Reports

Glazed Lunar Rocks: Origin by Impact

Abstract. *The glassy coating of lunar rock 12017 is enriched in 15 trace elements relative to the crystalline interior. It apparently consists chiefly of shock-melted rock, somewhat richer in rare earth elements and alkali metals than rock 12017 itself. The glass has been contaminated by about 0.5 percent carbonaceous-chondrite-like material or, alternatively, by a mixture of 0.06 to 0.3 percent fractionated meteoritic material and approximately 10 to 15 percent local soil. The glazing seems to represent molten material splashed from a nearby meteorite impact and not in situ melting by a sudden increase in solar luminosity.*

Glazed lunar rocks, lying in small craters, were observed and photographed during the Apollo 11 mission, but no specimens were collected. A detailed examination of the photographic evidence prompted Gold (*1*) to propose glazing to be the result of radiative heating by a giant solar outburst. This suggestion was extended by Mueller and Hinsch (*2*) to explain the origin of glassy particles in lunar fines and, at least in part, the depletion of volatiles in lunar basalts. The radiative heating hypothesis has not escaped criticism (*3–5*). Impact ejecta have been proposed by Greenwood and Heiken (*5*) as a more probable source of the glass coating, whereas a volcanic origin was favored by Green (*3*).

Several glazed specimens were returned from the Apollo 12 landing site (*6*), one being rock 12017, a type 1 porphyritic basalt (*7*). Portions (0.05 to 0.1 g each) of the glassy exterior and crystalline interior of rock 12017 have been analyzed for 15 trace elements by neutron activation procedures outlined previously (*8*). The analytical results are given in Table 1.

For every element measured, the abundance in the glass is higher than in the interior, in some instances by more than a factor of 10. Clearly a simple isochemical melting process by radiative heating cannot be the cause of the observed vitrification. Many of the elements analyzed are very volatile and would be among the first to be lost by any selective evaporation process. Thus, the observed enrichment cannot be ascribed to volatilization of major element oxides.

Table 1. Abundances of 15 trace elements in the crystalline interior and glass exterior of lunar rock 12017. Analytical precision as determined from replicates of standard basalt BCR-1 is $\pm \leqq 10$ percent for most elements; for Ag, Au, and Ir, it is $\sim$10 to 20 percent, and for Te, $\sim$20 to 30 percent. Sampling error would increase these estimates slightly. For the upper regolith, the values shown are the mean of three samples; for the lower regolith, the mean of two samples; and for the crater rim, the mean of eight determinations for three samples. Abbreviations: ppb, parts per billion; ppm, parts per million.

Element	Rock 12017		Soil		
	Interior	Exterior	Upper regolith	Lower regolith	Crater rim
Ir (ppb)	0.20	2.6	7.5	9.0	4.1
Au (ppb)	0.07	1.2	2.2	2.1	1.5
Zn (ppm)	1.0	3.3	6.0	4.9	5.5
Cd (ppb)	1.1	5.4	56	49	26
Ag (ppb)	1.5	2.8	28*	5.4	6.8
Bi (ppb)	0.25	0.59	2.7	1.3	0.53
Tl (ppb)	0.34	0.88	1.4	2.3	3.0
Br (ppb)	16	49	130	120	150
Te (ppb)	20	70	100	60	33
Se (ppb)	156	182	240	240	195
Ga (ppm)	2.9	3.3	4.5	5.1	4.4
Rb (ppm)	1.1	2.3	7.0	9.9	7.0
Cs (ppb)	45	87	280	350	340
In† (ppb)	2.0	5.1			
Co (ppm)	32	44	39		44

* Possibly contaminated. † Values for soils were discarded because of possible contamination.

Because the lunar soil is enriched in these same elements relative to the crystalline rocks, at first sight it appears a likely parent material for the glass. The trace element distribution of Apollo 12 soils has been studied by Laul *et al.* (*9*), who find that chemically these elements fall into three main groups: upper regolith soils (samples 12070, 12025,72, and 12028,90), lower regolith soils (samples 12028,121 and 12028,145), and crater rim soils (samples 12032, 12033, and 12037). Mean abundances in each group are given in Table 1.

