GLASSY SPHERULES IN SUEVITE FROM THE RIES CRATER, GERMANY, WITH IMPLICATIONS FOR THE FORMATION OF METEORITIC CHONDRULES.

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In order to constrain impact theories for the origin of meteoritic chondrules, we have examined 53 glassy spherules (with a wide range of devitrification but on a fine scale), 5 lithic spherules, 10 accretionary spherules, and two irregular glass fragments (of similar size to the spherules) from the suevite of the Ries Crater in Germany. These objects indicate that size-sorted glassy spherules can be produced by impact although in the case of the Ries impact they are rare. Except when badly weathered, the spherules have the same composition as the macroscopic glasses. Ballistic calculations for the Ries impact and laboratory experiments suggest that little or no devitrification should have occurred during free-flight, and that the devitrification that is observed occurred subsequently. The lack of coarse-grained devitrification textures in the spherules is not an argument against the formation of meteoritic chondrules by impact, but is the result of very fast cooling rates for Ries ejecta. The rarity of the glassy spherules, compared to meteoritic chondrules, cannot be addressed until we have a better understanding of nature of asteroid surfaces and processes occurring during their early impact history.

Suevite, impact melt rock from the Ries Crater in Germany, contains material showing a wide variety of shock effects, from relatively unaltered target materials to macroscopic irregular shards of glass (1). Present in the breccias are glassy spherules that have been likened to meteorite chondrules (2,3). Since many workers have suggested that meteorite chondrules formed by impact (4-7), and since many devitrified and glassy spherules in lunar regolith samples are widely thought to be of impact origin (8-12), we have been examining the spherules in the Ries suevite in order to better evaluate the likelihood of chondrule formation by impact. We have examined ten thin sections (provided by Professor W. v. Engelhardt) of suevite from the Amerdingen, Aufhausen, Oberringingen and Mauren quarries and the Wõrnitzostheim drill hole and found glassy spherules in all but the Oberringingen section. We found 67 spherules and 19 perfectly circular holes in the section where spherules had been plucked during sample preparation. This is equivalent to >0.8 spherules cm^{-2}, *c.f.* Graup's figure of 0.96 spherules cm^{-2} (4). The bulk compositions of 22 spherules and two irregular glass shards of comparable dimension were determined by electron microprobe analysis.

Table 1. Sizes of glassy spherules in Ries suevite.

Site	Diameter (μm)	Diameter ratio*
Amerdingen	134±41	1.17±0.16
Aufhausen	196±103	1.20±0.30
Mauren	277±161	1.23±0.49
Wõrnitzostheim	184±118	1.20±0.27
Category 1	128±37	1.25±0.24
Category 2	151±67	1.05±0.08
Category 3	175±108	1.12±0.16
Category 4	404±23	1.83±0.49
Category 5	309±101	1.39±0.30

* Ratio of maximum to minimum diameter.

Table 2. Number and the distribution of categories of glassy spherules in the Ries suevite sections studied.

	Total*	Category 1	2	3	4	5	Mixed†
Amerdingen	19	7	1	6	0	5	1
Aufhausen	44	7	9	15	4	4	5
Mauren	7	0	5	1	1	0	0
Wõrnitzostheim	16	5	2	7	0	1	1

* Includes a few objects that could not be classified.

† Mostly glassy objects that were gradational or zoned.

The spherules were sorted into those that were glassy and showing only incipient, weak or partial crystallization (category 2), those that were well-crystallized and multimineralic (category 3), rounded lithic spherules and calcite spherule pseudomorphs (category 4) and accretionary spherules (category 5). The holes were referred to as category 1. Table 1 lists means and standard deviations for their sizes and the ratios of their largest and smallest diameters. Except for categories 4 and 5, diameters are close to 160 μm and are within ~20% of being perfectly circular in section. Categories 4 and 5 are 2-3 times larger and more elliptical. The data for the individual sites are consistent with the relative abundance of spherule categories at each site (Table 2).

