Tektite Glass in Apollo 12 Sample

Abstract. *The glassy portion of lunar sample 12013 from Apollo 12 is chemically more like some tektites from Java than like any terrestrial igneous rock. It satisfies all the chemical criteria for a tektite. Tektites are relatively recent and acid rocks, whereas the moon is chiefly ancient and basaltic; hence, tektites are probably ejected volcanically, rather than by impact, from the moon.*

A comparison of lunar sample 12013 from Apollo 12 (*1*) with javanites (tektites from Java) J-86 and J-87 (*2*) and with two terrestrial igneous rocks is given in Table 1.

The terrestrial samples were chosen from the 4950 superior analyses of fresh rocks by Washington (*3*) by first calculating the normative mineral composition for sample 12013 as follows (where values are in percent by weight): quartz, 21.1; orthoclase, 11.7; albite, 5.8; anorthite, 23.9; diopside, 3.2; hedenbergite, 3.0; hypersthene, 28.1; ilmenite, 2.3. In the C.I.P.W. system the Roman numeral represents class, the first Arabic numeral represents order, the second Arabic numeral represents rang, and the third Arabic numeral represents subrang. Broadly speaking, the class measures progress from salic toward femic rocks. Among the salic rocks, the order is determined by the ratio of quartz to feldspar. The rang is determined by the ratio of alkali feldspar to calcic feldspar, and the subrang is the ratio of orthoclase to albite. The classification then follows as II,3,3,2; II,4,3,2; III,3,3,2; or III,4,3,2, with the ambiguity due to the fact that some ratios are close to the boundary values. Of these classifications, the first two have one analysis each (shown in Table 1); the last two are vacant.

Clearly, sample 12013 is more like the javanites than like the terrestrial rocks, even if the differences in the oxidation state of the iron and in the water content are, for the moment, overlooked. To understand why it is so difficult to find parallel terrestrial rocks, it is useful to look at appendix 2 of Washington (*3*, p. 1158). We see that, in classes II and III, the first three orders are nearly empty; also, in this part of the table there are very few rocks in subrang 2. Since the order depends primarily on the silica content, the first statement means that, for the kind of oxide ratios that we observe, the silica content of sample 12013 is unusually high. Since the subrang depends on the potash content, the second statement means that the analysis is unusual because it indicates that sample 12013 is more potassic than similar terrestrial rocks. In addition, it is clear from Table 1 that even those rare terrestrial rocks that do fall in these categories do not have as much MgO as does sample 12013.

Mueller, Loewinson-Lessing, and Pinson and Schnetzler (*4*) make it clear that these points are precisely those on which tektites differ from terrestrial igneous rocks. A tektite generally resembles an unusually potassic intermediate igneous rock that has been diluted with too much SiO_2; this resemblance is especially clear in the ratio of divalent metal oxides to monovalent metal oxides.

It has often been suggested (*5*) that these chemical peculiarities are the result of a sedimentary origin: the excess silica is attributed to mechanical differentiation of a sediment, with enhancement of the quartz content; the general deficiency of alkalis to leaching; and the potassic character to the tendency of clays to hold potash. It is now clear that these arguments are not compelling; the moon can produce the same properties.

Three other characteristics of tektites should be mentioned for comparison:

1) They are glass. According to J. R. Arnold (*6*), the portion of sample 12013 used for the analysis was the amorphous part.

2) They are deficient in water. Since the Apollo 11 analyses indicate a low water content for the moon as a whole, it is safe to predict that sample 12013 will also show a low water content, of the order of 100 parts per million, rather than 10,000 parts per million as in terrestrial rocks.

3) The Fe^{3+}/Fe^{2+} ratio is very low, of the order of 0.1. Since the Apollo 11 analyses indicate a low ferric-ferrous ratio for the moon, it is a safe assumption that sample 12013 will also show a low ferric-ferrous ratio, well below the typical terrestrial values of the order of 1.

Table 1. Comparison of lunar sample 12013 from Apollo 12 with two javanites and two terrestrial igneous rocks.

