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Reprinted from
E⊕S
Vol. 54, No. 6, June 1973

ORIGIN OF ORANGE GLASS SPHERULES IN APOLLO-17 SAMPLE 74220

Edwin Roedder: U.S. Geol. Survey, Washington, D.C. 20244
Paul W. Weiblen

Three mechanisms proposed for the origin of this orange soil (and for similar aggregations from other lunar sites) are: I) vapor condensation; II) volcanic fire fountaining; and III) meteorite impact on solid lunar crust. We believe that each of these is precluded for the orange soil by one or more lines of evidence; hence, we have proposed a fourth origin, IV) meteorite impact on liquid lava containing olivine phenocrysts.

Our sample consists of grains almost 100% <0.3mm that are ~99 percent smooth shiny spherules (or broken fragments) of transparent orange glass and the opaque partly crystallized equivalent of the orange glass. This material came from a much larger volume of orange soil in the outcrop, but all orange glass in our sample has an extremely uniform index of refraction (~1.712). In contrast, other lunar sample spherules range from 1.50 to 1.75. The orange glass is also completely free of bubbles to the limit of resolution of the light microscope, whereas bubbles are present in many other spherule samples. The color varies with thickness from yellow-orange to red-brown. The spherules appear spherical, but many, even as small as 40μm, are oblate spheroids with axial ratios as low as 0.42 (Fig. 1). Some have fissioned during free flight, as those described from Apollo-11 soils.

Although many have been chipped or broken since solidification, only a few appear to have landed while still soft. One notable exception is the occurrence of small spherules of orange glass conforming and adhering to the surface of larger black spherules; presumable this collision occurred during flight because of relatively small differences in individual velocities or trajectories.

Where free of crystals, the orange glass is remarkably uniform in composition within particles (Fig. 2b) and from one particle to another. Table 1 gives the average of 12 individual spherule analyses; the major elements do not vary outside the precision of any individual analysis--1 to 5 percent of the amount present. The composition is that of an ilmenite-olivine mare basalt, as shown by the CIPW norm.

Most important is the presence of relatively coarse, solid, sharply euhedral olivine crystals (Fo88) as long as 320µm, embedded in orange glass (or its black crystalline equivalent) that has smoothly convex to almost circular outer surfaces (see Fig. 3 and arrows on Fig. 4). These occur in ~0.2 percent of the spherules >150µm. The gross composition of such spherules would reach a maximum of perhaps 80 percent olivine. Electron microprobe traces across them reveal neither compositional zoning in the phenocrysts nor gradients in the adjacent glass. Similar olivine occurs as finer sized fragments, in part with adhering glass. We conclude that these crystals are equilibrated phenocrysts that were present in an essentially liquid lava prior to impact.

The black spherules (and fragments) are believed to have been orange ones that have crystallized in part. They now contain globular dark masses of extremely fine opaque dendrites or consist of 1-5µm laths of olivine (~Fo70) decorated by even thinner platelets of an opaque Fe-Ti phase. Rapid crystallization of olivine apparently enriched the adjacent melt in Ti, causing precipitation. Some orange spherules have only a few oxide-decorated olivine laths in somewhat lighter colored glass depleted in Mg, Fe, and Ti (Fig. 2a,c), but with gross compositions very similar to that of the orange glass. Although this sequence of olivine and then Fe-Ti oxides may not represent equilibrium, it does agree with the sequence found for mare basalt magmas from melt inclusions (Roedder and Weiblen, 1970), and experimentally (Ringwood and Green, 1972).

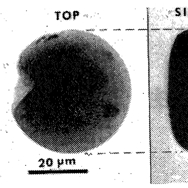
The composition of the orange-glass spherules is so similar to some other individual spherule compositions (e.g. Chao, et al., 1970 ; Ware and Lovering, 1970) that the differences could be only analytical. However, in these other sites, spherules constitute only a very minor component, and with few exceptions, they vary grossly in composition from one spherule to another.