The last two groups may be excluded at once. The Bi contents relative to Ir are too low to enable any self-consistent mixture of soil and crystalline rock to emulate the composition of 12017 glass. Further comparison shows that the upper regolith soil is too enriched in many of these elements to be the sole starting material for the formation of the glass. The trace element distribution of the glass cannot be matched by any simple binary mixture of soil and crystalline rock. If we consider the rare earth element abundances in 12017 glass reported by Goles *et al.* (*10*) we find that the light rare earth elements are too depleted relative to heavy rare earth elements to match the upper regolith soil; in fact, they resemble more closely a lunar igneous rock pattern (*10, 11*). We also find that Rb, Cs, Bi, and particularly Cd are depleted compared with the rare earth elements. It might be postulated that the depletion of these four elements is due to a volatilization process. This seems unlikely, however, as Th (*10*), a very refractory element, is depleted to exactly the same extent as Rb and Cs. Moreover, the Cs/Th and Rb/Th ratios are almost constant in soil, glass, and crystalline rock, which indicates that very little if any elemental fractionation by volatilization has taken place. We cannot completely rule out the possibility that Cd alone was volatilized to $\sim$70 percent. But the melting point of the glass is several hundred degrees above the volatilization temperatures of Cs and

Rb (*12*), and one would therefore expect these elements to be depleted as well, contrary to observation.

In previous work (*8, 9*), we have shown that elemental enrichment of lunar soil can be largely attributed to a meteoritic component equivalent to 1 or 2 percent chondritic material. Further enhancement of some elements (notably Rb, Cs, Cd, Tl) is due to a third alkali-rich component, not represented among the crystalline rocks so far collected. The third component is discussed more fully elsewhere (*9, 11*).

In order to characterize the meteoritic component in 12017 glass, we must correct for the indigenous abundances in the parent rock. No wholly satisfactory candidate for the parent rock of the glass is thus far known from studies of the Apollo 12 rocks; but, since the elements of interest do not vary greatly from one rock to another, we shall use the "12017 interior" values as an approximation of indigenous abundances. The difference between glass and interior then yields a nominal meteoritic component. To characterize this more closely, we have normalized the data to type 1 carbonaceous chondrite abundances (Fig. 1). We have plotted only those elements that show well-defined enrichments—that is, by a factor of 2 or more. Indium and thallium were excluded; the first, because of possible contamination from In-Ag gaskets on lunar sample containers, and the second, for reasons to be given later.

The distribution is essentially flat, which implies that the meteoritic component was of primitive composition, similar to carbonaceous or enstatite chondrites. (A solar-wind origin is qualitatively acceptable on compositional grounds but is quantitatively inadequate by many orders of magnitude.) Differentiated meteoritic material alone would give a totally dissimilar pattern. For example, ordinary chondrites would have given a stepwise pattern parallel to the dashed line in Fig. 1. Iron meteorites would yield high abundances of Ir and Au, and much lower abundances of the remaining elements.

The mean value for the meteoritic contribution calculated from these seven elements is equivalent to 0.5 ± 0.1 percent C1 material, which is considerably less than the value of about 1.8 to 1.9 percent found in Apollo 11 and Apollo 12 soils and breccias. This is not surprising. Much of the meteoritic material in the soil derives from micrometeorites and multiple impacts, whereas that in the 12017 glass is probably due to a single impact of a crater-forming projectile.

Some compositional differences between glass and interior cannot be attributed to meteoritic material. In particular, the parent material of the glass must have been slightly richer in Th, rare earth elements, and alkali metals than is the 12017 basalt (*10*). Thallium in lunar rocks is correlated with Rb and Cs, and thus a meteoritic Tl component calculated relative to the alkali-poor rock 12017 may be an overestimate. In principle, a corrected value for meteoritic Tl can be derived by using the known correlation with the other alkali metals (*8, 13*). Compounding of errors renders this procedure unattractive, and for this reason Tl was not included in the meteoritic component calculation.