Oxide	Sample 12013	J-87	J-86	II3, 3,2	II4, 3,2
SiO_2	61	63.5	64.1	64.4	61.0
TiO_2	1.2	0.8	0.8		
Al_2O_3	12	12.6	12.2	14.1	16.0
Fe_2O_3				6.1	5.4
FeO	10	8.5	9.0	3.7	1.0
MgO	6.0	6.8	8.0	2.0	3.0
CaO	6.3	3.8	3.2	4.5	5.4
Na_2O	0.69	0.7	0.8	0.6	1.4
K_2O	2.0	1.5	1.5	3.7	5.6
H_2O				0.8	0.8

Against the identification of the glass in sample 12013 as tektite glass is the fact that the agreement of the trace elements is unsatisfactory, as can be seen by comparing javanite J-86 (*7*) with sample 12013. Discrepancies of a factor of 10 occur for Zr and Y; smaller, but still significant, discrepancies are found for other trace elements. This objection may not be serious; at the present time very little is known about the trace element composition of tektites in this range of silica content. Most of the material is in the form of microtektites; and, although they form the vast majority of all tektite material on the earth, the total amount in the laboratories is still too small for trace element analysis.

A more important objection concerns the mode of removal of tektites from the moon. If they are removed by impact, as has generally been believed hitherto (*8*), then a tektite would be expected to be a random sample of the lunar surface, apart from the selection effects having to do with survival of the initial shock, the descent through the earth's atmosphere, and the attack by ground chemicals. It is reasonably sure, however, that the lunar maria are as much as 3.7 billion years old (*9*), and the lunar highlands are generally thought to be older still. The tektites cannot come from typical mare areas, because there is good evidence that the maria are basaltic; they cannot come from typical highland areas, because these areas must be old and they may well be anorthositic (*10*). Tektites have differentiation ages that are less than 500 million years, with the exception of the Ivory Coast tektites, which are interpreted as having a differentiation age of 2 billion years (*11*). How can we explain the production of relatively young, acid rocks from a terrain that is predominantly either old or basaltic?

A second difficulty concerns the lack of meteorites on the earth that have the composition of any of the lunar sites investigated so far. It appears that impact alone rarely removes centimetersized particles from the moon. Öpik (*12*) has pointed out that shock alone will not give high velocity to large particles. Although Öpik himself states that large particles can be given high velocities by the gas ball produced in an impact, it is interesting to note that most of the large crystalline fragments in the Apollo 11 sample fall in a narrow compositional range and are not shocked, as if they came from the local bedrock. The fines, on the other hand, are often strongly shocked and correspond to a much wider range of composition, including fragments that come, according to Wood *et al.* (*10*), from the highlands. It would seem that the gas propulsion process is relatively unimportant in impacts and that the main shock mechanism could either produce small particles at high speed or larger particles at low speed.

These two difficulties can both be solved if we assume that tektites are propelled from the moon not by impact but by volcanism, as suggested by Verbeek (*13*). Gas escaping into a vacuum reaches a limiting velocity $V_{\lim}$ given (*14*) by

$$V_{\lim} = (2c_pT)^{1/2}$$

where c_p is the specific heat at constant pressure and T is the absolute temperature. Thus, at the lunar magmatic temperature of 1200°C, $V_{\lim}$ is about 6.6 km sec^{-1} for hydrogen and 2.4 km sec^{-1} for water. Under the reducing conditions of the moon, hydrogen is a plausible gas. [Note that Kozyrev (*15*), working at 150 Å/mm, found a line at 4634 Å, near the strongest line of the blue portion of the spectrum of H_2, coming from Aristarchus (*16*).]

Note that, since particle size is a high inverse power of the velocity according to Opik, the above objection against lunar origin by impact applies with even greater force against a terrestrial origin by impact, because the velocities demanded are at least 50 percent higher in the terrestrial case.

The geochemical significance of a volcanic, as opposed to an impact, origin for the tektites lies in the fact that the materials erupted from a volcano will be expected to have differentiation ages that are nearly the same as the date of the eruption. This will be approximately true even for materials torn loose from the volcanic pile by a later eruption, since volcanism does not usually continue long at any one site. In addition, only acid volcanoes give rise to paroxysmal outbursts; the basaltic volcanoes generally produce gentler flows. The reason is believed to be connected with the viscosity of the magma; it would therefore be valid for the moon.

If tektites are really propelled by volcanism, the K-Ar clock on tektites was set not by impact but by volcanism. Volcanism is more plausible than impact because it is found impossible in the laboratory (*17*) to reset the K-Ar clock without volatilizing the rock. Laboratory treatment, like impact, involves times that are short compared with volcanic processes. The Rb/Sr ages can also be interpreted in terms of low ages of differentiation, if we are prepared to believe that the initial $^{87}Sr/^{86}Sr$ ratio (before the last stage of differentiation) was not near 0.700 but near 0.720.