Most of the present spherules have compositions that plot in the same field of the AFM diagram as macroscopic irregular glasses analyzed by Stähle (13) and glassy spherules analyzed by Gräup (4), although the present spherules produce a "tail" that approaches and almost reaches the alkali corner of the diagram. There is no obvious relationship between composition and size, but most of the spherules in the tail are category 3 and their analyses sum to 90-95% (*c.f.* the main cluster where sums were 98-102%). Irregular glass fragment 4-3A plots near the alkali corner while 4-3B is fairly close to the main field. The present spherules have normative feldspar compositions that

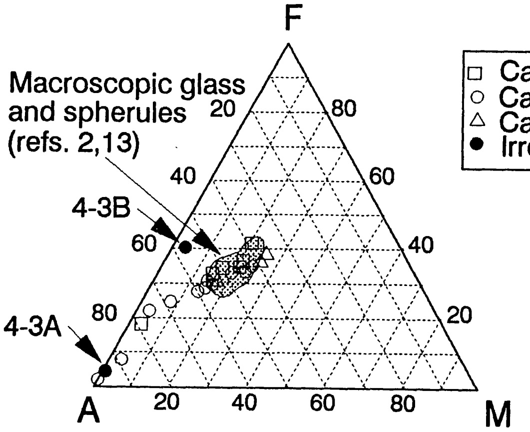

Fig. 1. AFM diagram for spherules from the Ries suevite, two irregular glass fragments of comparable dimensions, and the fields occupied by literature data for macroscopic glass bombs (Stahle, ref. 13) and glassy spherules (Graup, ref. 2).

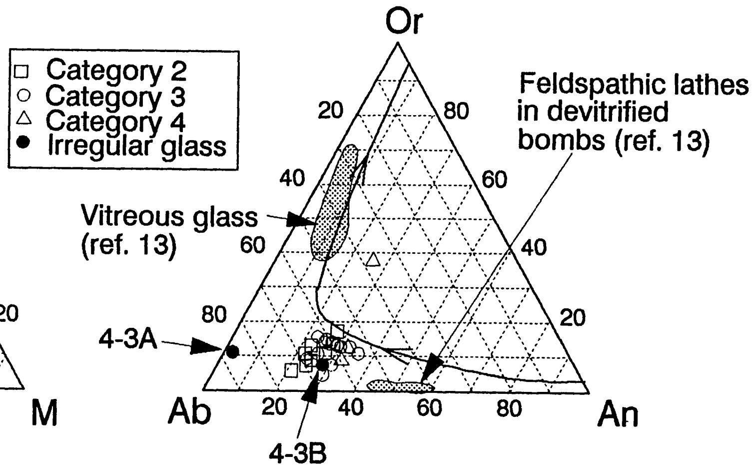

Fig. 2. Feldspar ternary (mole %) for feldspar lathes and normative compositions for glass in macroscopic devitrified bombs (data from Stahle, ref. 13) and the present glass spherules and irregular glass fragments. The fractional crystallization line is shown.

plot between the literature data for pure macroscopic glass and feldspathic lathes in macroscopic glass bombs (Figure 2), and the three components can be related by fractional crystallization. These data also suggest that the tail in Figure 1 reflects different proportions in the feldspar and mafic components.

Our data suggest that the glassy spherules in the suevite are samples of the melt that provided the larger glass masses, but that preferential aqueous alteration of the mafic minerals has caused some of them, and glass fragment 4-3A, to show marked deviations. The production of glass spherules requires cooling rates faster than 1-100°C/s (13-16). We have performed ballistic calculations, based on the size of the crater and using the equations and procedures described by Melosh (17), and find that such cooling rates are consistent with formation during the Ries impact. We found that while material ejected from within 0.1 crater radii of the center achieves escape velocity, flight times decrease very rapidly from 14 min to 20 sec, and ballistic range decreases from several 10^3 km to the crater rim, as distance of the source material from the center of the crater increases. Material ejected from about 0.5 crater radii lands at about the site of the suevite with flight times of ~1 minute with a corresponding cooling rate of ~15°C/s. In constrast, similar calculations for the Imbrium impact on the Moon produced flight times of ~40 min and cooling rates slow enough for coarse-grained devitrification textures (Sears *et al.*, this volume). We conclude that all or most of the devitrification observed in the present spherules occurred subsequent to free-flight, a conclusion that is consistent with petrographic considerations (18). The lack of coarse-grained internal textures in the Ries spherules cannot be used as an argument against an impact origin for meteorite chondrules, neither can the size-sorting of meteorite chondrules because the Ries chondrules are also well-sorted. The small number of Ries spherules (and the small amount impact melt), in contrast to the abundance of chondrules in certain meteorites, remains to be explained. However, some lunar regolith breccias contain similar abundances of devitrified glass spherules as some meteorites contain chondrules (19, Sears *et al.*, this volume), and melt production during impact on porous surfaces of small planetary bodies is not well-understood (H. J. Melosh, per. comm.). We see no evidence in the Ries spherules for meteoritic chondrules not being of impact origin.

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