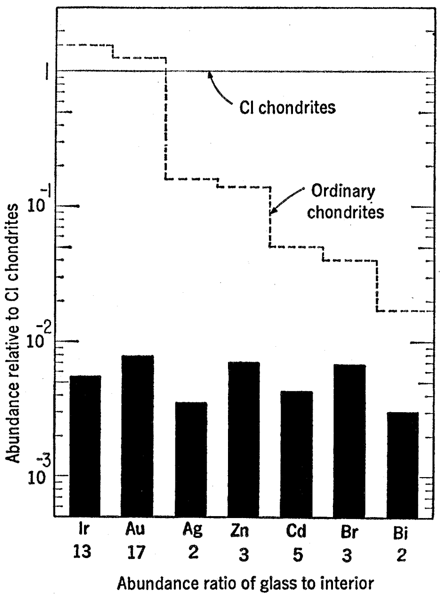

Fig. 1. Seven elements that are rare in lunar rocks but abundant in meteorites are enriched in glassy coating relative to the interior of lunar rock 12017. Enrichment factors are given on the abscissa. Bars represent excess in glass normalized to abundance in type 1 carbonaceous chondrites. The distribution is essentially flat, which suggests that the meteoritic component (about 0.5 ± 0.1 percent) had a primitive composition, similar to carbonaceous or enstatite chondrites. Ordinary chondrite material alone would have given a pattern parallel to the dashed line. The distribution can also be matched by a mixture of crystalline rock and 10 to 15 percent upper regolith soil, with 0.3 percent ordinary chondrite or 0.06 percent group I iron meteorite material. Apparently the glassy coating represents splashed-on impact ejecta, not a glazing produced by an intense burst of solar heat.

The resolution of our method does not exclude the possibility of a fractionated meteoritic component in the glass, if we allow a small amount of upper regolith soil to provide the observed abundances of volatile elements. Some evidence for this is found in Fig. 1, where Ag and Bi are lower relative to Ir and Au than would be expected for a type 1 carbonaceous chondrite pattern. The trace element abundances of the glass can be reasonably well matched by a mixture of crystalline rock and 10 to 15 percent upper regolith soil, plus a small fractionated meteoritic component (for example, about 0.3 percent ordinary chondrite or 0.06 percent group I iron meteorite).

Recent evidence presented by Hörz *et al.* (*14*) points unequivocally to an impact origin for the 12017 glass. Stereomicroscopic observations reveal that the melt from which the glass solidified was produced by shock compression and that the glass was deposited upon the rock at a relative velocity sufficient to fracture the substrate by shock. Shock melting requires minimum impact velocities of several kilometers per second, which are attained in primary impacts but not in secondary events. The observations by Hörz *et al.* (*14*) clearly substantiate a meteoritic impact origin for the glass coating on rock 12017, as proposed in this report and, more generally, by Greenwood and Heiken (*5*). In addition, they show that the glass was splashed onto the rock from some external source and was not formed in situ.

Gold's hypothesis (*1*) applied specifically to glass-covered rocks lying in small fresh craters, and there is no evidence that rock 12017 was found in such a location. Nevertheless, the glassy coating on at least one rock is now known to be the result of meteoritic impact. The application of Occam's Razor requires that we consider mechanisms by which such rocks could become located preferentially at the bottom of small fresh craters before we accept a radically new origin such as radiative heating. The question could be settled decisively if a glazed rock from a small fresh-looking crater were to be returned for analysis.

