indicate that the bulk rock has been shocked; 2) the pyroxene-plagioclase intergrowth shows no shock effects and its texture indicates crystallization at the same time as devitrification of the maskelynite, indicating that the intergrowth crystallized after the shock; thus, 3) the melt must be a partial melt formed after the shock. In fact, Warren et al. did not identify this domain as impact melt but instead suggested that some (or all?) of it might be partly digested clastic material. In the definition of impact-melt breccia cited and apparently accepted by Warren et al. (from French 1998), impact-melt breccia contains 25–75% melt. If this rock is an impact-melt breccia, some significant part of it should have been impact melt. Which part?

Some of the disagreements between our view of Dhofar 026 and the view of Warren et al. may be semantic. Some of the statements made by Warren et al. suggested that, in their work, they are using the term "impact melt" differently than we do. We, and authors who have described the process that forms impact melt (e.g., Dence 1971; Grieve et al. 1977; Simonds 1975; Simonds et al. 1976; Phinney and Simonds 1977; Stöffler et al. 1991; French 1998; and Melosh 1989), apply this term only to rock converted to melt by the passage of a shock wave (with the caveat that the shock-generated melt, which is superheated, assimilates inclusions engulfed during movement of the melt; such assimilated material, which is dissolved within the melt, probably constitutes a small fraction of the total melt volume). According to the authors cited above, the process that forms impact melt is distinctive and different from melting by thermal conduction (diffusion of heat into a volume of rock from nearby, hotter material). Warren et al. appeared to define impact melt more broadly and did not appear to distinguish between melt formed by shock and melt formed by conductive heating, as indicated by one of their reasons for classifying Dhofar 026 as an impact melt: the "strong likelihood that an impact was the proximal, if not instantaneous, cause of . . . melting." This statement implied that Warren et al. would classify as an impact melt any rock that has been partially melted by thermal conduction if the ultimate source of the heat might have been an impact. In our paper, we urged that the term "impact melt" be restricted to rocks in which the bulk of the melt formed by shock-induced fusion, a usage consistent with the original usage of the term. If Warren et al. use a different, broader definition of this term, we urge them to elucidate their definition in order to forestall possible future confusion.

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