In Table 2 we list 10 lines of evidence for the four suggested modes of origin. Item 1: Very high rates of shear (and hence rotation) are required to distort droplets as small as 40µm into oblate spheroids (Fig. 1) against the restoring force of surface tension. We believe that such high shear rates cannot be obtained in a volcanic fire fountain or on condensation from a vapor. We suggest also that the lack of Pele's hair in the lunar soils in general and its complete absence in sample 74220 is probably because most melt disaggregation occurs early in the ejection process, before the temperature can drop to the point of filament formation. Presumably this disaggregation continued down to the minimum threshold spherule diameter found (~12µm), yielding the surprisingly uniform small particle size found. Item 2: The olivine phenocrysts effectively preclude two of the four modes of origin. These phenocrysts must have crystallized before the spherules were formed, and they are quite different from the later olivine laths. Item 3: A melt of this composition can be expected to nucleate and crystallize rapidly--much more rapidly than ordinary terrestrial basalts. Rapid-quenching experiments on the orange glass in vacuum have permitted us to estimate that cooling rates >1000°C/sec were needed to maintain these as glass. Such rates are very likely for minute projectiles from an impact event that leave the central source of radiant heat at high velocity; they seem almost impossible to achieve, however, for any volume of material in a volcanic fire fountain. Item 4: This uniformity is difficult to explain by anything except possibly a very large impact on solid rock, but this is negated by items 2, 7, and 8. Items 5 and 6: Terrestrial basaltic fire fountains do form spherules (usually spherical), but only as a very minor product, mixed with much larger quantities of much coarser material (spatter, cinder, Pele's hair, etc.). Items 7 and 8: Various hypervelocity impact-cratering studies (Short, 1969) have shown that only about one percent of the material ejected is liquid melt (glass), generally well dispersed through the other debris. Glass (± iron droplets) is formed only in the region of extreme temperatures. Impact into lava would be expected to eject large volumes of liquid, most of which would have almost no additional heating from impact. A small number of spherules showing evidence of very high shock-wave pressures (such as shocked or partly melted olivines) should be present in the orange soil and might be recognized in a larger aliquot. Item 9: The lack of hypervelocity "zap pits" on the orange spherules has been mentioned by others as evidence against an impact origin, because such pits are abundant in other impact glass spherules. This lack may merely result from the relative lack of exposure of the orange soil to later gardening at the lunar surface. Item 10: This might seem trivial, but we believe it effectively eliminates volcanic fire fountaining as a mode of origin. Terrestrial fountaining is generally believed to be driven by rapid gas-bubble nucleation and expansion. The resulting spherules (except those $\leq 30\mu m$) almost always contain gas bubbles. In contrast, not a single bubble, even as small as 0.5µm, was found in any of our much larger orange-glass spherules. This result also implies that the lunar lava impacted was extremely low in volatile materials.

We believe that the relatively minor differences in composition between the orange glass and the various available high-titanium mare basalt samples are readily explicable and hence not of serious import. Similarly, the chronological coincidence involved in impact into liquid lava is not unexpected in view of the evidence presented by Wasserburg (and others) at the Fourth Lunar Science Conf. for a cataclysmic event on the moon about 3.7 b.y. ago, when this sample was formed.

The difference between the black and orange spherules might arise from different cooling rates caused by slightly different trajectories, or from thermal stratification of the lava lake before impact. The occasional crystalline basaltic rock fragment in the orange soil might be part of a solidified crust. Such impacts onto crusted lava should yield craters with very different characteristics from those formed in solid lava flows, and the maria should be examined for evidence of such craters.

Chao, E.C.T., Boreman, J.A., Minkin, J.A., and James, O.B., Jour. Geophys. Res. 75, 7456, (1970).
Ringwood, A.E., and Green, D.H., Earth Plan. Sci. Letters 14, 14 (1972)
Roedder, E., and Weiblen, P.W., Proc. Apollo 11 Lunar Sci. Conf. 1, 833, Pergamon Press, N.Y. (1970)
Short, N.M., Modern Geology 1, 81, (1969)
Ware, N.G. and Lovering, J.F., Science 167, 519 (1970).



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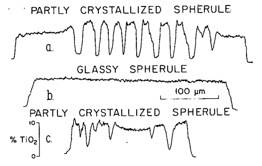
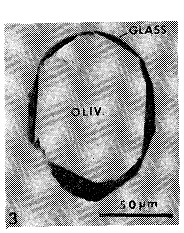


Fig. 2 TiKα probe traces

Table 1. Orange glass 74220,70 (wt.%)

SiO_2	39.5	or	0.5
Al_2O_3	6.41	ab	4.3
FeO	22.2	an	15.0
MgO	14.4	wo	8.4
CaO	7.13	en	18.5
Na_2O	0.51	fs	13.7
K_2O	0.08	fo	12.3
TiO_2	8.56	fa	10.1
P_2O_5	0.05	il	16.3
MnO	0.32	cm	0.8
Cr_2O_3	0.52	ap	0.1
Total	99.68		100.0



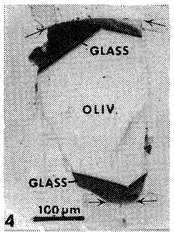


Table 2. Applicability of data to the four proposed modes of origin of the orange soil spherules (see text). X-Precludes; D-Difficult to explain; P-Permissive but not exclusive.

Line of evidence	I	II	III	IV
1.High speed of rotation during cooling	X	X	P	P
2.Euhedral sharp phenocrysts of olivine	X	P	X	P
3.High rate of cooling	D	X	P	P
4.Uniformity of composition of glass	D	P	D	P
5.Apparent large amount of spherules at site	P	X	D	P
6.Absence of coarse glass blebs of same comp.	P	X	P	P
7.Absence of shocked rock debris	P	P	D	P
8.Absence of minute iron metal dust in glass	P	P	D	P
9.Absence of zap pits on spherule surfaces	P	P	P	P
10.Complete lack of bubbles	P	X	P	P