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Acadian Orogeny: An Abrupt and Brief Event

Abstract. *Rubidium-strontium dating indicates the Barre-type granites in eastern Vermont were emplaced at least 380 × 10⁶ years ago. This result suggests the Acadian orogeny was more abrupt than previously suspected, and is consistent with the hypothesis that the orogeny involves a collision between two sialic plates.*

The Devonian Acadian orogeny has long been recognized as encompassing the most intense period of deformation, regional metamorphism, and granite intrusion affecting the northern Appalachian Mountains. Throughout much of the region the relative sequence of events was as follows: (i) deposition of geosynclinal sediments as young as Early Devonian, (ii) deformation and regional metamorphism, and (iii) emplacement of granitic plutons. Many radiometric ages have been measured on the metamorphic rocks and the granites, but the values show a wide spread indicating some combination of slow cooling and younger thermal disturbances. This report presents a refinement of the measurement of the age of a series of granites in eastern Vermont, which results in a minimum age older than previously suspected. In conjunction with other data this result indicates that the Acadian orogeny was a very abrupt event. The data permit a span of not more than 30 × 10^6 years for a sequence of orogenic events which included the formation of large-scale nappes and the burial of rocks initially at the surface to a depth of 12 to 15 km prior to the emplacement of the granites.

A series of some 20 discordant granite plutons ranging from 0.5 to 10 km in diameter crop out in a 200-km belt along the eastern border of Vermont (*1*). The well-known monument stone quarried at Barre, Vermont, is typical of the granites, hence the application of the term, Barre-type granites, to the series. Medium-grained, equigranular, slightly foliated quartz-monzonite is the dominant and characteristic rock type, although some of the plutons contain minor amounts of rocks ranging from ultramafic and mafic to granitic in the strict sense. Primary muscovite coexisting with biotite and abundant quartz are characteristic of the granitic rocks. As will be demonstrated later, these granites were intruded late in the sequence of Acadian events, hence, dating the granites should give a reliable minimum age for the major Acadian events.

A K/Ar age of 349 × 10^6 years was previously reported for the Adamant granite northwest of Barre (*2*). This is recognized as a minimum age inasmuch as the same authors demonstrated that the region has been affected by later disturbances. Attempts to refine this age measurement have been frustrating. Within each pluton the granitic rocks are too homogeneous in their Rb and Sr content to yield whole-rock isochrons with adequately defined slopes, and the Rb/Sr ratios are too low to yield reliable "single-point" ages. There is no basis for assuming that the separate plutons are comagmatic or even that they formed at the same time, so there are no grounds for constructing an isochron for the series as a whole. Samples weighing 50 kg have yielded only a few milligrams of very fine-grained zircon, hence dating by this technique has not been attempted.

An attempt to see through these later disturbances has been made by studying the systematics of the mineral ages. Consistent with previous experience, coarse muscovite seems to retain most successfully its accumulated radiogenic strontium (Table 1). Coarse muscovite from the northernmost pluton yields an Rb/Sr age of 380 × 10^6 years, and samples of coarse muscovite handpicked from the southernmost pluton yield apparent ages of 383 × 10^6 and 377 × 10^6 years (*3*). These are regarded as reliable minimum ages for the plutons.

The biotite ages decrease systematically from north to south, which suggests a southward increase in the intensity of subsequent disturbance. Fine-grained muscovite fractions from the granites are also disturbed. Two of the granites yielded only the fine-grained muscovite, with apparent ages very close to those of the biotites. At first glance these might appear to be concordant-mica ages indicating these two plutons are younger than the others. Data on plagioclase and microcline, however, demonstrate that these rocks have also been disturbed. The apparent concordance is not significant.

The granites intrude country rock which was already intensely deformed and regionally metamorphosed. Large recumbent folds are indicated by the complex map pattern of the Standing Pond Amphibolite marker horizon (*4*, *5*). Rotated garnet porphyroblasts and the orientation of other porphyroblasts in planes parallel to the axial surfaces of the recumbent folds indicate that medium- to relatively high-temperature regional metamorphism accompanied this phase of the deformation (*6*). In most of eastern Vermont this metamorphism was of biotite to garnet grade, but there are several areas where the intensity reached kyanite-staurolite grade.

The contact aureoles (sillimanite- or andalusite-grade) surrounding the granite bodies are superposed on this earlier regional metamorphism, the pattern of whose isograds shows little correlation with the distribution of the granites. The granite bodies are only weakly foliated. They are sharply discordant and, although slightly elongated parallel to the regional trend, are much less deformed than the country rock. Locally (for example, around the Black Mountain granite at the southern end