Urey (*18*) has attacked the notion of a lunar origin for tektites on the ground that the tektites that missed the earth on the first pass would go into space. After a period of the order of 100,000 years, they would encounter the earth again; thus a worldwide distribution of tektites would be produced, which is contrary to fact. Urey's calculation neglects the focusing effect of the earth's gravitational field. In addition, a number of authors (*19*) have shown that tektites are rapidly destroyed in space either as a result of rotational bursting induced by solar radiation or as a result of impact by micrometeorites, and hence they do not return to the earth.

In conclusion, the glass of sample 12013 appears to be tektite glass by all the usual tests. Its constitution answers the arguments given by proponents of the terrestrial origin of tektites to the effect that only sedimentary processes can produce the typical tektite composition. There appears to be no sound reason not to say that tektites come from the moon.

JOHN A. O'KEEFE
Laboratory for Space Physics,
Goddard Space Flight Center,
Greenbelt, Maryland 20771

References and Notes

1. Lunar Sample Preliminary Examination Team, *Science* **167**, 1325 (1970).
2. W. A. Cassidy, B. P. Glass, B. C. Heezen, *J. Geophys. Res.* **74**, 1008 (1969).
3. H. S. Washington, *U.S. Geol. Surv. Prof. Pap. 99* (1917).
4. F. P. Mueller, *Geol. Mag. Decade 6* **2**, 206 (1915); F. Loewinson-Lessing, *Dokl. Akad. Nauk SSSR* **6**, 209 (1936); C. C. Schnetzler and W. H. Pinson, Jr., in *Tektites*, J. A. O'Keefe, Ed. (Univ. of Chicago Press, Chicago, 1963).
5. V. E. Barnes, *Univ. Texas Publ. 3945* (1939); H. C. Urey, *Publ. Nat. Acad. Sci. 41* (1955); S. R. Taylor and M. Kaye, *Geochim. Cosmochim. Acta* **33**, 1083 (1969).
6. J. R. Arnold, personal communication.
7. D. R. Chapman and L. C. Scheiber, *J. Geophys. Res.* **74**, 6737 (1969).
8. J. A. O'Keefe, in *Tektites*, J. A. O'Keefe, Ed. (Univ. of Chicago Press, Chicago, 1963).
9. Lunar Sample Analysis Planning Team, *Science* **167**, 449 (1970).
10. J. A. Wood, U. B. Marvin, B. V. Powell, J. S. Dickey, Jr., *Smithson. Astrophys. Obs. Spec. Rep. 307* (1970).
11. C. C. Schnetzler, W. H. Pinson, P. M. Hurley, *Science* **151**, 817 (1966).
12. E. J. Öpik, *Irish Astron. J.* **8**, 185 (1968).
13. R. D. M. Verbeek, *Kon. Ned. Akad. Wetensch. Versl. Gewone Vergad. Afd. Natuurk.* **5**, 421 (1897).
14. K. Oswatitsch, *Gas Dynamics* (Academic Press, New York, 1956).
15. N. Kozyrev, *Nature* **198**, 979 (1963).
16. Note that if this observation is correct, the excitation would have to be by static electricity, since the lower excitation potentials of the H_2 lines are over 10 volts.
17. I. McDougall and J. F. Lovering, *Geochim. Cosmochim. Acta* **33**, 1057 (1969).
18. H. C. Urey, *Science* **137**, 746 (1962).
19. S. J. Paddack, *J. Geophys. Res.* **74**, 4379 (1969); V. V. Radzievsky, *Dokl. Akad. Nauk SSSR* **97**, 49 (1954); D. E. Gault and J. A. Wedekind, *J. Geophys. Res.* **74**, 6780 (1969).

28 April 1970

Geological History of the Western North Pacific

Abstract. *A considerable portion of the abyssal floor of the western North Pacific was already receiving pelagic sediment in late Jurassic time. Carbonate sediments were later replaced by abyssal clays as the basin deepened and bottom waters became more aggressive. The resulting facies boundary, which can be recognized on seismic profiles, is broadly transgressive; it ranges in age from mid-Cretaceous in the western Pacific to Oligocene in the central Pacific. Cherts are encountered at and below the major facies boundary and appear to have been formed by postdepositional processes.*

The greatest surprise that the geologic study of the oceans has provided in the last decade is the youth of the oceanic crust as compared with the age of the crust of the continents. Geological and geophysical evidences of many sorts (*1*) have suggested that the crust grows by the accretion of mantle-derived ultramafic rocks and basalt in the axial zone of the Mid-Oceanic Ridge to form there a "volcanic oceanic basement." As newly formed basement